How can Health Technology Assessment (HTA) support the optimal use of high-cost devices? A case study of robotic-assisted surgery in Scotland.

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Executive summary

Background and aims

Health technology assessment is a multidisciplinary process that evaluates the safety, efficacy, and cost-effectiveness of healthcare interventions, guiding evidence-based decisions and addressing social, organisational, and ethical issues. Traditionally, health technology assessment has been effectively applied to new drugs for reimbursement decisions post-regulatory approval, leveraging clear evidence on costs and consequences. However, high-cost medical devices present unique challenges that complicate the health technology assessment process, such as incremental development, context dependency (i.e. organisational impact), quality variation (i.e. evidence uncertainties) and physical mode of action (i.e. device-operator interaction). Additionally, health technology assessment is often overlooked at the time of equipment purchase, leading to uncertainties in assessing long-term value and impact.

Surgical robotics, specifically robotic-assisted surgery, exemplifies these challenges. Robotic-assisted surgery systems are expensive, complex, and have been rapidly adopted despite ongoing debates about their evidence base. In Scotland, significant investments in surgical robots were made in 2021, aiming to improve access to minimally invasive procedures and reduce health inequalities. Decision-makers now face the challenge of expanding robotic-assisted surgery services amidst these uncertainties.

Given the ongoing adoption and expansion of robotic-assisted surgery in Scotland, this thesis proposes there could be a role for health technology assessment methodology in addressing these associated uncertainties and helping decision-makers to prioritise the expansion.

This thesis aims to investigate whether health technology assessment can support the optimal use and implementation decisions for high-cost devices by taking a case study of robotic-assisted surgery in Scotland. This study seeks to determine how health technology assessment can guide future investment and expansion decisions, ultimately informing strategies for integrating innovative technologies into healthcare systems effectively.

Methods

To explore the role of health technology assessment in optimising the use of robotic-assisted surgery for Scottish decision-makers, this research employed a multi-step approach.

First, an overview review of clinical effectiveness evidence was conducted to identify which specialties and procedures were most likely to benefit from the expansion of robotic-assisted surgery. This review aimed to map the current landscape of evidence across intra-cavity procedures and pinpoint areas with the most robust comparative outcomes, thereby guiding where the use of robotic-assisted surgery may be most clinically appropriate.

Secondly, a scoping review of economic evaluations of robotic-assisted surgery was undertaken to identify what economic methods have been used in analysing robot-assisted surgery, to investigate how they addressed the challenges of robotic-assisted surgery in economic evaluation research and to explore what opportunity there is to improve methods of evaluation. Insights gained from this analysis informed the design of a tailored approach for economic evaluation of high-cost devices.

Third, a two-stage economic model was developed, informed by both the evidence reviews and stakeholder consultations which helped shape the model's scope and assumptions to ensure it addressed relevant policy questions and practical constraints. The first-stage model was a short-term, procedure-specific cost-utility analysis comparing robotic-assisted surgery with laparoscopic and open surgery across selected procedures: prostatectomy, colorectal resection, hysterectomy, and pancreaticoduodenectomy. The second-stage model integrated this into a system-level platform model, allowing for exploration of case-mix strategies, annual procedure volumes, and surgical replacement proportions across specialties. This experimental model enables decision-makers to simulate various utilisation scenarios and identify more efficient strategies for shared robotic-assisted surgery platform use under different capacity and investment constraints.

Results

From the overview of systematic reviews, most evidence was available in urology, colorectal, hepatopancreaticobiliary and gynaecology. A total of 165 systematic reviews were included comparing robotic-assisted surgery to laparoscopic and open surgery. In my developed novel evidence map, it presented the strength of evidence and its orientation. Within the selected procedures, the evidence (such as conversion rate, estimated blood loss, length of hospital stay, and postoperative complication) was largely neutral or positive for robotic-assisted surgery compared to both laparoscopic and open approaches with the exception of operative time. Evidence was more positive compared with open surgery. I found that most systematic reviews were of low quality due to a failure to deal with the inherent bias in observational evidence.

In the scoping review of economic evaluations, a total of 50 studies addressing the economic analysis of robotic-assisted surgery were identified. Cost-utility analysis (46%) was the most commonly applied economic evaluation method, followed by cost-consequence analysis (32%). Generally, I found the evidence on the cost-effectiveness of robotic-assisted surgery compared to open and/or laparoscopic surgery was mixed, with evaluations having a high degree of heterogeneity including multiple indications, outcomes, comparators, time horizons, perspectives and settings. Distinctive features related to the assessment of robotic-assisted surgery were under-addressed in economic evaluations. Only 40% of the included studies considered learning curve and organisational impact including capital cost investment, annual volume of procedures and platform sharing, and less than 12% of the included studies reflected on incremental innovation and dynamic pricing. Only two studies addressed the fact that the surgical platform was shared. Overall, a large proportion of economic evaluations did not explicitly account for the specific characteristics of robotic-assisted surgery. It is clear that to have a more realistic assessment of the cost-effectiveness of robotic-assisted surgery, economic analysis should consider these distinctive features to ensure its optimal utilisation in clinical practice.

In the two-stage economic model evaluation, stage one demonstrated that while robotic-assisted surgery consistently offered higher utility gains compared to laparoscopic and open surgery, its cost-effectiveness varied significantly by procedure. Among the procedures studied, robotic-assisted surgery was not cost-effective against laparoscopic surgery, but showed more favourable results when replacing open surgery, particularly in prostatectomy. Scenario analyses indicated that removing capital costs, representing settings where surgical robots are donated or externally funded, substantially improved the cost-effectiveness of robotic-assisted surgery. However, even in such cases, the opportunity cost of the capital investment must still be considered, especially when viewed from a system or national perspective. Sensitivity analyses identified utility values, length of stay, and operative time as the most influential drivers of cost-effectiveness. These variables also helped explain the findings of the threshold analyses, which showed that increasing the proportion of open surgery replaced by robotic-assisted surgery consistently reduced incremental cost-effectiveness ratios. Stage two extended the analysis to the system level, showing that cost-effectiveness depends on both procedural mix and surgical volume. Economies of scale were critical, with most strategies only becoming cost-effective at ≥350 cases annually, or when focused on high-impact procedures. These findings highlight that RAS can represent value for money if strategically deployed at sufficient volumes and targeted to procedures with the greatest marginal benefit.

Conclusion

This thesis highlights the critical role of health technology assessment in supporting the optimal adoption and utilisation of high-cost medical devices, with a specific focus on robotic-assisted surgery. The research demonstrates that health technology assessment provides a vital tool for decision-makers, facilitating a structured approach to assess the clinical effectiveness, cost-effectiveness, and broader implications of innovative technologies.

The overview of clinical effectiveness narratively summarises the evidence and maps it into a novel evidence spectrum. It showed that evidence for robotic-assisted surgery is largely neutral or positive compared to laparoscopic and open approaches. This suggests that selective adoption of robotic-assisted surgery could improve patient outcomes through strategic replacement of more invasive techniques.

The scoping review of economic evaluations revealed that key features unique to robotic-assisted surgery, such as the learning curve, platform-sharing potential, volume sensitivity, and dynamic pricing, are often neglected in existing models. Incorporating these elements can offer a more realistic and comprehensive understanding of robotic-assisted surgery's value, guiding more efficient decisions around adoption and scale-up.

Building on these insights, a two-stage system-level economic model was developed, offering a novel approach to guide resource allocation and utilisation strategies post-acquisition. Stage one assessed procedure-level cost-effectiveness; stage two allowed decision-makers to test alternative configuration scenarios, such as case-mix, annual volumes, and replacement strategies, based on their local context. The framework provides decision-makers with a practical tool for planning, emphasising that the role of RAS lies not only in clinical outcomes but also in enabling broader access to minimally invasive surgery and guiding resource-efficient service delivery.

While the model provides recommended prioritisation strategies, successful implementation depends on operational realities such as workforce capacity, procedural demand, and existing infrastructure. Nonetheless, its adaptability allows for iterative refinement as new data and service constraints emerge.

Ultimately, this thesis demonstrates that HTA can be applied not only at the point of adoption but throughout the technology's lifecycle, from early evaluation to post-investment optimisation. Though centred on RAS, the insights and methods presented here are generalisable to other high-cost, cross-specialty platform technologies. The research provides a robust and adaptable framework for ensuring that such innovations are integrated into healthcare systems in a cost-effective, evidence-informed, and context-sensitive manner.

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Author's Declaration

I declare that this dissertation is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution. This PhD research was self-funded and received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. I declare that I have no conflicts of interest.

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Publications and presentations

The following publications and conference presentations are a result of the research conducted for this PhD.

Published

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Lai TJ, Heggie R, Kamaruzaman HF, Bouttell J, Boyd KA. **Economic Evaluation of Robotic-Assisted Surgery: Methods, Challenges, and Opportunities: A scoping review**. Applied Health Economics and Health Policy. 2024 Sep 27.

In preparation

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Published Conference Presentations, Posters & Competition

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Lai TJ, Heggie R, Bouttell J, Boyd KA (2023). SA50 **Economic Evaluation of Robotic-Assisted Surgery: Methods, Challenges, and Opportunities**. ISPOR Europe 2023, Copenhagen, Denmark. Value in Health, Volume 26, Issue 11, S2.

Lai TJ (2023). **Is it worth investing in surgical robots?** Three minutes Thesis. STEMM Winner & Finalist. University of Glasgow.

Abbreviations

CBA	Cost-Benefit Analysis
CCA	Cost-Consequence Analysis
CEA	Cost-Effectiveness Analysis
CHEERS	Consolidated Health Economic Evaluation Reporting Standards
CMA	Cost-Minimisation Analysis
CUA	Cost-Utility Analysis
EMA	European Medicines Agency
EQ-5D	European Quality of Life Five Dimension
EU	European Union
FDA	Food and Drug Administration
GI	Gastro-Intestinal
HPB	Hepato-Pancreatico-Biliary
HTA	Health technology assessment
ICER	Incremental Cost-effectiveness Ratio
IDEAL	Idea, Development, Exploration, Assessment, and Long-term Study
INMB	Incremental Net Monetary Benefit
LS	Laparoscopic Surgery
MD	Medical Device
MDR	Medical Device Regulation
MIS	Minimally Invasive Surgery
MRC	Medical Research Council
NHS	National Health Service
NICE	National Institute for Health and Care Excellence
NIHR	National Institute of Health Research
NMB	Net Monetary Benefit
NSF	National Strategic Framework
OWSA	One-Way deterministic Sensitivity Analyses
QALY	Quality-adjusted Life Year
RAS	Robotic-Assisted Surgery
RCT	Randomised Controlled Trial
RWE	Real-world Evidence
SHTG	Scottish Health Technologies Group

SRs	Systematic reviews
UK	United Kingdom
US	United State
WTP	Willingness To Pay

Chapter 1 Introduction

1.1 Health technology assessment

Health technology assessment (HTA) can inform evidence-based healthcare decision-making via a multidisciplinary process to systematically examine the safety, efficacy, and cost-effectiveness of new healthcare interventions, and identify any social, organisational, and ethical issues concerning adoption (Banta and Jonsson, 2009, Battista and Hodge, 1999). In essence, the primary objective of HTA is to measure the value of health technologies, emphasising the inclusion of supplementary evidence and criteria that capture multiple dimensions of value (Goodman, 2014).

A health technology itself is a very broad term; is an intervention developed to prevent, diagnose, or treat medical conditions; promote health; provide rehabilitation; or organise healthcare delivery. The intervention can be a test, device, medicine, vaccine, procedure, program, or system (Goodman, 2014, HTAi, 2020). The central purpose is to inform decision-making in order to promote an equitable, efficient, and high-quality health system.

HTA has traditionally been applied to new health technologies, especially drugs, as part of a reimbursement decision-making process once the technology has satisfied regulatory approval. HTA is then used to synthesis evidence on costs and consequences, alongside the associated uncertainty (Claxton et al., 2002). From a broader perspective, the definition of HTA has been updated by the INAHTA[1] and HTAi[2] and described as a process adopting explicit methods to determine the value of health technology at different points in its lifecycle (O'Rourke et al., 2020, HTAi, 2020, INAHTA, 2020).

Within the context of HTA, which is underpinned by a comprehensive evaluation, the aim is to apprise policymakers of the societal value associated with a specific allocation of resources, ultimately seeking to enhance social welfare (Angelis et

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[1] International Network of Agencies for Health Technology Assessment

[2] Health Technology Assessment International

al., 2018, Nicod and Kanavos, 2016). HTA can be considered as a “bridge” between the scientific evidence and the decision maker’s choice (Lampe et al., 2009).

1.2 Challenges of medical devices assessment

The medical device (MD) industry is one of the most dynamic contributors to health innovation, with thousands of new products introduced to the market each year (Kirisits and Redekop, 2013). The wide range of technologies classified under the term ‘medical devices’ has faced growing scrutiny concerning their assessment. In the evaluation process, several device-specific factors have emerged, each of which can complicate comprehensive assessments.

According to the European Union Directive (EU, 1993, EU, 2007, EU, 2017), a medical device is defined as any instrument, apparatus, software, material, or other article intended for use alone or in combination with accessories for diagnostic and/or therapeutic purposes, where such use is essential for its proper application.

Kirisits et al (Kirisits and Redekop, 2013) categorised the device-specific factors into external factors and device-level factors. External factors, such as the regulatory requirements a medical device manufacturer must meet before gaining market approval, as well as early-market rapid diffusion, resulting in challenges of balance timeless of evaluation against availability of evidence. Regarding device-level factors, they include the challenge of conducting randomised controlled trials (RCTs) in this space. RCTs can be particularly difficult due to ethical concerns and patient reluctance, especially when surgical procedures are involved. This leads to clinical data quality issues. Other factors, such as procedural integration, means that many devices need to be used as part of a medical procedure, and a lot of them are designed to serve multiple purposes. A surgery-related device often involves a learning curve, especially comparing a traditional surgical procedure with a new procedure involving a device. The clinical outcomes from RCTs can vary depending on the skill and experience of the surgeon and surgical team. It can be the skill in the intervention and or comparator arms. This device-operator interaction introduces potential confounders in the analysis of a device’s efficacy. Additionally, organisational implications of device introduction, especially larger and more complex devices, such as electromechanical equipment (e.g., X-ray and MRI machines), require significant upfront investments to yield long-term benefits. These investments are often accompanied by substantial annual operating costs. To address potential concerns from healthcare payers regarding these initial investments, it is crucial to provide a comprehensive analysis of upfront costs, ongoing expenses, and anticipated benefits over time to enable efficient and fully informed decisions. Influential factors also can be related to their user-driven nature, which often necessitates continuous iterative improvements or modifications. This dynamic nature, coupled with the shorter lifespan of many devices, contributes to significant variability in pricing. Medical devices may frequently undergo updates that can affect their performance and cost-effectiveness. The high sunk costs associated with the development of new medical devices, along with the depreciation of technology over time, further complicate the pricing landscape.

These unique characteristics of MDs including diversity, complexity, incremental innovation, context dependency and physical mode of action pose additional challenges to their assessment.

1.3 Motivation

Surgical robotics are an example of innovative technologies that are expensive, complex, and have uncertain clinical effectiveness. Nevertheless, they have been rapidly adopted worldwide in recent years.

In Scotland, robotic assisted surgery (RAS) was first introduced at the Aberdeen Royal Infirmary with the approval in 2014 of a minimally invasive theatre investment. The year after, the purchase of a robotic surgery system allowed the National Health Service (NHS) Grampian to provide a RAS service in prostate cancer (NHSGrampian, 2020). In 2021, the Scottish government announced a national investment of £20 million in 10 surgical robots to improve equity of access to non-invasive procedures and to reduce health inequalities (NHSScotland, 2021b). Unlike drugs, there is no standard HTA process for high-cost medical devices in

Scotland. Instead, investment was government-led and to my knowledge, the procurement process did not involve HTA.

Having invested in the robots, decision-makers are now facing the challenge of how to establish agreed surgical expansion areas for RAS across Scotland. The national RAS review group consensus is that NHS Scotland, in the next horizon of expansion of RAS, should focus on oncological, gynaecology and colorectal, alongside the continued progression in urology and thoracic. Hepato-pancreato-biliary and upper gastrointestinal could be considered also in future development to reduce unwarranted variation.

Scottish decision makers now face decisions about the best way to utilise the purchased robotic systems. It is therefore a timely topic to consider for a case study that can explore whether HTA can be used to support the decision issues of future investment or implementation decisions for high-cost devices. Further exploration is warranted to understand how HTA can be used to optimise its use and direct expansion of capacity when a decision is being made.

1.4 Aims and objectives

The overall aim of the thesis is to investigate whether (and how) HTA can be used to support the optimal use of high-cost devices for implementation decisions. The case study here focuses on the use of RAS in Scotland. The first step in HTA is to establish safety and efficacy evidence base. Therefore, I assume it is key for Scottish decision-makers is to ensure that patient safety is prioritised and that the selected procedures considered for RAS are at least equally effective compared to traditional methods and to understand the procedures where RAS would likely expand next. Secondly, Scottish decision-makers must assess the cost-effectiveness of RAS for selected procedures. Importantly, it is necessary for Scottish decision makers to optimise the initial investment and to maximise the cost-efficient use of RAS. Thus, I also needed to understand what methods had previously been used to conduct the economic evaluation element of RAS and what challenged were faced in order to help me design my approach and make it adoptable and feasible.

Therefore, this thesis will adopt an HTA approach and address the following research questions:

1. Does the current clinical effectiveness evidence support the adoption of RAS in intracavity procedures identified in Scotland?

2. How has cost-effectiveness been assessed and what economic evidence is there to support the use of RAS?

3. What can economic analysis contribute to decisions on how to optimise utilisation of RAS?

1.5 Thesis structure

Chapter 1 introduced the thesis. I began by providing some background to the issue for the assessment of medical devices. I then showed the current issues of surgical robots' adoption that Scottish decision-makers are facing and specified the objectives of my thesis.

Chapter 2 reviews current literature and guidelines and explores the context of healthcare innovation and complex interventions. This poses the evaluation challenges around RAS as a complex surgical innovation.

Chapter 3 comprises an overview of systematic reviews and addresses the first research question. This review aims to identify the current state of clinical effectiveness for the robotic surgery system and to explore the evidence on the specialties which have been identified of interest to NHS Scotland.

Chapter 4 comprises a scoping review and addresses the second research question. This review aims to identify the cost-effectiveness evidence of RAS and determine what economic evaluation methods have been used to assess RAS and how the challenges in the evaluation of RAS have been addressed in the economic evaluation literature.

Chapter 5 presents an experimental economic evaluation model and addresses the third research question. It aims to explore how economic analysis can inform optimal utilisation strategies for robotic-assisted surgery and guide strategic planning and resource allocation in real-world healthcare settings.

Chapter 6 provides an overall discussion, synthesising findings from the three studies. It reflects on the contribution of this research to the wider field of HTA for high-cost technologies, outlines key implications for policy and practice, offers practical recommendations, and identifies areas for future research.

Chapter 2 Context

This chapter will explore the context and challenges of evaluating high-cost innovations such as surgical robotics. I will focus on the aspects that complicate their assessment by reviewing current literature and guidelines.

First, the timing of evaluating medical innovations is crucial but challenging (Section 2.1). Medical innovations, like surgical robotics, often diffuse rapidly, leading to situations where their use outpaces the availability of evidence. This creates uncertainty about when and how to evaluate and regulate these innovations effectively.

Second, medical devices and surgical innovations present unique characteristics (Section 2.2). Medical devices undergo incremental development which is context-dependent and face quality variations, such as evidence uncertainties. These factors complicate the evaluation process and demand different methodological approaches.

Third, many device-related innovations, including surgical robotics, can be considered complex interventions due to the multiple inter-related stages involved (Section 2.3). The complexity of these stages contributes to the overall challenges of evaluating such technologies.

Finally, I will examine the current theoretical frameworks relevant to these aspects and discuss how they can be integrated to form the methodological approach used in this thesis (Section 2.4).

2.1 Innovation in healthcare

2.1.1 Definition of healthcare innovation and its issues

The development of innovative healthcare technologies is encouraged as they promise advancements in addressing global health problems. The World Health Organization (WHO) has envisioned a global health innovation movement to expedite the realisation of 'health for all' and health-related sustainable development goals. This movement aims to enhance the efficiency, effectiveness, quality, sustainability, safety, and affordability of healthcare. It encompasses improvements in health policies, practices, systems, products, technologies, services, and delivery methods to enhance treatment, diagnosis, education, prevention, and access to healthcare. (Schweitzer et al., 2015, WHO, 2022).

'Innovation' is often positively regarded, receiving unqualified praise for its effects. However, the role of innovation in quality improvement is complex. Dixon-Woods et al identified three paradoxes of innovation in healthcare (Dixon-Woods et al., 2011). First, there is the paradox of 'uptake of the dubious, rejection of the good.' Some innovations spread rapidly but lack proven value, have restricted applicability, or pose risks. The absence of proven efficacy could potentially lead to efficacious innovations remaining undiscovered, hindering their diffusion. Second, 'the wisdom and failings of democracy'. Participatory, cooperative approaches may be the best way of achieving sustainable, positive innovation. However, professional groups are themselves susceptible to persuasion and manipulation by commercial forces either directly or indirectly that may cripple their ability to display in the interests of the public good. Thus, relying merely on such approaches may impede positive innovation. Third, 'health systems are never able to keep up'. The pace of innovation is so fast that quality improvement systems are rarely able to catch up. Once quality-assurance systems have kept up with the 'new' modality, things have already moved on again. As a result, having a cycle of renewal and reinvention of innovation creates turbulence in organisations. Improvement depends upon change, but change is always followed by new challenges. Dixon-Woods et al pointed out that the current evaluation of innovation is often too narrowly focused on the effects of new practices or technologies. It was argued that new approaches to address these issues are needed.

2.1.2 Diffusion of innovations

James W. Dearing and Jeffrey G. Cox proposed a framework, 'The Diffusion of Innovations Theory' to explain how new ideas, technologies, and practices spread through society (Dearing and Cox, 2018). This theory has evolved over the years, and its origins can be traced back to the early 20th century. The first major study of diffusion was conducted by French sociologist Gabriel Tarde, who proposed that innovations spread through society through imitation. Later, American sociologist Everett Rogers expanded on Tarde's work and developed the Diffusion of Innovations Theory.

According to the theory, the adoption of new ideas or technologies follows a predictable pattern. It begins with innovators, a small group of people who are willing to take risks and try new things. Next are the early adopters, who are opinion leaders and serve as role models for others. The early majority and late majority follow, who are more cautious and adopt new innovations after they have been proven effective. Finally, the laggards, who are resistant to change and adopt new innovations only when they have become mainstream.

The theory is based on several key principles, including innovation, communication channels, social systems, time, and adopters. Innovations are new ideas, technologies, or practices that are perceived as better than the existing ones. Communication channels are the means by which information about innovations is transmitted, such as mass media or personal networks. Social systems are the groups, organisations, or communities in which innovations are adopted. Time refers to the rate at which innovations are adopted, and adopters are the individuals or organisations that adopt new innovations. The authors also highlight the different stages of the diffusion process, including knowledge, persuasion, decision, implementation, and confirmation.

James W. Dearing and Jeffrey G. Cox indicated the importance of understanding the context of the healthcare system and the social and cultural factors that may affect the adoption and implementation of new health interventions. The authors suggested that a deep understanding of the social and cultural context can help to tailor the implementation strategy and increase the chances of successful adoption and implementation.

However, there are challenges associated with the diffusion of innovations in healthcare. It is noted that the adoption and implementation of new health interventions often face resistance from stakeholders, including healthcare providers, patients, and policymakers. Resistance can arise from a lack of evidence, concerns about safety, costs, and uncertainty about the benefits of the innovation.

2.1.3 Dilemma of control in innovation

David Collingridge was one of the crucial pioneers in the field of science and technology studies. He developed a distinctive and substantive line of thinking concerning the ‘social control of technology’ and brought contemporary concerns about responsibility and accountability in innovation, public engagement with science and technology, and the role of scientific expertise in technology policy (Collingridge, 1982). Responsible innovation has been a concern, focusing on the risks and 'control' in the governance of science and technology. This includes challenges in coordinating different governance methods, understandings, and responsibilities, especially with emerging technologies (Donnelley, 1989). Stilgoe et al also indicated that the governance of emerging science and innovation is a major challenge for contemporary democracies (Stilgoe et al., 2013). There have been concerns, especially about the environmental and health consequences associated with the operation of new technologies implicated in scientific discoveries and inventions (Stirling, 2016) . The 'dilemma of control' was the most frequently discussed theme, and it can be summarised as follows: *“attempting to control a technology is difficult…because during its early stages, when it can be controlled, not enough can be known about its harmful social consequences to warrant controlling its development; but by the time these consequences are apparent, control has become costly and slow”* (Collingridge, 1982). This ‘Collingridge dilemma’ can be reflected in the development of health technology, when consequences are clear, ’control’ is drastic and costly as the technology has been well diffused and integrated into healthcare system (Genus and Stirling, 2018, Collingridge, 1982). Buxton’s research on the topic of problems in the appraisal of new health technology also indicated that *“It’s always too early to assess a new technology until, suddenly it’s too late!”* (Buxton, 1987). In the case of high-cost innovative devices, such as surgical robotics, where evaluation may follow the initial investment, evaluation could be thought of as being ‘too late’.

Medical innovations, such as surgical robotics, often spread rapidly, sparking debates about appropriate evaluation methods. This can lead to their adoption outpacing the availability of evidence, creating uncertainty about the timing and approach to effective evaluation and regulation. This is particularly relevant for high-cost innovative devices like surgical robotics, where evaluation often takes place after the initial investment, making it potentially "too late" to address any unforeseen issues. Many may argue that the horse has bolted and robotic surgery is here to stay (Paul et al., 2013). Dahm et al (Dahm et al., 2014) noted that society has been fortunate that RAS in prostatectomy has not faced significant problems, especially considering the concerns raised about other robotic surgery applications. However, as the use of RAS expands into other specialties, we still lack certain evidence to fully assess its broader impact and effectiveness. While RAS has shown promise in certain areas, more comprehensive and timely evaluations are needed to ensure its safe and effective use across various surgical fields.

2.2 Innovation development and assessment

2.2.1 Medical devices and their challenges of assessment

A "medical device" under the EU MDR 2017/745 (EU, 2017) refers to any instrument, apparatus, software, implant, reagent, or similar article intended for use in humans for medical purposes, such as diagnosis, prevention, monitoring, treatment, or alleviation of diseases and injuries. It also includes devices used for modifying anatomy, physiological processes, or providing medical information through in vitro examinations of specimens. Medical devices do not achieve their principal effect through pharmacological, immunological, or metabolic means, though they may assist in these functions. The difference between medical devices and other health products is their mechanism of action which is physical rather than biochemical, and it does not achieve its principal intended action in or on the human body by pharmacological, immunological, or metabolic means, but may be assisted in its function (EU, 2007, Taylor and Iglesias, 2009).

MDs are complex because they often involve a user, and their impact may be dependent on the context of their use. That means that the innovative proposition is potentially wider in scope in that they have to be developed from an incremental improvement of existing technology to a completely new treatment modality which solves a problem that cannot be managed by existing treatment options. (Gelijns, 1990, Campbell, 2008). A single medical device is user-driven and may be subject to continuous iterative improvements or modifications, while the new drug may remain on the market for many years with no fundamental changes once it is approved (Gelijns, 1990).

Due to the characteristics of MDs, including diversity, complexity and incremental innovation, there have been a number of reported challenges for their assessment.

Sorenson et al. (Sorenson et al., 2011) discussed the challenges associated with the assessment of MDs. They highlight the complexities of evaluating medical devices. One of the main challenges in assessing medical devices is the lack of standardisation in terms of data collection and reporting. MDs are often developed and marketed in a decentralised way, with different manufacturers collecting data in different ways. This can make it difficult to compare the outcomes of different devices and to identify the most effective devices. Schnell-Inderst et al. (Schnell-Inderst et al., 2015) also highlight the lack of available evidence for medical devices, as many devices are developed and marketed without undergoing rigorous clinical trials. In most cases of running clinical trials, patients can be reluctant to enter RCTs if they are concerned about being randomised to an invasive surgical procedure and/or may not get the device/intervention they want. Due to ethics, patient and professionals generally know which device has been used, but it is with the risk that biases can be introduced.

A further challenge in assessing medical devices is the differences in regulatory requirements across countries (Sorenson et al., 2011). Different countries have different regulatory frameworks for assessing medical devices, which can lead to differences in the evidence required for approval. This can make it difficult to compare the effectiveness and safety of devices across different markets. For example, in the case of a surgical device, Transcatheter Aortic Valve Implantation (TAVI), the US Food and Drug Administration (FDA) required that its clinical evidence should be the same as for drugs, based on RCTs, while the EU European

Medicines Agency (EMA) required the establishment of a clinical registry to conduct observational research (Sorenson and Drummond, 2014).

Schnell-Inderst et al. (Schnell-Inderst et al., 2015) argues that there is a need for a more systematic approach to the assessment of MDs, which takes into account the specific characteristics of each device. This would involve developing standardised methods for data collection and reporting, as well as more appropriate methods for evaluating the clinical effectiveness of medical devices. The authors also emphasised the importance of collaboration between stakeholders, including manufacturers, healthcare providers, and regulators, to ensure that assessments of medical devices are consistent and transparent.

Previous research (Drummond et al., 2009, Taylor and Iglesias, 2009, Sorenson et al., 2011, Schnell-Inderst et al., 2015, Craig et al., 2015, Drummond et al., 2018) have all indicated that the distinctive characteristics of MDs that differ from drugs include the physical mechanism of action, the iterative and rapid development process, and external factors such as regulation. These differences can make it difficult to perform comparative effectiveness research and require modifications to assessment methods.

Some MDs are related to surgical procedures. For example, high-risk implantable devices are combined with surgical procedures and are part of a complex intervention. The impact of a medical device's effectiveness can be influenced by various contextual factors, such as the characteristics of its users, additional care provided, and other therapies used alongside it. This complicates the process of measuring the size of its treatment effect, and the complexity and invasiveness of the device can also pose challenges in conducting RCTs. A surgery-related device often involves a ‘learning curve’, especially comparing a traditional surgical procedure with a procedure involving a new device. The clinical outcomes from RCTs can depend on the skill or experience of the surgeon. User performance has device-operator interaction that is a potential confounder in the analysis of the efficacy of devices. This can be viewed as the ‘learning curve of the device-user interaction’. The iteration of MD with short product life cycles, also makes it challenging to conduct RCTs with sufficient sample size and follow-up. Additionally, device introduction policy in hospitals, e.g. training programmes, allows the whole surgical and support team to become more familiar with the technology which might benefit operative time and clinical outcomes. The implementation of high-cost medical devices has significant organisational impact, requiring capital investment and training. This is related to wider economic and organisational implications that may be important for harnessing the improvement of the cost-effectiveness of a device (Schnell-Inderst et al., 2015, Tarricone et al., 2017a).

Regulatory bodies in Europe and the US primarily emphasise safety and performance when assessing medical devices for market access, rather than clinical effectiveness. This often leads to a lack of evidence on clinical effectiveness during the initial market access phase for many medical devices. MDs can take a route of premarket approval, US FDA "510(k) procedure". The manufacturer only has to submit the substantial equivalent of the new product research (Sorenson and Drummond, 2014). This premarket approval process does not incentivise extensive clinical studies pre-approval and leads to lower evidentiary standards (Broholm et al., 2016). The da Vinci robotic device (Intuitive Surgical, CA, USA) obtained FDA approval through a premarket approval pathway (Dahm et al., 2014).

Given the need for a systematic approach for evaluating the clinical effectiveness of MDs, a new Medical Device Regulation (MDR) (Regulation 2017/745/EC) (EU, 2017) was published in 2017. According to the new MDR (2017/745/EC), 'clinical evaluation' refers to a systematic and planned process to continuously generate, collect, analyse and assess the clinical data pertaining to a device in order to verify the safety and performance, including clinical benefits, of the device when used as intended by the manufacturer. Clinical evaluation is conducted throughout the life cycle of a medical device, as an ongoing process. MDR uses a rule-based classification scheme for medical devices. All devices fall into four basic categories: non-invasive devices, invasive medical devices, active medical devices, and special rules (including contraceptive, disinfectant, and radiological diagnostic medical devices). There are 22 rules in Annex VIII of the MDR, including: duration of use, invasiveness, active devices, and level of regulatory control. These devices are further segmented into the classes noted below.

Table 2.2-1 Risk class of Medical Devices based on Regulation 2017/745/EC

Class	Risk
Class I	• Provided non-sterile or do not have a measuring function (low risk) • Provided sterile and/or have a measuring function (low/medium risk); the MDR adds to this group, reusable surgical instruments as Class I reusable surgical instruments.
Class IIa	medium risk
Class IIb	medium/high risk
Class III	high risk; active implantable devices follow this requirement.

Although the new Medical Device Regulation (MDR) (Regulation 2017/745/EC) (EU, 2017) has been updated which strengthens and emphasises the clinical evaluation, the surgical robots e.g. da Vincci have attained approval before this new MDR. However, based on the new MDR, most surgical robots are classified as Class IIb due to their role in assisting surgery and the associated risks. However, the specific classification can vary based on the device's intended use, complexity, and interaction with patient safety.

2.2.2 Robot-assisted surgery and its current usage

For decades, scientists have made efforts to overcome the issues with invasive surgery, including reducing complications and trauma through the use of new instruments and smarter techniques. Conventional intra-cavity minimally invasive surgery (MIS) was developed using laparoscopic surgery (LS). Intra-cavity access is gained through very small multiple incisions, which are less invasive and less traumatic than conventional incisions, avoiding wound-related morbidity with better cosmetic results compared to open surgery. Since the 1980s, MIS has rapidly grown as it is viewed as more desirable (Siddaiah-Subramanya et al., 2017, Jaffray, 2005, George et al., 2018). RAS can be seen as an extension of LS. It is a telemanipulation system comprising a surgeon console, computerised control system, and patient-side cart that houses the robotic arms with a dual telescope and surgical instruments. RAS offers improved dexterity, better ergonomics, and enhanced fixed operator-controlled visualisation and retraction, thus improving the capabilities of surgeons during complex surgery (Siddaiah-Subramanya et al., 2017). In 2000, RAS was approved by the U.S. Food and Drug Administration (FDA) and European Medicines Agency (EMA) with the CE (Conformité Européenne) mark for the use of urologic, general laparoscopic, gynaecologic laparoscopic, general non-cardiovascular thoracoscopic, and thoracoscopically-assisted cardiotomy surgical procedures in adults and paediatrics (FDA, Intuitive, 2001, Meadows, 2005). The use of RAS has grown rapidly and is performed worldwide, with 12 million procedures performed using the da Vinci® system since 2000 to date. In the past five years, the number of da Vinci® systems installed worldwide has grown by an average of 11% per year (Intutive, 2022). RAS is primarily concentrated in urology, gynaecology, and general surgery. In these specialties, the technology is often promoted as a solution to address certain technical or anatomical challenges specific to various surgical procedures.

Given the motivation of this thesis is a case study in Scotland, here provides the background information of the use of RAS in Scotland based on the National Strategic Framework report. Before the National RAS investment decision, patients across Scotland did not have equal access to minimally invasive surgery (MIS) or RAS for the same condition, leading to inconsistent outcomes (quality control issue) and inequalities in access. Therefore, the NHS Scotland National Planning Board wanted to address this issue, reducing unwarranted variation in surgical approaches, especially for cancer surgery.

In Scotland, two Minimally Invasive Theatres (MITs) investments were approved from local authority in 2014 at Aberdeen Royal Infirmary which recognised the first RAS introduction. The year after, the business case got approval for the purchase of the first robot da Vinci® system that allowed the NHS Grampian to provide the first RAS service with the indication of prostate cancer (NHS-GRAMPIAN, 2020). Before the Scottish government level investment in 2021 to purchase ten surgical robots , there were five surgical systems in clinical use within intracavity surgery which is available in NHSScotland which are (i) Da Vinci® RAS system in NHS Greater Glasgow and Clyde; (ii) Da Vinci® and Versus® RAS systems in NHS Lothian; (iii) Da Vinci® RAS system in NHS Grampian; (iv) Da Vinci® RAS system in Golden Jubilee National Hospital, providing specialist thoracic surgery since 2018 (SHTG, 2021). Dundee Institute for Healthcare Simulation also has an older DaVinci® system, which is only suitable for training purposes.

According to National Strategic Framework in Scotland, the three regional robotic systems were initially used for robotic-assisted radical prostatectomy, supported by funding from the Scottish Government, charities, and local Board funds. NHS Grampian was an early adopter of RAS for partial nephrectomies and hysterectomies. In 2018/19, the Edinburgh and Glasgow teams began performing robotic-assisted partial nephrectomies. Plans are currently underway to expand RAS into areas such as colorectal surgery and trans-oral robotic surgery for selected head and neck cancer cases. NHS Lothian has recently partnered with the Versius® Surgical robotic system under a contract that includes a planned review after 12 months to assess the program and decide on its continuation. The programme is starting with RAS for rectal cancer, following the evidence (SHTG, 2018b). HTA agency in Scotland - 'Scottish Health Technologies Group (SHTG)' has conducted rapid reviews and provided advice on usage of robot-assisted partial nephrectomy for renal cancer (SHTG, 2018a), transoralrobotic surgery (TORS) for oropharyngeal and laryngeal cancer (SHTG, 2018c), and robotic rectal cancer surgery (SHTG, 2018b). A lately report from SHTG (Harbour, 2019) which comparing evidence for cancer indications has indicated the quantity and quality of evidence varies significantly between cancer indications.

The National Strategic Framework report analysed 2018/19 data for Scotland and all NHS Boards, providing insights into surgical approaches across different disease areas. In gynaecological oncology, a total of 1,046 hysterectomies for cancer diagnosis were performed that year. Of these, 53% were conducted via open surgery, 44% were performed laparoscopically, and only 3% were carried out using RAS. For colorectal, in 2018/19, 1,607 rectal resections were performed that year, with 71.5% done by open surgery, 28.5% by laparoscopic methods, and 0% by RAS. (During the time of writing this thesis, I received the data showing that Glasgow Royal Infirmary is currently increasing the proportion of using RAS). For urology, in 2018/19, there were 612 prostatectomies performed, with 5.2% done by open surgery, 13.9% laparoscopically, and 80.9% using RAS. For 161 partial nephrectomies, 56.5% were open, 6.8% laparoscopic, and 36.6% by RAS. Finally, of 200 cystectomies, 88.5% were open, 1.5% laparoscopic, and 10% by RAS. Unwarranted variation in some HPB surgeries has been highlighted by the HPB National Managed Clinical Network to the National Planning Executive Group, prompting the exploration of pancreatic surgery and RAS. In 2018/19, 268 pancreatic surgeries were performed in Scotland, with 97.4% done via open surgery and 2.6% laparoscopically, suggesting potential benefits of RAS for this complex surgery.

2.2.3 Surgical innovation and its assessment

Surgical innovation refers to the development and introduction of new techniques, technologies, procedures, or approaches in surgery aimed at improving patient outcomes, enhancing surgical precision, reducing complications, and optimising healthcare efficiency. This can include new surgical techniques (e.g., minimally invasive surgery), advancements in surgical tools and devices (e.g., robotic systems, laser surgery), improved perioperative care strategies (e.g., enhanced recovery protocols) and new biomaterials and implants (e.g., 3D-printed prosthetics). Recent advancements in surgical technology, including robotics, AI, 3D printing, and regenerative medicine, have seen significant growth. For instance, the use of robotic systems in general surgeries has surged, with more than 50% of surgeons incorporating robotics into their procedures by 2023, compared to far fewer a decade ago (RCS, 2018, Brodie and Vasdev, 2018, RCS, 2019).

An earlier initiative between 2007 to 2009 highlighted this issue of conducting high-quality trials in surgery and discussed what could be done to improve the evidence base for surgery. It was addressed that surgical innovations inevitably follow a pathway with important differences from that followed by pharmacological developments and that a different approach to evaluation is therefore needed. Some interventional therapies also depend on surgeon skill and the intervention being tailored to the patient, such as cardiac catheterisation and endoscopic techniques. This initiative stressed the progress through an iterative process of research, clinical trials, and real-world application. Subsequently, a five-stage framework, the 'IDEAL' (**I**dea, **D**evelopment, **E**xploration, **A**ssessment, and **L**ong-term Study) was shaped that recommended how methodology and reporting of research at each of these stages could be improved. This IDEAL framework conceptualises the evidence shaping process for surgical innovation including surgical operations, invasive medical devices and other complex therapeutic interventions. This framework is published at https://www.ideal-collaboration.net/the-ideal-framework/ describing the key issues reported in the Lancet publications in 2009 (Barkun et al., 2009, Ergina et al., 2009, McCulloch et al., 2009). The IDEAL framework was subsequently further detailed in three publications in the British Medical Journal (BMJ) in 2013 providing methodological guidance which defined a key research question for each stage (McCulloch et al., 2013, Ergina et al., 2013, Cook et al., 2013). In short words, the IDEAL framework, designed for surgical innovation, offers a structured evaluation pathway, involving preclinical testing, effectiveness studies, and long-term monitoring (Cook et al., 2013, Ergina et al., 2013, McCulloch et al., 2013).

Robotic surgery, like other innovative surgical technologies, is often introduced without systematic testing, bypassing traditional medical therapeutics evaluation. Adoption is based on non-comparative retrospective evidence of potential patient benefits rather than stepwise feasibility studies (Sheetz et al., 2020). Innovation without careful evaluation, driven by uncertainty, the desire to improve, and personal biases, can put patient safety at risk (RCSEngland, 2018). Research has shown that surgical innovators often omit stages in evidence generation, with a lack of randomised controlled studies and an over-reliance on observational studies and implementation into practice data (McCulloch et al., 2018). The updated IDEAL framework encourages real-world evidence (RWE) for long-term monitoring. This is partly because there are many difficulties in conducting randomised studies for surgical innovation which include preferences from patients and surgeons, unwillingness to accept randomisation, difficulties in concealing allocation, inadequate subjects for effect size, learning curve and incremental innovation (Paul et al., 2013). Moreover, evidence of clinical effectiveness can be lacking in surgical innovation because regulatory pathways do not incentivise evidence generation and a limited number of clinical studies are required for approval (Broholm et al., 2016, Dahm et al., 2014). Dahm et al discussed these issues in the case of RAS and proposed the application of the IDEAL framework to RAS. They indicated that the current approach to device approval is unlikely to change in the near future. Therefore, the clinical and research community has a responsibility to impose its own standards regarding the use of RAS. They also indicated, it is likely that payers will seek stronger evidence of the therapeutic benefits of device-related procedures in the future.

RAS is particularly demanding to evaluate because, unlike a single-indication intervention, it is a multi-use platform applied across diverse surgical specialties (e.g., urology, colorectal, gynaecology). The costs and benefits of RAS may differ substantially between these indications, raising methodological challenges in terms of how to allocate capital and training costs, how to capture variation in outcomes, and how to reflect differential uptake across specialties. These cross-specialty dynamics set RAS apart from many other technologies and underscore the need for proactive evaluation and ongoing monitoring to ensure that its overall value is assessed appropriately (Paul et al., 2013).

Yet, the complexity of evaluating surgical robotics extends beyond the current IDEAL framework and the limits of classical evidence-based medicine. Addressing this challenge requires involvement from a diverse range of stakeholders to consider all relevant aspects. To tackle this, the IDEAL Robotics Colloquium (Marcus et al., 2024) was established, aiming to propose a comprehensive and practical guide for the evaluation of surgical robots, utilising the established IDEAL study stages as a template. The IDEAL Robotics Colloquium proposes a comprehensive guide for evaluating surgical robots, addressing safety, feasibility, effectiveness, and long-term performance (Marcus et al., 2024). The paper provides detailed recommendations for each stage of the robotic surgery evaluation life cycle in three parts. Firstly, it dissects the safety and feasibility of new robotic concepts in preclinical and early clinical studies (IDEAL stages 0, 1, and 2a). Next, it reviews the pivotal phase where the effectiveness of robotic interventions is studied on a larger scale and compared against current best practice (IDEAL stages 2b and 3). Finally, it considers IDEAL stage 4, focusing on long-term monitoring of performance in real-world settings. The analysis generates stage-specific recommendations for the systematic evaluation of robots in surgery. **Table 2.2-2** gives the summary of this IDEAL framework for surgical robotics.

The updated IDEAL Framework for surgical robotics introduces several new concepts to address the unique challenges of this rapidly evolving field. It incorporates multifaceted perspectives—device, clinician, patient, and system—to ensure a comprehensive evaluation. AI integration is emphasised, with separate evaluations before integration and assessments based on autonomy level and risk. In the IDEAL framework for surgical robotics, it not only pinpoints the challenges but offers recommendations to address the issues. The framework addresses regulatory and standardisation issues, advocating for uniform technical and clinical data publication. It also focuses on human factors and ergonomics, including clinician-device interaction and the reliability of autonomous systems. Transparent consent processes and clear information for patients are prioritised. Additionally, the framework highlights the importance of early and iterative economic modelling, life cycle assessments, and global impact evaluations. It recommends standardised training programmes and credentialing for surgeons using robotic systems. Furthermore, it promotes sustainable practices to minimise environmental harm and improve access in low-resource settings. Finally, the framework emphasises sustainable practices, minimising environmental harm, and improving access in low-resource settings, reflecting the complexity and multifaceted nature of surgical robotics evaluation and implementation. From a system perspective, stakeholders from low-resource settings should be included in modelling the capacity, benefits, and risks of robotic surgery, ensuring a comprehensive comparison with available alternatives.

This IDEAL Robotics Colloquium addresses a challenge in robotic surgery evaluation which particularly emphasises this innovation can be properly evaluated. In summary, the IDEAL framework for RAS ensures that new robotic surgical techniques and devices are introduced in a structured and evidence-based manner, ensuring their safety, effectiveness, and clinical relevance through every stage of their development and use.

This thesis integrates IDEAL discussions on the challenges and opportunities associated with RAS and acknowledges that RAS is in a dynamic phase of adoption, where both clinical practices and evidence are still evolving. The framework informed the need for a system-wide perspective, highlighting that alongside robust clinical evidence, implementation challenges, organisational impact. This aligns with the thesis's emphasis on multidisciplinary HTA methods and its role to support informed decision-making throughout the technology's lifecycle.

Table 2.2-2 Summary of the IDEAL for surgical robotics from the IDEAL Robotics Colloquium

Stage of innovation	Updated IDEAL Framework for surgical robotics	Key challenges of IDEAL Framework for surgical robotics	Key recommendations of IDEAL Framework for surgical robotics
Pre-IDEAL Pre-clinical	**Purpose**: assess safety and feasibility	Device Perspective • Regulatory requirements vary among national regulators, influenced by geopolitical, economic, and legal factors. • International standards focus on technical aspects, not clinical metrics. • Complementary technologies, especially AI, add complexity to development, calibration, and evaluation. Clinician Perspective • Introducing a robotic device is multifaceted for clinicians, involving investigation of robot interaction with the surgical team. • The integration of AI could alter responsibility and liability paradigms. • Trust of the surgical team, especially in systems with autonomous components, needs consideration. Patient Perspective • Growing complexity of robotic systems makes it difficult for patients to understand and trust. • Patients in early clinical studies may struggle to grasp risks, compare treatment options, or be aware of vested interests. System Perspective • Societal costs must be considered in evaluating the impact of surgical robots in health systems. • Early health economic evaluations lack standardization, acting as exploratory tools for decision-making and future cost-effectiveness insights.	Device Performance Assessment: • Standardise the publication of technical and clinical data. • **Stage 0**: AI-integrated robot evaluation should initially examine AI facets separately, followed by in silico and simulator-based assessment of the integrated robot. • **Stage 1:** beyond should assess the integrated robot in a clinical context, using clinical outcomes, guided by reporting guidelines (for example, DECIDE-AI). • Evaluate robotic autonomy based on level and risk Clinician • Define, analyse and iterate clinician–device integration accounting for stakeholder perspectives, clinician behaviour and cognitive workload. • For autonomous systems, evaluate the reliability of handover mechanisms and reasons for human takeover. Patient • Ensure transparent consent processes regarding theoretical risks, evidence, system failure mitigation, autonomy level, surgical team experience and potential conflicts of interest. System • Perform early and iterative economic modelling, using exploratory analyses to guide cost-effective development and prevent future research wastage. • Consider the impact of surgical robots on different healthcare ecosystems, using life cycle assessments, reverse engineering and frugal design concepts where possible to improve accessibility and sustainability.
Stage 1 Idea First in human	**Purpose**: first-in-human study		
Stage 2a Development Single centre/single intervention; case series/prospective cohort	**Purpose**: prospective development ahead of further collaborative evaluation and comparative assessment.		

		• Gaps in evaluating environmental sustainability and global applicability of surgical robots exist. • Early and systematic analyses of unmet needs, health economics, and sustainability play a vital role in guiding efficient device development and avoiding waste.	
Stage 2b Exploration Bridge from observational to comparative evaluation. Purpose is to gain data to decide if and how to test in a robust RCT or other appropriate pivotal design	**Purpose**: Achieving expert consensus due to the nature of the patients and procedures to be studied in trials, to avoid bias due to learning curves or wide variations in performance.	Device Perspective • Limited high-quality comparative trials with inconclusive evidence. • Methodological limitations in reporting outcome measures and safety. • Rapid evolution of robots challenges evaluation; AI-enabled systems may render studies outdated. • Uncertainty complicates decision-making for definitive randomised clinical trials. Clinician Perspective • Crucial human factors, occupational consequences of surgery and ergonomic innovation conflict in evidence • Surgeon experience and learning curves introduce potential variation and bias in trials. • Reliable learning curve assessment requires analysis of meaningful operation quality measures. • Standardised team training is essential for comparative evaluation, but no consensus on mandatory requirements. Patient Perspective • Patient acceptability is challenging to define and assess for surgical robots. • Comprehensive understanding of robotic surgery among patients is limited.	Device • Risks and benefits of surgical robots must be evaluated through prospective data collection using a suitable study design, mutually agreed dataset, appropriate analysis techniques and assessment of study-specific confounders. • Robot re-evaluation for alternative indications should be based on risk, autonomy level and available evidence. Clinician • Validated tools and qualitative research should be used to explore human factors. • The real-world learning curve for surgical robots must be investigated. Metrics should be collected from direct supervision of both real-world and simulated use cases. • Establish institutional clinical governance policies with consistent specifications on surgeon training, audit and ethics. Patient • Explore robotic surgery acceptability through assessing patient perspectives, understanding, and consent. • Maintain transparency with participants regarding existing evidence, development stage, conflicts of interest, surgical experience, complications and alternative treatment. System
Stage 3 Assessment Definitive comparative evaluation of main efficacy and safety aspects of new technique against current best treatment.	**Purpose**: Testing evidence from collaborative perspective cohort studies in a range of potentially appropriate settings and indications and facilitate definitive randomised comparative studies against an appropriate control group		

		• Patient perceptions influenced by media, industry, and marketing psychology. • Importance of providing clear, accurate non-technical explanations to patients for informed consent. System Perspective • Broad systems perspective needed for comparative surgical robotic evaluation. • Economic viability, cost evaluation, and environmental impact considerations. • Adoption of single-use robotic tools raises environmental concerns. • Understanding global impact, including challenges in low-income settings. • Consideration of ethics in terms of the impact on access to care for disadvantaged populations.	• Economic impact analysis of healthcare costs associated with robotic intervention should be measured in comparative studies, including clinically and system-relevant outcomes over a sufficient length of follow-up. • Include stakeholders from low-resource settings in modelling capacity, benefit and risks of robot use, compared against available alternatives. • Life cycle assessments of surgical robots should be compared to the current gold-standard treatment.
Stage 4 Long term monitoring	**Purpose**: Surveillance **Number & Types of Patients:** All eligible **Number & Types of Surgeons:** All eligible **Output**: Description; audit; regional variation; quality assurance; risk adjustment **Intervention**: Stable **Method**: Registry; routine database; rare-case reports **Outcomes**: Rare events; long-term outcomes; quality assurance **Additions**: Registries for devices – IDEAL-D Registries at earlier stages of IDEAL	Device Perspective • Long-term monitoring critical for safety, evolution, and longevity. • Existing device monitoring systems criticized for being passive and inconsistent. • Incentives lacking for comprehensive, unbiased outcome data. • Need for robust evaluation systems supplementing standard outcomes with additional datasets. Clinician Perspective • Challenges in training, credentialing, and determining accountability for adverse outcomes. • Risk in untrained hands; inadequate training prolongs learning curves. • Inconsistent and non-standardised robotic surgery training.	Device • Long-term monitoring should be led by RWD tailored to provide high-quality, transparent and valid data. • Evaluation of surgical robots must be customised to accommodate for their dynamic nature, specifically with regards to AI-enabled systems and to detect device creep. Clinician • Standardised training programs, informed by comparative stage findings, should be used and recognized by accrediting bodies. • Surgeon revalidation and credentialing should be performed to ensure robotic surgery skills are maintained to a high standard. • All adverse events should undergo human and systems factors analysis with dedicated experts. Patient

		• Sparse research on learning curves for surgical robots. Patient Perspective • Patients have limited access to scientific evidence due to regulatory processes. • Patient perceptions influenced by various stakeholders. • Potential misinformation leading to false reassurance or lack of awareness. System Perspective • Long-term evaluation needed for cost-effectiveness and sustainability. • Health economic analyses should be updated with real-world data. • Potential access and equity issues with high-cost investments. • Consideration of environmental impacts through life cycle assessments. • Need for innovators to adopt sustainable practices and minimise environmental harms. • Complex interventions in complex adaptive systems require monitoring infrastructure and governance.	• Registries and long-term monitoring studies should be independently procured, and readily available in formats that are understandable to patients. • Patient-reported outcome measures should predominate in long-term monitoring studies to ensure outcomes remain patient centred. System • Cost-effectiveness analysis of surgical robots should be performed, informed by real-world, data-driven, decision-analytic modelling. • International forums should assess and mitigate global health inequities introduced by surgical robotics. • Sustainability and environmental impact assessment are imperative in long-term evaluation, guided by regular consultation with expert stakeholders.

2.3 Complex interventions

2.3.1 Definition of complex interventions

Complex interventions refer to interventions that contain several interacting components and are used in various fields such as health service, public health practice, and social policy. Complexity is defined by several dimensions such as the range of possible outcomes, their variability in the target population, and the degree of flexibility allowed in the intervention (Campbell, 2000, Craig et al., 2008). Some devices can be considered as complex interventions, such as a device-involved surgery that involves surgeon-related factors, procedure-related risks, and the range of outcomes. (Ergina et al., 2009).

A new core guidance for complex interventions was updated and published in 2021 jointly commissioned by Medical Research Council (MRC) and the National Institute of Health Research (NIHR) to maximise the efficiency, use, and impact of research on complex interventions (Skivington et al., 2021). In this updated guideline, the definition of complex interventions was emphasised again, highlighting their special characteristics, such as the flexibility in intervention delivery and adherence that allow for variation. Standardisation of complex interventions could relate more to the underlying process and functions than to the specific form of components delivered, which means it allows an implementation to vary across different contexts yet maintain the integrity of the core intervention components (Hawe et al., 2004). For instance, in the ROMIO pilot trial (Blencowe et al., 2016), the protocols were designed with flexibility, and photography was subsequently agreed upon for use in monitoring the main trial delivery for minimally invasive oesophagectomy. Therefore, it is essential to focus not only on the design of the intervention itself but also on its mechanisms of change and/or the resources needed to support it (Blencowe et al., 2019). These all have an impact on real-world implementation. For example, taking an innovative intervention, such as robot-assisted surgery, a process evaluation conducted alongside a trial showed key contextual factors to support effective implementation, including engaging staff at different levels, such as whole team training with inexperienced surgeons of using RAS (Randell et al., 2017).

2.3.2 Framework for developing and evaluating complex interventions

The MRC framework published in 2021 (Skivington et al., 2021) uses a pluralistic approach for guiding the design and conduct of complex intervention research which identifies four perspectives in line with a broader conception of complexity - (i) efficacy, (ii) effectiveness, (iii) theory-based, and (iv) systems. Subsequently, phases and core elements of complex intervention research have been highlighted, which are: the development or identification of the intervention, feasibility, evaluation, and implementation **(Figure 2.3-1)**.

The core elements of complex intervention research compose context, programme theory, stakeholder engagement, key uncertainties identification, intervention refinement and economic considerations. Context encompasses any feature of the circumstances in which an intervention is conceived, developed, evaluated, and implemented. It recognises the dynamic and multi-dimensional nature of factors influencing intervention effectiveness across physical, social, cultural, political, and economic dimensions. Programme theory describes how an intervention is expected to produce its effects and under what conditions. It should be tested, refined, and used to guide the identification of uncertainties and research questions at all stages of the intervention process. Stakeholders include individuals targeted by the intervention, those involved in development or delivery, and those with personal or professional interests affected. Meaningful engagement with stakeholders throughout the research process is essential for prioritizing questions, co-developing programme theory, and overcoming practical obstacles. Key uncertainties identification is acknowledging and addressing uncertainties at each phase of the research process. Effectively understanding and framing research questions is crucial, especially in complex intervention studies that demand a flexible and adaptive approach due to key uncertainties. Intervention refinement is the fine-tuning or making changes to the intervention after a preliminary version (prototype) has been developed. Engaging potential users and stakeholders for feedback and improvements, ensures feasibility, acceptability, and effectiveness. Economic considerations involve determining the comparative resource and outcome consequences of interventions for individuals and organizations affected. Incorporating economic evaluation throughout the research process, including cost-benefit analysis and cost-consequence analysis.

Engaging economic expertise is recommended early on to assess costs and benefits relevant to decision-makers.

As shown in **Figure 2.3-1**, there are phases alongside the core elements. Development or identification of complex intervention: this initial phase is about conceiving and planning interventions, which may include adapting existing strategies to new contexts or populations. It highlights the importance of clearly articulating the theoretical basis (programme theory) for interventions, even in policy-led initiatives. The feasibility study serves as a critical checkpoint, assessing predefined criteria related to both the evaluation design and the intervention itself. Overlooked in the past, feasibility testing is now recognised as essential for ensuring practicality, acceptability, and cost-effectiveness. Collaborative evaluability assessment with stakeholders helps determine the viability of an evaluation. Evaluation: expanding beyond mere effectiveness, the evaluation phase considers broader impacts, mechanisms, and interactions with the context. It takes a holistic approach, incorporating various study designs (quantitative, qualitative, and mixed methods) and prioritising stakeholder involvement in outcome selection and transparent reporting. Process Evaluation: this phase delves into the intricacies of implementation, examining fidelity, quality, mechanisms of change, and contextual influences. It provides valuable insights into why interventions succeed or fail, balancing theory building and evidence production through case studies or simulations. Implementation: early consideration of implementation is crucial for widespread adoption and sustainability. This phase addresses specific outcomes, the implementation strategy, and contextual factors. It allows flexibility for adaptation across different contexts while emphasizing the preservation of key program functions. Integration with Economic Considerations: economic evaluation is seamlessly integrated throughout the process, assessing both resource and outcome consequences. Stakeholder engagement in framing research questions and transparent reporting of economic analyses are emphasised. Challenges related to interventions across sectors, where payers and beneficiaries may differ, are carefully considered.

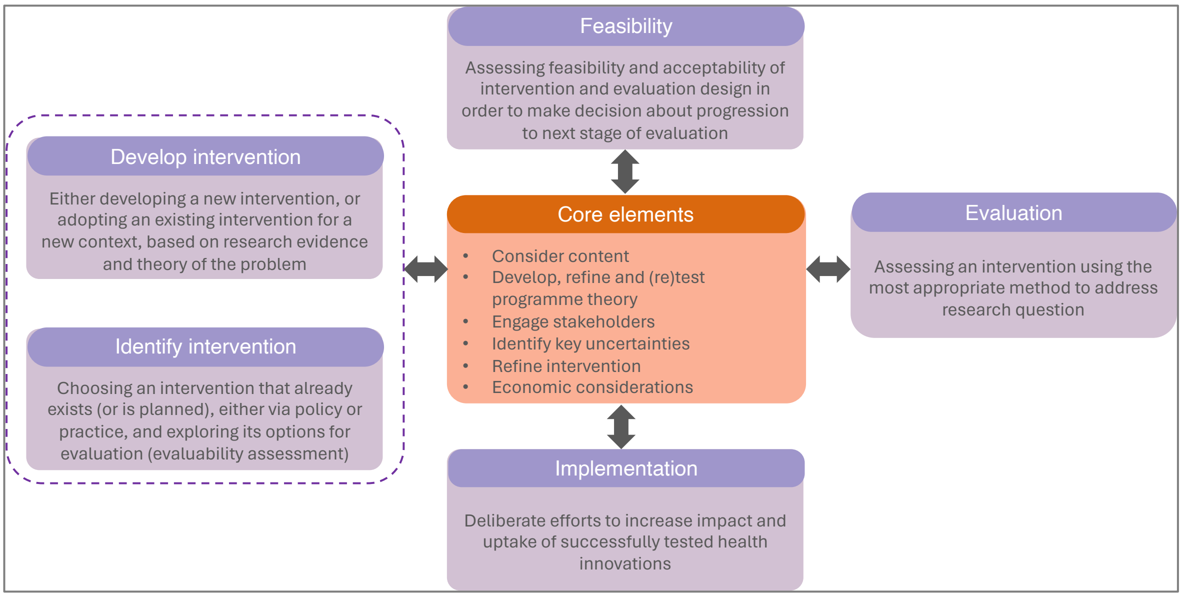


Figure 2.3-1 Framework for developing and evaluating complex interventions

Source: A new framework for developing and evaluating complex interventions: update of Medical Research Council guidance (Skivington et al., 2021)

The intervention design and assessment unfolds as a continuous process, with each phase building upon the previous one, from development to feasibility, evaluation, process evaluation, and implementation. Each phase emphasises stakeholder engagement, theoretical clarity, feasibility testing, and flexibility for adaptation to real-world contexts. Economic considerations are woven throughout the process to ensure practicality and cost-effectiveness.

RAS can be considered a complex intervention, as its evaluation requires attention not only to clinical outcomes but also to the organisational, contextual, and system-level factors that influence adoption and sustainability. The MRC Complex Interventions Framework is therefore highly relevant to this work, as it provides a structured approach for addressing such complexities. In the context of RAS, the framework emphasises the importance of context (e.g., hospital infrastructure, workforce capacity, funding models), programme theory (e.g., how RAS is expected to generate clinical and system benefits while managing risks such as learning curves), and stakeholder engagement (e.g., surgeons, administrators, patients, policymakers).

In this thesis, the framework informs the rationale for extending the evaluation of RAS beyond clinical effectiveness alone, highlighting the need to incorporate cost-effectiveness, budget impact, organisational implications, and equity considerations.

In this thesis, I reflect on and apply this framework that RAS evaluation can extend beyond clinical effectiveness to encompass system-wide factors, ensuring its adoption is evidence-based, cost-effective, and sustainable across different healthcare settings.

2.4 Impact of context on assessment of RAS

In this chapter, I have explored the intricacies of healthcare innovation like RAS, particularly focusing on the diffusion of new technologies and the associated challenges. In the rapid diffusion of new technologies, every stage of the diffusion process is complicated including knowledge, persuasion, decision, implementation, and confirmation. The adoption and implementation of new technologies involve the broader context of the healthcare system, as well as societal and cultural factors. Stakeholders may hold differing opinions on adoption, with concerns ranging from safety and costs to evidence uncertainty. This creates a persistent dilemma for decision-makers regarding when to control and how to assess the use of new technologies. In surgical robotics, evaluation often follows initial investment, raising concerns that it may come 'too late.' Many argue that RAS is now an established reality, making retrospective assessment less impactful. However, as its use expands into new specialties, there remains a lack of robust evidence to fully assess its broader impact and effectiveness. While RAS has demonstrated promise in specific areas, comprehensive and timely evaluations are crucial to ensure its safe and effective integration across diverse surgical fields.

Previous studies have indicated the challenge in assessing medical devices, including learning curves, incremental innovation, dynamic pricing, organisational impact, and quality variation (Tarricone et al., 2017b, Ergina et al., 2009, Craig et al., 2015). Surgical robotics, like other device-related surgical innovations, the evaluation of RAS presents unique challenges due to its inherent characteristics. These challenges are even more pronounced in the evaluation of RAS due to its complexity, high cost, and application across multiple specialties.

Surgical robotics exhibit the features of device-related innovations, complex interventions, and platform technologies. Like other surgical devices, RAS requires operator proficiency, features a learning curve, and is subject to technical evolution. As a complex intervention, RAS involves interacting components, such as surgical teams, training systems, and institutional processes, whose outcomes depend heavily on the healthcare context. Finally, as a platform technology, RAS supports multiple indications across specialties, requiring strategic planning, shared use, and ongoing investment, making its assessment inherently system-level and context-specific (see **Figure 2.4-1**). These overlapping characteristics complicate assessment and reinforce the need for multidisciplinary, context-aware evaluation approaches.

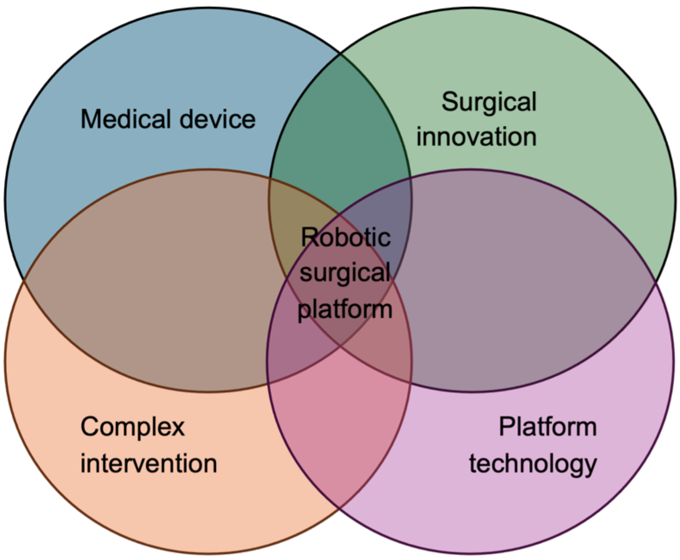


Figure 2.4-1 Venn diagram of RAS characteristics

IDEAL framework for surgical robotics (Marcus et al., 2024) incorporates multifaceted perspectives—device, clinician, patient, and system-wide perspective—to ensure a comprehensive evaluation. It highlights the need for robust evidence to support the use of robotic technologies in healthcare. This framework emphasises the assessment of safety, feasibility, effectiveness, and long-term performance, integrating diverse perspectives to encourage a comprehensive and adaptive evaluation process. The MRC complex intervention framework provides a structured approach (multiple inter-related stages) for evaluating RAS by addressing key factors (e.g. context, stakeholder engagement and uncertainty identification etc.) that influence its implementation, adoption, and long-term sustainability.

In this chapter, I review the IDEAL framework and the MRC complex intervention framework, both of which provide structured approaches for evaluating surgical innovations such as RAS. These frameworks emphasise the importance of staged, iterative evaluation, stakeholder engagement, and system-wide perspectives. Together, these frameworks establish a structured foundation for assessing the clinical effectiveness, economic viability, and long-term sustainability of RAS. Several critical issues and challenges have been identified. These include the need for well-timed and iterative assessment procedures, the involvement of diverse stakeholders, transparent regulatory processes, and continuous evidence generation. In the following chapters, I will integrate these structured frameworks and further expand on them to ensure that the adoption of RAS is evidence-based, cost-effective, and sustainable across diverse healthcare settings.

Building on these insights, Chapter 3 focuses on evaluating the clinical relevance and effectiveness of RAS. Following the IDEAL framework, this chapter assesses RAS, ensuring that its implementation aligns with robust evidence-based practices. Additionally, by incorporating the MRC complex intervention framework, Chapter 3 identifies key uncertainties in the evidence base in order to guide the utilisation across healthcare settings.

Chapter 4 builds on this by shifting the focus to economic evaluation. It uses the structured considerations of both frameworks to review how existing cost-effectiveness studies have addressed, or failed to address, the distinctive challenges of evaluating RAS. These include learning curves, organisational impact, and procedural variability. The chapter identifies methodological limitations in current economic evaluations and sets the groundwork for a more tailored approach.

Chapter 5 responds directly to the gaps identified in Chapters 3 and 4 by developing a novel economic model. Informed by the MRC framework's emphasis on feasibility and systems thinking, and the IDEAL framework's recognition of innovation pathways, this model addresses both procedural-level and system-level decision-making. This modelling approach reflects the broader implementation questions posed in Chapter 2,3 and 4, offering a tool for optimising RAS adoption within real-world constraints.

Together, these chapters reflect a cohesive and iterative application of the IDEAL and MRC frameworks, underpinned by HTA methodology, ensuring that clinical and economic evidence is systematically integrated into a system-level perspective on RAS adoption and optimisation.

Chapter 3 Overview Of Clinical Evidence In Robotic-Assisted Surgery

In Chapter 3, I aim to answer the research question (1):

- Does the current clinical effectiveness evidence support the adoption of RAS in intracavity procedures identified in Scotland?

A modified version of this chapter has been published at BMJ Open on the title of **'The Clinical Effectiveness of Robotic versus Laparoscopic and Open Surgery: An overview of systematic reviews'**.

3.1 Introduction

The first step in applying HTA is to establish a strong evidence base for effectiveness. This is particularly crucial for Scottish decision-makers, who must ensure that any considered procedures are at least as effective as traditional methods. As discussed in the previous chapter, guiding the implementation of RAS requires aligning its utilisation with robust evidence-based practices to support informed decision-making and optimise patient outcomes.

Robotic-assisted surgery (RAS) is an extension of Laparoscopic Surgery (LS) that was introduced to overcome the limitations of laparoscopy to assist in surgical procedures. It has been claimed that RAS offers improved dexterity, better ergonomics, and enhanced fixed operator-controlled visualisation and retraction, thus improving the capabilities of surgeons during complex surgery (Siddaiah-Subramanya et al., 2017, Peters et al., 2018). Advocates of RAS claim benefits for patients including fewer conversions, less blood loss, fewer perioperative complications, shorter hospital stays, and faster recovery compared to conventional surgeries. Although RAS has been widely and quickly adopted, the available evidence regarding its superiority over laparoscopic or open approaches in terms of key surgical outcomes is inconclusive. Some randomised controlled trials (RCTs) have been conducted in urological, colorectal, and gynaecological surgery to compare RAS with conventional laparoscopic or open techniques, but these studies have mainly shown insignificant difference in surgical outcomes (Gala et al., 2014, Steffens et al., 2017, Coughlin et al., 2018, Ilic et al., 2018, Prete et al., 2018, Prodromidou, 2020). A previous overview review found limited evidence, with only 18 RCTs across various surgical procedures comparing robotic surgery to conventional approaches, highlighting challenges in drawing overall conclusions on the sustained effectiveness of robotic surgery (Muaddi, 2021).

Many countries are currently investing in RAS. The most widespread growth of RAS is in urology, with over 90% of prostatectomies in the USA and over 85% in the UK over the past decade. In urology, almost all regions of Europe and North America have access to RAS which is now considered standard of care for prostatectomy (Crew, 2020). Globally, other specialties like upper and lower gastrointestinal surgery, hepatopancreaticobiliary surgery, and gynaecology have also experienced increased RAS volume, though it currently constitutes a small proportion of total procedural volume (Maynou et al., 2021).

Research has shown that innovators often omit stages in evidence generation with a lack of randomised controlled studies and an extensive reliance on observational studies and implementation into practice (McCulloch et al., 2018). This is partly because there are many difficulties in conducting randomised studies for surgical innovation which include preferences from patients and surgeons, unwillingness to accept randomisation, difficulties in concealing allocation, inadequate subjects for effect size, learning curve and incremental innovation (Paul et al., 2013). Moreover, evidence of clinical effectiveness can be lacking in surgical innovation because regulatory pathways do not incentivise evidence generation and a limited number of clinical studies are required for approval (Broholm et al., 2016, Dahm et al., 2014).

Given the rapid growth of RAS, there remains a critical need to appraise the evidence underpinning ongoing expansion to ensure value and optimal use of resources. It is important to establish the strength of the evidence base for RAS across specialties to aid adoption decisions in non-urology fields. In the context of this expansion of capacity and uncertain evidence of clinical outcomes, to facilitate this decision-making process, my objective was to present evidence comparing outcomes across different intracavity procedures, in four clinical specialties (colorectal, gynaecology, upper gastrointestinal (GI) and hepatopancreaticobiliary (HPB), where RAS versus laparoscopic or open surgery is still in equipoise and currently being introduced, also for the interest of NHS Scotland.

3.2 Methods

3.2.1 Description of approach used

A review of reviews approach is also known as an overview of reviews or umbrella reviews. It could be considered a recent development in the methods of evidence synthesis that generally helps summarise broad issues and current knowledge on a topic, to signpost the reader to evidence, summarise existing research, and highlight where an absence of evidence may exist. In other words, it can compare the findings of several reviews and identify the reasons for conflicting results (Hunt et al., 2018). Therefore, overview of reviews is most frequently employed where multiple systematic reviews already exist on similar or related topics, and aim to systematically bring together, appraise, and synthesise the results of related systematic reviews. The overview of reviews attempts to address a growing need to filter the information overload, improve access to targeted information and inform healthcare decision-making (Smith et al., 2011, Hartling et al., 2012).

There are some existing guidelines on the methodology for conducting an overview of reviews. The framework is useful for planning these evaluations and for planning methods required to deal with challenges that arise when conducting an overview (Aromataris et al., 2015, Aromataris and Riitano, 2014, Smith et al., 2011, Lunny et al., 2017). It can generally be presented as four steps of conducting an overview: (i) specification of the purpose, objectives and scope, (ii) specification of the eligibility criteria, (iii) search methods and (iv) data extraction. This framework taken aligned with guidance by using a clearly defined research question, adopting a systematic approach to searching for relevant review articles, and reporting the results of the search using the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) (Page et al., 2021).

The methodology for the overview review is different from the guidelines for a traditional umbrella review, it includes both systematic and narrative reviews instead of only systematic review (Greenhalgh et al., 2018). It can be seen as a systematic and narrative combined approach that plays an important role in expanding the understanding not only of the topic in question but also of the reasons why it has been studied in a particular way. And the interpretations can be variously made with respect to what we know about it and the nature of the knowledge base.

It is suggested that complex interventions should use a mixed-method evidence synthesis approach that can give the potential choice that includes the types of quantitative and/or qualitative studies for the review (Petticrew et al., 2013). The mixed methods approach proposed by Petticrew et al. (Petticrew et al., 2013) is relevant to this work as it offers a structured way to synthesise both quantitative and qualitative evidence, essential for evaluating complex healthcare interventions like RAS. Applying this approach allows for the integration of diverse evidence types, such as clinical outcomes (quantitative) and surgeon experiences (qualitative), providing a comprehensive understanding. Petticrew et al. highlight how narrative summary approaches (e.g. tabular, and graphical methods) can be used to syntheses and explore complex interventions, not just by combining but by integrating evidence from various sources to illuminate different facets of complexity. For example, graphical summaries can be used as an analytical tool to help explore sources of variability among studies.

Given the breadth of our subject that surgical robotic systems can be used in various clinical fields and also viewed as a complex intervention, an overview of reviews would be an ideal approach for those who are seeking to ensure that their decisions are evidence-based in order to inform clinical practice. Therefore, given the breadth of our scope, I adopted the overview of reviews approach as described by Cochrane methods (Pollock et al., 2020) and followed Preferred Reporting Items for Overviews of Reviews (PRIOR) on reporting (Gates et al., 2022). To align with the framework of planning methods for the overview of reviews, paragraphs of specifications are addressed as follows.

3.2.2 Search methods for identification of reviews

On advice from a University of Glasgow Information Scientist, I adopted a search strategy developed by Health Improvement Scotland (requested on 26/04/2021). It was developed for the overview of RAS on both clinical effectiveness and cost-effectiveness evidence but has yet been published (since 23/04/2019). The search strategy was designed to identify systematic reviews comparing RAS to conventional surgical approaches in humans. I took the developed search strategy which uses the databases Ovid Medline, Embase and the Cochrane Library. I limited the search to the most recent years (from 04/2017 to 12/2023) given the incremental evidence generation and clinical setting changes. The list of the search terms can be found in **Appendix 1 - Database search terms for the overview** review.

3.2.3 Eligibility criteria for considering studies for the reviews

As my aim was to gain an overview of the clinical effectiveness evidence for the use of RAS, no certain population and outcomes were limited initially. I selected published systematic reviews (SRs) regarding an evaluation of robotic surgery in any surgical field in comparison to the conventional surgical approach (laparoscopic or open) and included any outcome measure. I excluded any systematic review which looked at aspects of RAS other than the clinical effectiveness of RAS compared to open or laparoscopic surgery that had no clinical data or measures for our outcomes. I excluded reviews which were unable to differentiate between RAS and other minimally invasive techniques. Studies other than systematic reviews were excluded. I also excluded the grey literature (ie, conference abstracts) and review protocols as they generally provide insufficient information (Toma et al., 2006). Reviews not in English were excluded, as there is evidence that such language exclusion does not cause bias (Morrison et al., 2012). The eligibility criteria are addressed in **Table 3.2-1**

Table 3.2-1 Inclusion/ exclusion criteria for the systematic review of clinical effectiveness

Component	Inclusion Criteria	Exclusion criteria
P - Population	Any	Not on surgery received patients (i.e. surgeon training, surgeon learning curve, surgeon impacts, incentive)
I - Intervention	Robotic surgery systems	Not RAS; relevant devices
C - Comparators	Conventional surgery (laparoscopic or open)	Surgery unable to differentiate between RAS and other minimally invasive techniques
O - Outcome	Any	
S - Study designs	Systematic Review	Comprehensive reviews, Economic evaluation (i.e. not on effectiveness)

3.2.4 Study selection

I screened the titles and abstracts of the identified articles. Duplicate publications were managed and removed using Endnote software X9 (Bramer et al., 2016). A random sample of 10% with excel algorithm of papers was screened by two supervisors (KB and JB), quality management steps, to confirm the exclusion criteria and ensure a systematic approach to eligibility criteria (NICE, 2014a, Sekhon et al., 2017). Where I was uncertain about whether to include a paper, this was reviewed by my supervisors (K.B. and J.B.) and any disagreements were resolved by discussion. I introduced a two-stage study selection as we wanted to identify the volume of current evidence across specialties and to examine the strength of evidence in areas where RAS is still in equipoise.

In stage one, I screened the titles and abstracts to identify all systematic reviews of the clinical effectiveness of RAS versus laparoscopic and open surgery. Stage one mapped the full body of RAS systematic reviews across all specialties, establishing where the evidence base lay and whether it aligned with procedures prioritised by the Scottish Government. These obtained reviews were then categorised by specialty in order to obtain the landscape of clinical uses of RAS. In stage two, it was narrowed this set to the targeted procedures for detailed synthesis in areas where equipoise persists. I focused on my review to a number of intracavity procedures in four specialties (colorectal, gynaecology, upper gastrointestinal (GI) and hepatopancreaticobiliary (HPB)) which interested by the Scottish National Planning Robotic Review Group from NHSScotland which are commonly performed (SHTG, 2021, NHSScotland, 2021a, NHSGrampian, 2020). Details of the study selection process are shown in the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) flow diagram (Page et al., 2021). Presenting the flow in two stages improves transparency by distinguishing the broad scoping from the focused analysis.

3.2.5 Data extraction and synthesis of results

I designed an electronic data extraction form (in Microsoft Excel 2010) for data extraction and management. In stage one, I identified specialties from titles and abstracts to present the evidence distribution of clinical use. Meanwhile, the common clinical outcomes were accordingly identified and taken to develop the data extraction form in Excel for later management and evaluation. The outcomes of interest identified from stage one are addressed in **Table 3.2-2.** These data from each study would be extracted if it was available. In stage two, I examined the full text of reviews of selective indications and extracted outcomes of interest. The extracted data from the systematic reviews included author, year of publication, setting, study design, sources, number of included studies, participants (i.e. diagnosis for procedures), intervention (types of interventions compared, numbers assigned in each group) and outcomes.

The high level of heterogeneity in the patient population and procedure precluded meta-analysis. Therefore, a narrative summary approach was applied to ensure a comprehensive evaluation (Petticrew et al., 2013). A descriptive analysis was conducted, and results were tabulated by outcome for six procedures—colorectal oncological resection, hysterectomy, liver resection, pancreatectomy, pancreaticoduodenectomy and gastrectomy—across four specialties of interest. I chose to use evidence spectrum to present the outcome as it has the advantage of easy interpretation. This method allowed for a structured comparison of outcomes while accommodating the variability inherent in the data.

Table 3.2-2 Extract contents of included studies

Component	Extract contents
Study details	● Author, year of published; study setting (including design, study sources, countries, and number of included studies)
Participants	● diagnosis/indication for procedure.
Intervention/ Comparator	● types of interventions compared; numbers assigned, and numbers analysed in each group.
Outcomes	● Total operating time; conversion rate; postoperative or intraoperative complications; complications; length of hospital stays; estimated blood loss; recurrence rate; reoperation rate. For cancer studies: overall survival; disease-free survival; lymph node yield.

For all SRs, I applied a synthesis approach with a narrative summary, presenting the findings in an evidence spectrum. Clinical outcomes for each procedure were categorised using broad descriptors—positive, neutral, or negative—based on statistical significance. A positive effect (green) indicated a statistically significant finding in favour of the robotic surgical approach, while a negative effect (red) signified a statistically significant finding in favour of the conventional surgical technique. A neutral effect (yellow) was assigned when no statistically significant difference was found between the two approaches. This does not imply that differences were absent or clinically unimportant, as non-significance may reflect limited statistical power, small sample sizes, or variability in outcomes. By way of example, a positive effect of RAS may be a lower complication rate, lower operative time or lower blood loss. It should be noted that these statistically significant findings may not indicate clinical significance. To quantify these descriptors, I counted their occurrences across SRs for each of the six procedures.

Furthermore, to capture the strength and variability of the evidence, I then visualised these descriptors using a flexible colour spectrum, rather than fixed categories. While the core traffic light colours (green, yellow, red) provided a foundational classification, their shades and blends conveyed additional nuance. Stronger evidence resulted in deeper or more saturated colours, while conflicting or inconclusive findings produced mixed tones, such as brown (see **Figure 3.2-1**). This dynamic representation allowed for a more fluid and interpretable synthesis, reflecting not only the direction of the evidence but also its consistency and strength across different studies. By incorporating this adaptable colour spectrum, I aimed to provide a more comprehensive and intuitive understanding of the comparative effectiveness of robotic and conventional surgical approaches.

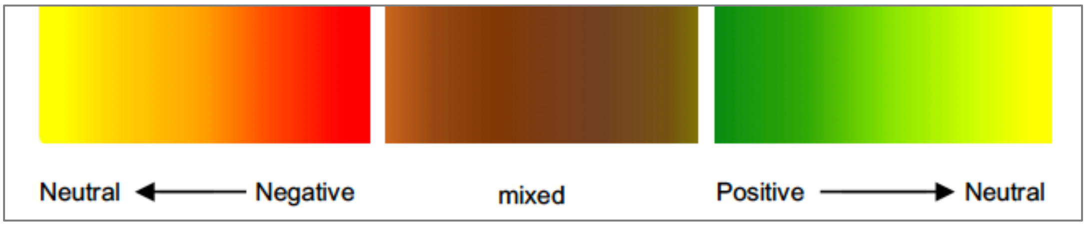


Figure 3.2-1 Evidence spectrum indication

I did not synthesise evidence quantitively; therefore, no sensitivity analyses were conducted to assess the robustness of the synthesised results. However, I provided information on the heterogeneity of each meta-analysis in **Appendix 3 - Clinical effectiveness of RAS**, if available.

3.2.6 Assessment of methodological quality and overlap management

A MeaSurement Tool to Assess systematic Reviews (AMSTAR)-2 aims to assist in the identification of high-quality systematic reviews with moves to base more decisions on real-world observational evidence. The quality of the included reviews was evaluated using the AMSTAR-2 tool which is designed to evaluate systematic reviews including both randomised and non-randomised study designs (Shea et al., 2017). This tool has 16 domains of which 7 are deemed critical. The 7 critical domains are protocol registration, adequacy of the literature search, justification for excluding studies, risk of bias assessment, appropriateness of methods used for meta-analysis, consideration of risk of bias, assessment presence and likely impact of publication bias. The 9 non-critical domains are PICO description (population, intervention, comparison, outcome), explanation of the study design, rationale of study selection, adequacy of data extraction, adequate details in the description of the included studies, reporting of sources of funding, assessment of potential impact of risk of bias, assessment of heterogeneity, and reporting of conflicts of interest. AMSTAR 2 is not intended to generate an overall score, and it classifies the quality of systematic reviews into 4 groups, high, moderate, low, or critically low. In order to be judged high quality a study must have no critical weaknesses and only one non-critical weakness. A review will be judged moderate when it has more than one non-critical weakness. A review will be judged low quality when it has one critical weakness and critically low when it has more than one critical weakness. The quality assessment of the reviews was not taken as an inclusion criterion but was presented alongside the descriptive analysis of the evidence by indication to allow the reader to form a judgement about the quality of the evidence available.

I was aware of a risk in reviews of systematic reviews that underlying studies may be included in more than one of the identified systematic reviews. This overlap may give excessive weight to certain studies and bias the results. Thus, I examined the level of overlap. There were different methods suggested in practical use for the overlap management across different research stages in the conduct of an overview review (Lunny et al., 2021). Since my research has certainly included all the reviews at the eligibility criteria stage and extracted all reviews at the data extraction stage, I have to manage my overlap at the evidence synthesis stage. I used the citation matrix to manage this issue and reported our findings (Pieper et al., 2014). In the citation matrix table, all the included SRs were listed on X-axis, and all the primary study sources were recorded including the name of the first author, publication year, and research location on the y-axis. Ticking mark method was used to identify in which publication was cited. I obtained the number of included primary publications, the total number of SRs and the sum of the ticked boxes for included publications. A method of "corrected covered area (CCA)" was introduced to measure the percentage of primary studies included more than once in a SR, and it is presented with overlaps percentage (%).

The formula below calculates the overlap by dividing the frequency of repeated occurrences of the index publication in other reviews by the product of index publication and reviews. The first occurrence of a primary study is defined as the index of publication. For those the estimated corrected covered area values, below 5% indicates slight overlap and 6% to 10% represents moderate overlap. The percentage of corrected covered area from 11% to 15% is defined as high overlap and more than 15% is very high.

$$\text{Corrected Covered Area} = \frac{N-r}{rc-r}$$

Where *N'* is the number if included publications (including double counting) in evidence synthesis (this is the sum of the ticked boxes in the citation matrix); there *r* is the number of index publication (number of rows) and *c* is the number of reviews (number is columns).

3.3 Results

3.3.1 Overview of study selection

Through the systematic search, 3,363 potentially relevant articles were obtained initially, 1,208 duplicates were removed and 2,155 were proceeded to screening. After screening of title and abstract, there were reports no retrieved due to no abstract (N=18) or not in English (n= 5) or wrong publication type (n=106). 1,398 articles which did not meet inclusion criteria were excluded due to, not on RAS or unable to differentiate from MIS (N=574), no comparator or mixed with other surgeries (N=209), not on surgery received patients (n=103), not on clinical efficacy (n=217), not SR study (N=295). As a result, the remaining 628 articles were categorised by specialty based on the titles and abstracts. After the specialty categorisation, 463 articles were excluded due to not targeted procedures in this review (N=451) and full-text not accessible (N=12). A total of 165 systematic reviews were included for this overview, and the study selection process is summarised in **Figure 3.3-1**.

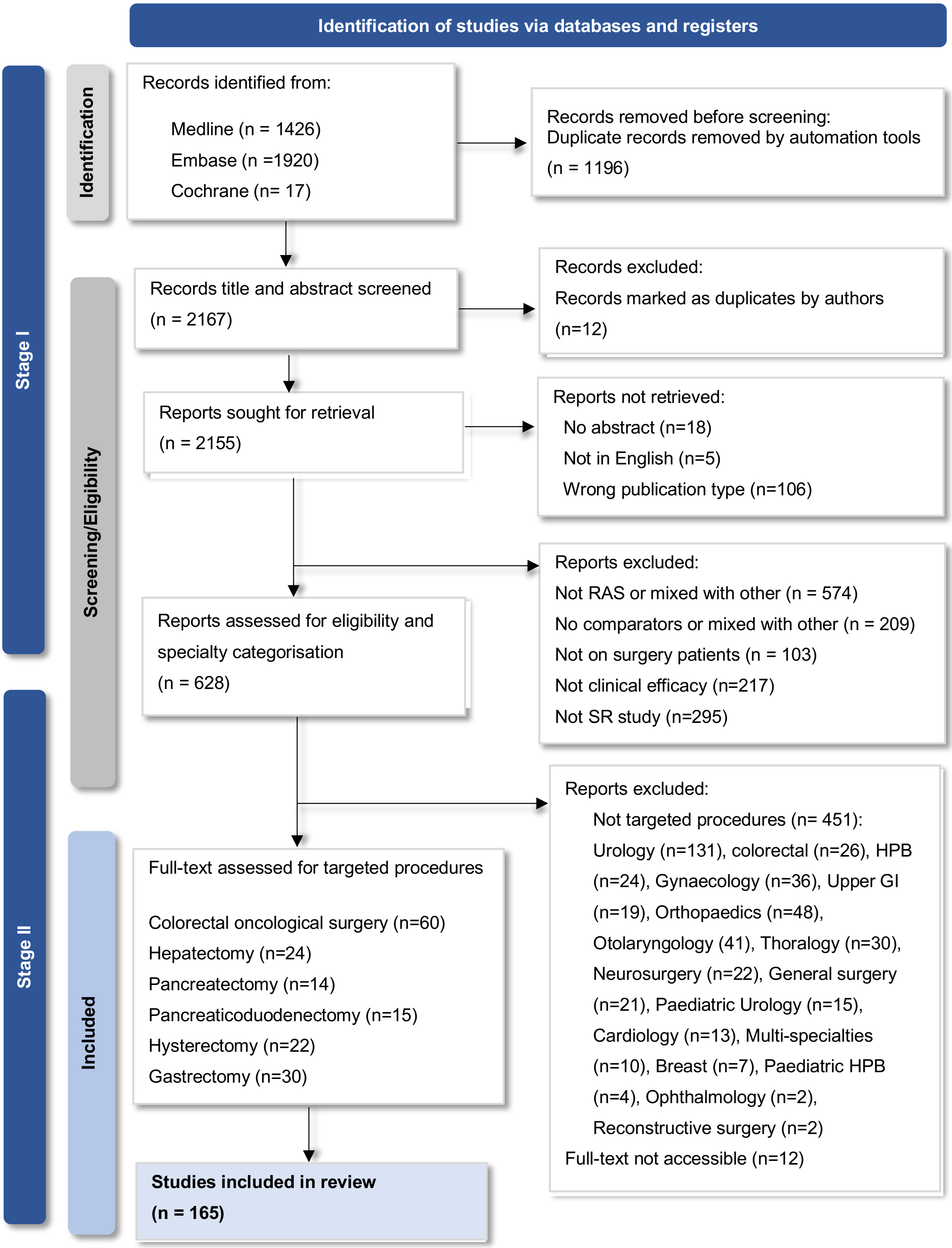


Figure 3.3-1 PRISMA flow diagram of systematic review selection process for the overview of reviews

3.3.2 Volume of reviews by specialty

This overview review included SRs published recent years from 2017 to 2023. **Figure 3.3-2** shows RAS in various clinical use and shows the volume of reviews identified by specialty. The highest number of reviews was identified in urology (n=131) where RAS is well-established, followed by colorectal (n=89), HPB (n=77), gynaecology (n=59) and upper GI (n=50). This distribution figure brieves information of RAS in clinical usage and an overview of the amount of evidence in different specialties.

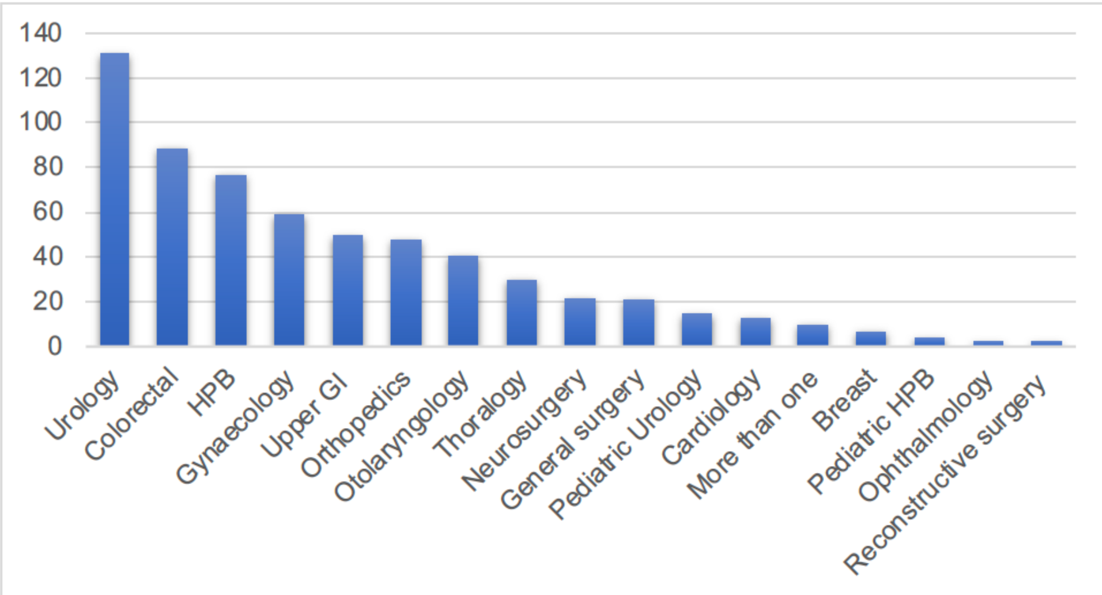


Figure 3.3-2 The number of systematic reviews distributed in different specialties

3.3.3 Evidence of clinical outcomes

A wide range of outcomes across the included systematic reviews were identified which are surgical outcomes, post-operative outcomes, oncological outcomes and long-term outcomes.

The conclusion of these clinical outcomes was summarised with descriptors of the traffic light colour, and their number of sources was recorded across every procedure. The underlying data is presented in **Figure 3.3-3**.

Figure 3.3-4 shows a comparison of clinical outcomes across procedures with a colour spectrum where red represents a negative, yellow neutral and green positive conclusion. When the evidence is mixed with positive, neutral and negative, it is indicated by brown. The gradient colour presents the strength of the evidence. By way of example, operative time across all indications is presented from orange to red. This means that this clinical outcome is from neutral to negative so operating times are the same or longer for RAS compared to LS and open surgery. Not all outcomes were relevant to all procedures. When an outcome was left blank in the evidence spectrum, it indicated that no data were available in the SRs. This absence of data could be due to two reasons: either the outcome was not reported because it was not considered relevant for a particular procedure, or no data were collected in the included studies.

Generally, RAS compared to conventional surgeries has an overall neutral in yellow and positive in green picture across all forms of outcome except operative time.

Figure 3.3-3 The number of evidence from systematic reviews by outcomes in different procedures

DFS, Disease-Free Survival; DRM, Distal Resection Margin; LOS, Length of Hospital Stays; LN, Lymph Node; OS, Overall Survival; PCRM, Positive Circumferential Resection Margin; PRM, Positive Resection Margin; R0, Margin-negative Resection

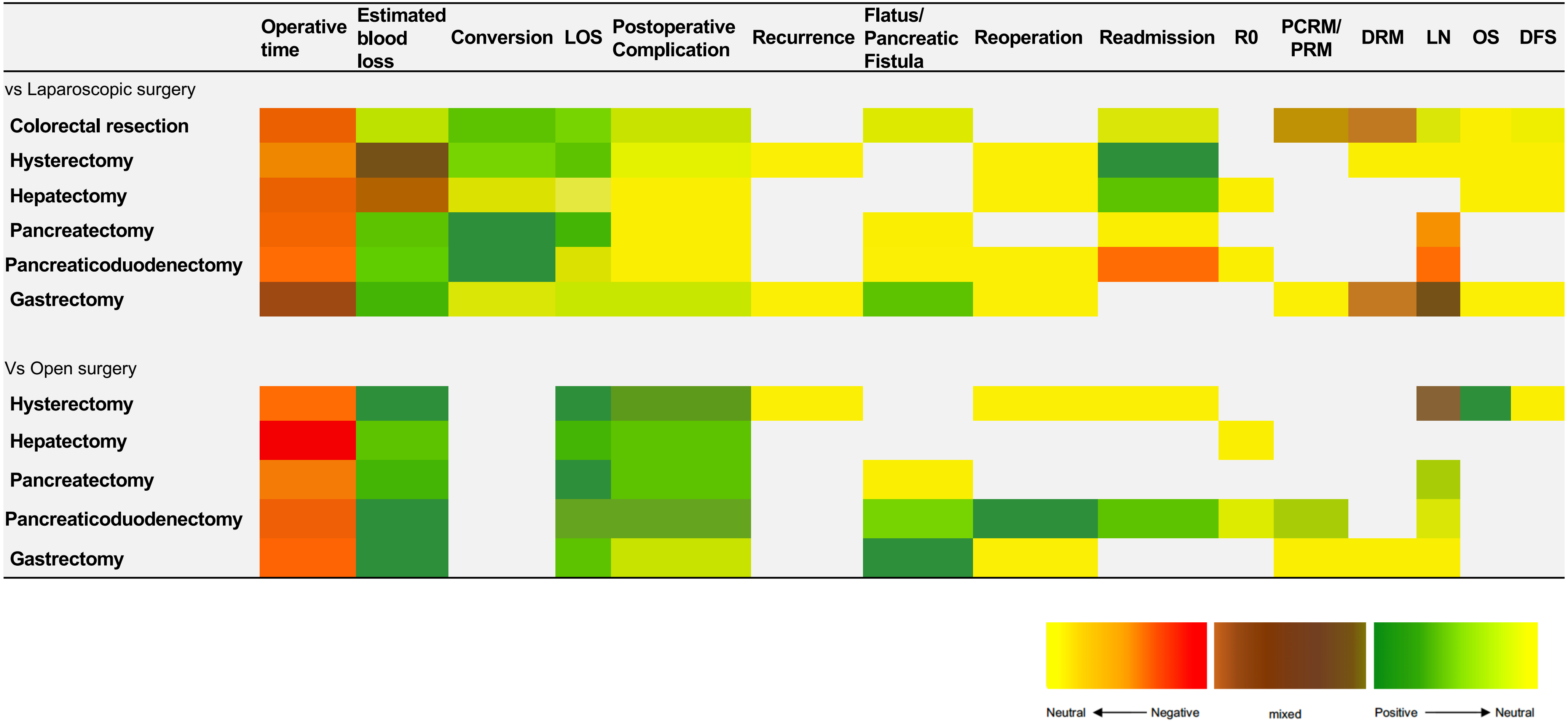


Figure 3.3-4 Evidence mapping across all targeted procedures

DFS, Disease-Free Survival; DRM, Distal Resection Margin; LOS, Length of Hospital Stays; LN, Lymph Node; OS, Overall Survival; PCRM, Positive Circumferential Resection Margin; PRM, Positive Resection Margin; R0, Margin-negative Resection

The detailed information for clinical effectiveness of the included systematic reviews is reported in **Appendix 3 - Clinical effectiveness of RAS.**

Operative time

Overall, operating times are equal or longer for RAS compared to LS and open surgery, hence the orange to red colour spectrum of evidence is presented in **Figure 3.3-4**.

In colorectal oncological resection, 28 out of 33 included meta-analysis studies (Eltair, 2020, Gavriilidis, 2020b, Huang, 2019, Li, 2017a, Ng, 2019, Ohtani, 2018, Pezzolla, 2018, Sheng, 2018, Simillis, 2019, Sun, 2019, Xu, 2017, Jones, 2018, Wang, 2020b, Butterworth et al., 2021, Genova et al., 2021, Safiejko et al., 2021, Zhang et al., 2021a, Zhu et al., 2021, Bianchi et al., 2022, Solaini et al., 2022, Tschann et al., 2022, Flynn et al., 2023, Huang et al., 2023c, Khajeh et al., 2023, Yang et al., 2023, Yao et al., 2023, Zheng et al., 2023a, Zheng et al., 2023b) and they all indicated total operating time on average in the RAS groups was significantly longer than the LS groups. In contrast, in gynaecology, 9 out of 12 studies reported insignificant operative time differences for hysterectomy compared to LS and 6 out of 9 studies compared to open surgery. Within HPB, the mean differences in operative time vary by procedures. In hepatectomy, 14 out of 18 reviews (Ciria, 2020, Hu, 2018, Hu, 2021, Kamarajah, 2020b, Wang, 2021, Wong, 2019, Zhang, 2020, Zhao, 2020, Wang et al., 2021, Aboudou et al., 2022, Hajibandeh et al., 2022, Lincango Naranjo et al., 2022, Rahimli et al., 2022, Guan, 2019) reported that RAS had a significantly longer operative time compared with LS, while all included reviews reported RAS had a significantly longer operative time compared with open surgery. In pancreatectomy, 2 out of 7 reviews (Niu, 2019, Mavrovounis, 2020) indicated that RAS had a significantly longer operative time compared with LS, 2 out of 4 reviews (Niu, 2019, Zhao, 2018) compared with open surgery. In pancreaticoduodenectomy, 1 out of 3 studies (Aiolfi, 2020) indicated RAS had a significantly had a significantly longer operative time compared with the LS approach, 9 out of 10 studies (Aiolfi, 2020, Podda, 2020, Shin, 2017, Zhao, 2018, Da Dong et al., 2021, Zhang et al., 2021b, Kabir et al., 2022, Fu et al., 2022, Yan, 2020) compared to open surgery. In the field of upper GI, 17 out of 18 reviews (Ai, 2019, Bobo, 2019, Chen, 2017, Guerrini, 2020, Ma, 2020, Wang, 2017a, Feng et al., 2021b, Zhang et al., 2021c, Baral et al., 2022, Gong et al., 2022, Jin et al., 2022, Sun et al., 2022, Iacovazzo et al., 2023, Yu et al., 2023, Magouliotis, 2017, Zhang et al., 2021d, Wang, 2017b) reported RAS for gastrectomy had significantly longer operative time compared with LS, and 4 out of 5 also had significantly longer operative time compared with open surgery (Caruso, 2017, Yang, 2017, Chen et al., 2022, Davey et al., 2023). However, there was one study that indicated robotic surgery had a significantly shorter operative time than open surgery (Aiolfi et al., 2021b). This study took results from a network meta-analysis, a technique which compares approaches both directly and indirectly to derive evidence of relative clinical effectiveness. Only one RCT involving RAS was included in the network which may limit the validity of the conclusion.

Estimated blood loss

With the exception of hysterectomy and hepatectomy (both versus laparoscopic surgery) where the evidence for estimated blood loss was mixed, all other evidence for this outcome was in favour of RAS or neutral, as illustrated by the yellow to green spectrum in **Figure 3.3-4**.

In the procedure of colorectal oncological resection, 12 out of 29 reviews (Ng, 2019, Simillis, 2019, Xu, 2017, Ma, 2019, Lee, 2018, Zhang et al., 2021a, Zhu et al., 2021, Solaini et al., 2022, Tschann et al., 2022, Huang et al., 2023c, Yao et al., 2023, Zheng et al., 2023b) reported RAS had significantly less blood loss than LS, but the other 17 reviews did not find statistically significant mean differences. However, in hysterectomy, the evidence was inconsistent depending on the comparative procedures. Within the 14 reviews comparing RAS to LS which had data on blood loss, 6 studies indicated significantly less blood loss (Laios, 2017, Prodromidou, 2020, Wang, 2020a, Kampers et al., 2022, Huang et al., 2023b, Lenfant et al., 2023), 2 study reported significantly more blood loss (Li, 2017b, Kampers et al., 2022), but 6 studies found no significant differences. When RAS was compared to open surgery, all 8 reviews found positively that RAS had significantly less blood loss (Park, 2017, Shi, 2019, Zhang, 2019, Li, 2017b, Wang, 2020a, Jin, 2018, Kampers et al., 2022, Lenfant et al., 2023). Within HPB, various effects could be seen depending on the procedure. For hepatectomy, among the articles comparing RAS to LS, mixed evidence was also identified. 5 studies reported significantly less blood loss (Coletta, 2021, Gavriilidis, 2020a, Kamarajah, 2020b, Gao et al., 2023, Mao et al., 2023), while another 4 studies (Ciria, 2020, Hu, 2018, Zhao, 2020, Guan, 2019) indicated a contrasting result in favour of LS. But when comparing to open surgery, 5 studies (Gavriilidis, 2020a, Zhao, 2020, Yeow et al., 2022, Papadopoulou et al., 2023, Xuea et al., 2023) indicated RAS was associated with significantly less blood loss, while the other 4 studies found no significant differences. For pancreatectomy, three review reported RAS had significantly less blood loss than LS (Gavriilidis, 2019, van Ramshorst et al., 2023, Di Martino et al., 2021), and 3 out of 4 reviews (Gavriilidis, 2019, Zhao, 2018, Zhou, 2020) reported RAS had significantly less blood loss than open surgery. For pancreaticoduodenectomy, 2 reviews identified RAS had significantly less blood loss than LS (Kabir et al., 2022, Ouyang et al., 2022), and all reviews indicated the result in favour of RAS compared to open surgery (Aiolfi, 2020, Podda, 2020, Shin, 2017, Yan, 2020, Zhao, 2018, Gavriilidis, 2019, Zhou, 2020, Da Dong et al., 2021, Zhang et al., 2021b, Kabir et al., 2022, Fu et al., 2022). In respect of gastrectomy, 16 out of 20 included studies (Caruso, 2017, Chen, 2017, Wang, 2017a, Ai, 2019, Bobo, 2019, Guerrini, 2020, Ma, 2020, Feng et al., 2021b, Zhang et al., 2021c, Ali et al., 2022, Baral et al., 2022, Gong et al., 2022, Jin et al., 2022, Sun et al., 2022, Multani et al., 2023, Zhang et al., 2021d) showed that RAS had significantly less blood loss compared to LS, while all reviews reported RAS had significantly less blood loss than open surgery (Ai, 2019, Aiolfi et al., 2021b, Bobo, 2019, Caruso, 2017, Chen, 2017, Guerrini, 2020, Ma, 2020, Wang, 2017a, Yang, 2017, Chen et al., 2022, Davey et al., 2023).

Conversion rate

Identified evidence across all procedures showed either positive or neutral results in the conversion rate for RAS compared to LS, green to yellow is presented in **Figure 3.3-4**.

Regarding colorectal oncological resection, 26 out of 35 included reviews (Gavriilidis, 2020b, Huang, 2019, Jones, 2018, Li, 2019, Li, 2017a, Ng, 2019, Ohtani, 2018, Pezzolla, 2018, Sun, 2019, Wang, 2020b, Xu, 2017, Lee, 2018, Ma, 2019, Phan, 2019, Safiejko et al., 2021, Zhu et al., 2021, Bianchi et al., 2022, Solaini et al., 2022, Tschann et al., 2022, Flynn et al., 2023, Huang et al., 2023c, Khajeh et al., 2023, Oweira et al., 2023, Seow et al., 2023, Yao et al., 2023, Zheng et al., 2023a, Zheng et al., 2023b) reported that RAS had significantly lower chances of conversion to open surgery compared to LS. In hysterectomy, 3 indicated RAS had significantly lower rates than LS (Laios, 2017, Wang, 2020a, Lenfant et al., 2023), and the other 3 reviews presented no significance. In respect of HPB, 5 of 20 included reviews indicated robotic hepatectomy had significantly lower conversion rates than LS (Coletta, 2021, Hu, 2021, Zhang, 2020, Hu et al., 2021, Mao et al., 2023). For pancreatectomy and pancreaticoduodenectomy, all 9 reviews suggested significantly lower conversion rates to open surgery than LS (Gavriilidis, 2019, Kamarajah, 2019, Lauretta, 2017, Mavrovounis, 2020, Aiolfi, 2020, Di Martino et al., 2021, Zhang et al., 2021b, Li et al., 2023, Kamarajah, 2020a). However, in gastrectomy, no significant conversion rate differences could be found from the included 13 out of 18 reviews.

Length of Hospital stay

Identified evidence across all procedures showed that RAS compared to LS or open surgery had an equivalent or shorter duration of hospitalisation, hence the green to yellow colour spectrum of evidence is presented in **Figure 3.3-4**.

Among the included reviews of colorectal oncology surgery, 16 out of 37 articles (Jones, 2018, Ng, 2019, Xu, 2017, Simillis, 2019, Hoshino, 2021, Ma, 2019, Wang, 2020b, Safiejko et al., 2021, Zhang et al., 2021a, Tschann et al., 2022, Flynn et al., 2023, Huang et al., 2023c, Yao et al., 2023, Zheng et al., 2023b, An et al., 2022, Ravindra et al., 2022) reported RAS had a significantly shorter duration of hospital stays than LS. For hysterectomy, 10 out of 13 studies (Laios, 2017, Lawrie, 2019, Park, 2017, Prodromidou, 2020, Wang, 2020a, Li, 2017b, Kampers et al., 2022, Lenfant et al., 2023, Marchand et al., 2023a, Marchand et al., 2023b) reported RAS had significantly shorter hospital stays than LS. Compared to open surgery, RAS also had a significantly shorter length of hospital stays (Park, 2017, Shi, 2019, Wang, 2020a, Zhang, 2019, Li, 2017b, Jin, 2018, Lenfant et al., 2023). In the field of HPB, only 2 studies for hepatectomy indicated RAS had a significantly shorter length of hospital stay than LS while the other 19 studies did not (Coletta, 2021, Mao et al., 2023). 8 out of 9 (Machairas, 2019, Wong, 2019, Ciria, 2020, Gavriilidis, 2020a, Zhao, 2020, Papadopoulou et al., 2023, Xuea et al., 2023, Lincango Naranjo et al., 2022) included studies showed significantly shorter duration than open surgery. Among the included systematic reviews for pancreatectomy and pancreaticoduodenectomy, 6 studies (Lauretta, 2017, Gavriilidis, 2019, Kamarajah, 2019, Niu, 2019, Rompianesi et al., 2021, Kamarajah, 2020a) reported RAS had a significantly shorter length of hospital stay than LS and almost all studies showed a significantly shorter length of hospital stay than open surgery (Fu et al., 2022, Da Dong et al., 2021, Zhou, 2020, Aiolfi, 2020, Yan, 2020, Niu, 2019, Gavriilidis, 2019, Zhao, 2018, Peng, 2017, Shin, 2017, Zhang et al., 2021b). As for gastrectomy, 5 out of 18 review (Feng et al., 2021b, Zhang et al., 2021d, Baral et al., 2022, Gong et al., 2022, Yu et al., 2023) found RAS had a significantly shorter length of hospital stay than LS, and 2 out of 4 reviews (Caruso, 2017, Chen et al., 2022) indicated RAS had a significantly shorter stay compared to open approach.

Postoperative complications

For postoperative complications among all procedures, identified evidence for comparing RAS to LS tend to be neutral, while comparing RAS to open surgery tend to be positive as illustrated in the green to yellow colour spectrum in **Figure 3.3-4**.

Among the identified reviews of colorectal oncology resection, 7 out of 30 articles (Xu, 2017, Wang, 2020b, An et al., 2022, Solaini et al., 2022, Huang et al., 2023c, Zheng et al., 2023a, Flynn et al., 2023) showed that RAS in postoperative complication results were significant compared to LS. In hysterectomy, only one study found RAS had significant lower postoperative complication than LS(Marchand et al., 2023a), while 5 out of 8 studies was in favour RAS than open approach (Li, 2017b, Jin, 2018, Shi, 2019, Wang, 2020a, Lenfant et al., 2023). In respect of HPB including hepatectomy, pancreatectomy and pancreaticoduodenectomy, no significant difference in postoperative complication rate was found compared to LS. Some positive evidence when RAS was compared to open surgery, 6 out of 11 reviews for hepatectomy (Gavriilidis, 2020a, Zhao, 2020, Wong, 2019, Ciria, 2020, Papadopoulou et al., 2023, Xuea et al., 2023), 2 out of 5 reviews for pancreatectomy (Zhao, 2018, Niu, 2019), and 6 out of 8 reviews for pancreaticoduodenectomy (Aiolfi, 2020, Zhao, 2018, Peng, 2017, Zhang et al., 2021b, Fu et al., 2022). For gastrectomy, 5 out of 18 (Feng et al., 2021b, Zhang et al., 2021c, Ali et al., 2022, Baral et al., 2022, Jin et al., 2022) found RAS had significant differences in postoperative complication rates compared to LS, and only one compared to open surgery (Chen et al., 2022).

Other clinical outcomes

There were other important outcomes were identified among the selective procedures such as reoperation and readmission presented in **Figure 3.3-4**.

It is noted that there was various evidence identified in outcomes of readmission across all selective procedures when RAS compared to LS. Some procedures reported on postoperative mortality (Behbehani, 2019, Behbehani, 2020, Aiolfi et al., 2021b, Bobo, 2019, Chen, 2017, Liao, 2019b, Ma, 2020).

Procedure-specific postoperative outcomes were also reported. For example, colorectal resection and gastrectomy had data on outcomes of first flatus (Jones, 2018, Simillis, 2019, Safiejko et al., 2021, Zheng et al., 2023a, Ma, 2020, Aiolfi et al., 2021b, Feng et al., 2021b, Iacovazzo et al., 2023, Jin et al., 2022, Sun et al., 2022, Yu et al., 2023, Zhang et al., 2021c), pancreatectomy and pancreaticoduodenectomy on outcomes of pancreatic fistula (Zhang et al., 2021b, Fu et al., 2022, Wang et al., 2023), and bile leak (Kornaropoulos, 2017). Colorectal resection had reported urinary outcomes and sexual function (Fleming et al., 2021, Tang, 2018, Wee et al., 2021, Yang and Zhou, 2023, Holmer, 2018, Kowalewski et al., 2021) and other outcomes such as Ileus and anastomotic leak (Tejedor, 2020, Waters, 2020, Kowalewski et al., 2021). More details for other clinical outcomes of the included systematic reviews can be found in **Appendix 3** - Clinical effectiveness of RAS.

Oncological outcomes

Different oncological outcomes were reported including number of lymph node yield and resection-related outcomes (distal resection margin, positive circumferential resection margin, positive resection margin and margin-negative resection). Mix evidence in oncological outcomes was found across all procedure especially when RAS compared to LS or open surgery, with brown colour in spectrum presented in **Figure 3.3-4**. For example, lymph node yield in hysterectomy, RAS compared to open surgery had one study with significant negative outcome (Wang, 2020a), 3 with positive outcome (Li, 2017b, Lawrie, 2019, Marchand et al., 2023a), and 4 with neutral. One study also reported para-aortic lymph nodes (Nevis, 2017). In gastrectomy, RAS compared to LS also found 8 with significant negative outcome (Ai, 2019, Bobo, 2019, Guerrini, 2020, Feng et al., 2021b, Ali et al., 2022, Baral et al., 2022, Jin et al., 2022, Zhang et al., 2021d), 2 with positive (Gong et al., 2022, Sun et al., 2022), and 7 with insignificant outcomes. In pancreatectomy and pancreaticoduodenectomy, RAS compared to LS had 1 out of 6 (Mavrovounis, 2020) and 2 out of 4 reviews (Ouyang et al., 2022, Kamarajah, 2020a) had negative significance. Other oncological outcome was used, for example, completeness of total mesorectum excision (Milone, 2019). More details can be reviewed in **Appendix 3 - Clinical effectiveness of RAS**.

Long-term outcomes

Some reviews comparing RAS to LS reported overall survival and disease-free survival outcomes. In most of studies, identified evidence was neutral with the yellow colour spectrum presented in **Figure 3.3-4**, except one study showing RAS compared to open surgery had significantly longer 3-year overall survival in hysterectomy (Shi, 2019).

3.3.4 Quality and overlap of included reviews

Figure 3.3-5 displays the quality of the systematic reviews was generally judged low or critically low across all procedures, using the AMSTAR-2 quality appraisal tool guidance (Shea et al., 2017). The characteristics of included reviews and quality assessment for specialties of interest are recorded in **Appendix 2 - Characteristics of included reviews and quality assessment from the overview** review.

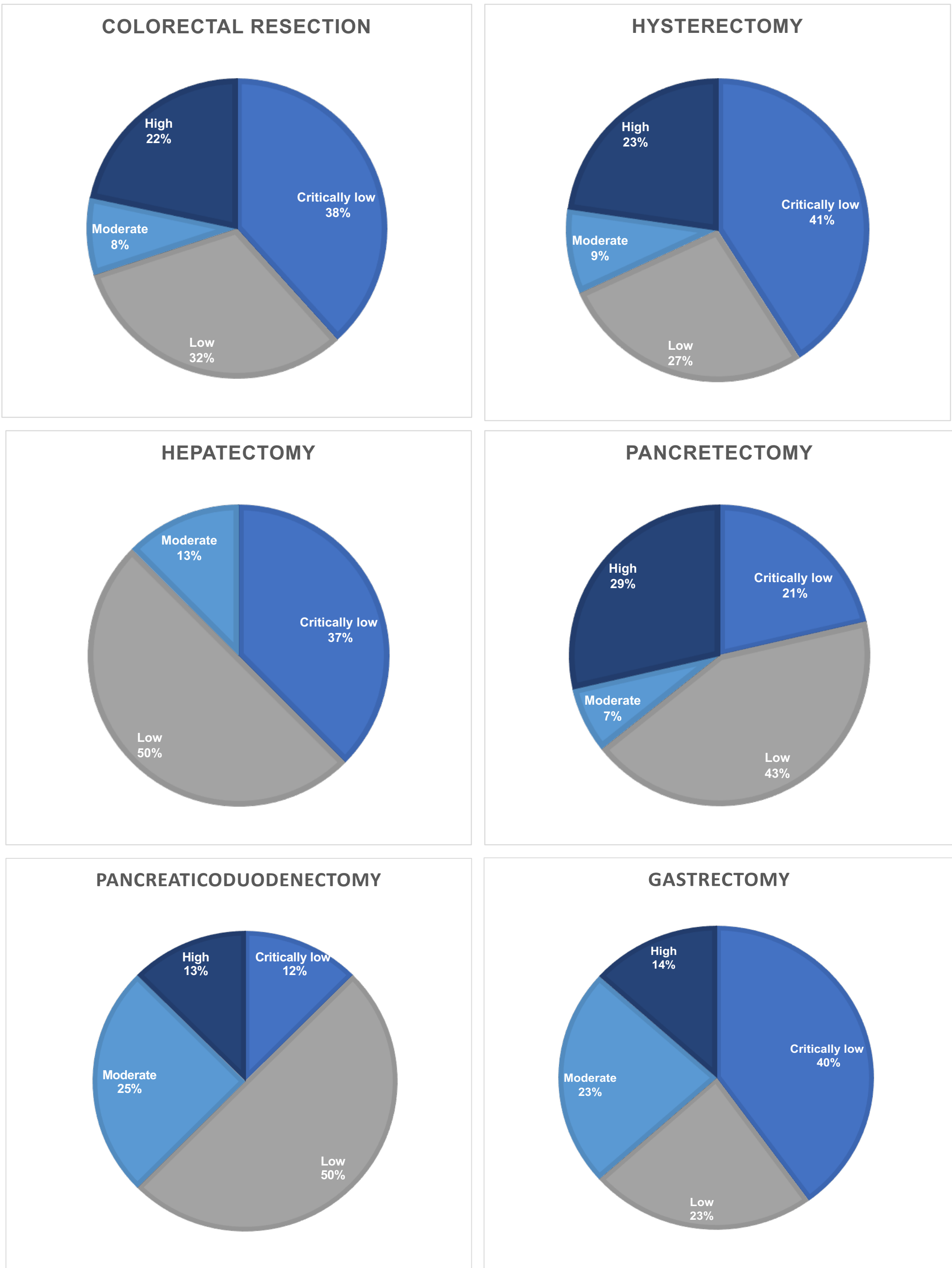


Figure 3.3-5 Quality assessment of systematic reviews in procedures of interest

This assessment identified the critically flaw domain that the source of their primary studies does not impact quality, but poor management for risk of bias and publication bias does.

Regarding overlap management, I used a citation matrix to correct the covered area value. In colorectal oncological surgery, the total number of ticked boxes was 454, with 175 index publications and 26 review studies. Based on these values, the corrected covered area for colorectal oncological surgery was calculated to be 6.4%, indicating a moderate level of overlap. For hysterectomy, the total number of ticked boxes was 442, with 289 index publications and 17 review studies. Based on these values, the corrected covered area was calculated to be 3.3%, indicating only a slight overlap. For hepatectomy, the total number of ticked boxes was 257, with 69 index publications and 21 review studies. The corrected covered area was calculated to be 13.62%. For pancreatectomy, the total number of ticked boxes was 182, with 62 index publications and 12 review studies, resulting in a corrected covered area of 17.6%. In pancreaticoduodenectomy, the total number of ticked boxes was 134, with 44 index publications and 10 review studies, leading to a corrected covered area of 22.73%. These are considered as high and very high overlap. For gastrectomy, the total number of ticked boxes was 417, with 138 index publications and 25 review studies, resulting in a corrected covered area of 8.42%, which indicate moderate.

Given this level of overlap, we were aware of the risk of double-counting of individual studies within systematic reviews would potentially impact on result and interpreted the evidence carefully.

3.4 Discussion

This review study aims to overview a broad picture of RAS in all clinical uses and take a further look at the evidence, focussing on procedures that are starting to be performed but where RAS is not the dominant approach. This study can support decision-makers in optimising the utilisation of this technology.

From my work on evidence volume by specialty the largest number of systematic reviews were found in urology, coloproctology, HPB and gynaecology. In this overview of systematic reviews of RAS compared to LS and open surgery, I focused on 6 procedures among 4 specialties and explored the variety of clinical outcomes under the categories of: surgical, postoperative, oncological, and long-term outcomes.

This review found that RAS operative time was generally longer across all procedures. On outcomes of estimated blood loss, RAS compared to open approach had less, but there was reported mixed evidence in hysterectomy and liver resection compared to LS. On the outcomes of conversion rate and length of hospital stay, all the evidence indicated RAS tends to have a lower conversion rate and shorter length of hospital stays whether compared to LS or open approach. RAS had lower postoperative complications compared to open approach but found no significant difference compared to LS. On the outcome of post-operative readmission across procedures, inconsistent results were identified. RAS had a lower post-operative readmission rate in hysterectomy and hepatectomy compared to LS but higher in pancreaticoduodenectomy compared to LS. For oncological outcomes, there was mix evidence found in lymph node yield numbers and distal resection margin comparing to LS. Furthermore, RAS did not improve overall survival or disease-free survival, except for hysterectomy compared with an open approach. Nevertheless, from our spectrum of evidence across surgical procedures, I found measured outcomes for RAS which compared LS and open surgery indicating that the evidence is more positive when compares to an open approach.

Almost equivalent clinical outcomes of RAS were identified except for operative time. Longer operative time is a historic phenomenon because RAS is a relatively new technology which has a steep learning curve for individual surgeons and the whole support team. I recognise that the primary studies from the included systematic reviews covered previously done RCTs and observational studies. This data might be out of date now. The specific operative approaches have been refined and taught. Therefore, this outcome may not be permanent and may improve over time as the whole surgical and support team become more familiar with the technology (Bach et al., 2014, Khadhouri et al., 2018, Taylor et al., 2015, Arquillière et al., 2023). In urology, where RAS is more established, evidence from large observational studies of robot-assisted laparoscopic prostatectomy shows a consistent decline in operative time and console time after overcoming the learning curve followed by a near-constant phase (Tamhankar et al., 2020). One study, also from urology, reported that surgeons with a higher caseload exhibited improved operative time compared to general caseload (266 minutes vs. 240 minutes, $P < 0.05$) (Perera et al., 2023).

A recent overview of reviews for RAS looked at multiple procedures (radical prostatectomy, hysterectomy, thoracic surgery (lobectomy and thymectomy), colorectal resection, nephrectomy, gastric, and hepatopancreaticobiliary procedures) and found, as I did, that RAS generally had longer operative time (Muaddi, 2021). It also found shorter operative time in hysterectomy for endometrial cancer and Roux-en-Y gastric bypass compared to LS. This may be because the review only looked at SRs including RCTs whereas my review has included a broader range of SRs which incorporated evidence from observational studies. I found shorter operative time in gastrectomy compared to LS and this finding was from a single network meta-analysis including a single RCT (Aiolfi et al., 2021b). As for the other overview of reviews which focused on a single procedure, one study targeting total mesorectal excision for rectal cancer also found that RAS had significantly longer operative time than LS and OS (Yamamoto, 2020). Another two overview reviews for gastric cancer indicated that patients treated with RAS had significantly less estimated blood loss and shorter time to resumption of oral intake but prolonged operating time than patients undergoing LS (Hoshino, 2020, Marano et al., 2021). In this overview, I also found RAS had significantly less estimated blood loss and a shorter time to resumption of oral intake than LS and open surgery in gastrectomy.

My finding here was consistent with another overview of SRs (Hoshino, 2020) which also included the quality assessment. In my study, the quality of individual studies was considered indirectly through the AMSTAR-2 assessment, focusing on how SRs addressed risk of bias, imprecision, and publication bias. While AMSTAR-2 evaluates review quality rather than individual studies, it highlights whether biases, such as selection and performance bias, were properly managed. Therefore, whether these SRs handled imprecision (e.g., confidence intervals, effect sizes) and publication bias (e.g., funnel plots, missing data) were taken into account. My findings of poor quality mainly relate to authors’ failure to explicitly deal with the bias inherent in observational studies. However, real-world evidence is critical in the evaluation of surgical techniques as randomisation is often difficult or impossible and randomised trial participants and surgeons may not be representative of the full population. This indicates that these reviews did not adequately account for the limitations of observational evidence, particularly selection and performance bias, which reduces certainty in their conclusions. As some SRs may fail to address these factors, the results should be interpreted with caution, as their conclusions might be skewed.

This review is the first review to summarise the full body of evidence of clinical outcomes of RAS and then further examine a number of specialties where there is still equipoise. This review is particularly relevant at the present time due to significant RAS expansion across non-urological specialities. This study synthesise evidence on RAS effectiveness across a wide range of procedures and outcomes. It is visually easier to interpret and more useful for practitioners and decision-makers compared to tables. This study allows readers can capture both a broad perspective of the evidence landscape and in-depth information on the certainty of evidence on patient-important outcomes. This evidence spectrum is a new contribution to this context summarise in existing literature. The result from this overview is likely to be generalisable as the SRs included studies from a broad range of settings. However, there are limitations in this study. I only included SRs focused on selective procedures within the recent years in the English language. It may have different results when RAS applies to different procedures. Despite the advantages of a narrative summary, the counting approach has downsides. It does not account for study quality, giving equal weight to all studies regardless of rigor. Publication bias may skew results, overrepresenting positive findings. Additionally, this approach does not consider effect size or the clinical significance of findings. Readers may misinterpret a higher study count as stronger evidence, overlooking contextual factors such as surgeon expertise and institutional differences.

These findings have different implications for different categories of stakeholders. For patients, these results suggest that it is safe to move to RAS for all procedures examined, with outcomes equivalent or superior to traditional surgical methods. However, caution is advised for new procedures, as the first procedures chosen for RAS may have been the most suitable. For surgeons and other clinicians, although operative times are generally longer, they can be reassured about patient outcomes, and the presence of RAS may bring other benefits. These benefits include the attraction and retention of surgeons, the enhancement of their skill sets, and the ability to work longer without fatigue or work longer before retirement. For healthcare providers, the use of RAS may bring the benefit of extending MIS to a larger proportion of patients. Where the uptake of LS has been low, perhaps due to technical difficulty, RAS may be more attractive to surgical teams (Maynou et al., 2021, Maynou et al., 2022). Previous research has investigated the scalability of MIS, indicating that RAS rapidly substitutes both open and laparoscopic surgery over time, resulting in a higher proportion of MIS overall (Maynou et al., 2022, Sheetz et al., 2020). RAS, initially adopted for urological procedures. However, the limited operational days of surgical hardware may prompt hospitals to cross-specialty utilisation for optimal return on investment. A UK NHS study from 2000 to 2018 highlights RAS substituting incumbent technologies and expanding into diverse surgical specialties (Maynou et al., 2022). One study showed the proportion of hospitals and surgeons performing robotic surgery for selective procedures (including inguinal hernia repair colectomy etc.) increased from 3.1% in the first year to 13.1% in the fourth year after the implementation of surgical robots, leading to a trend toward less laparoscopic surgery (−1.9%) being performed (Sheetz et al., 2020). Another example where LS expansion could be considered to have stalled in the UK is laparoscopic colonic surgery. Rates of open colorectal cancer surgery remain between 30%-40% and of those receiving laparoscopic resection, conversion to open surgery occurs in 10% in England and Wales (NBOCA, 2022). Once the investment in RAS has been made, there may also be a higher level of institutional buy-in to extending its use, increasing the total proportion of patients being treated in a minimally invasive manner. The main concern may be around operative time. It might be a short-term phenomenon akin to a learning curve and might change over time as teams get used to new equipment. Alternatively, longer operative time could be a necessary disadvantage of a more complex set of equipment. Accordingly, other concerns for healthcare providers include the real costs of longer operative time, whether fewer procedures are being done and waiting lists are growing, and whether higher prices charged for procedures compensate for the longer operative time.

In conclusion to this Chapter 3, the evidence suggests that RAS is a safe and effective alternative to LS and open surgery, with the potential to improve outcomes and enhance the capabilities of surgeons and healthcare providers and a particular opportunity to increase the proportion of minimally invasive approaches.

The study in Chapter 3 reflects on Chapter 2 frameworks, ensuring that implementation of RAS aligns with robust evidence-based practices. However, given the higher capital and running costs of the technology (i.e. purchase of the robot, maintenance costs and the costs of disposables) and the longer operative times associated with its use, there is a need for careful consideration of its cost-effectiveness. The aspects of cost-effectiveness and long-term sustainability of RAS from the framework require further investigation. Only through rigorous evaluation can we ensure that RAS is utilised in the most effective and sustainable manner possible after the initial investment, for the benefit of patients, surgeons, and healthcare systems as a whole. Further research is needed to fully evaluate the value of these improvements in outcomes and to assess whether they outweigh the cost implications of the technology.

Therefore, in the following chapters, I am going to explore further on this subject.

Chapter 4 The Use Of Economic Evaluation Methodology In Robotic-Assisted Surgery

In Chapter 4, I aim to answer the research question (2):

- How has cost-effectiveness been assessed and what economic evidence is there to support the use of RAS?

A modified version of this chapter has been accepted by Applied Health Economics and Health Policy on the title of **'Economic Evaluations of Robotic-Assisted Surgery: Methods, Challenges, and Opportunities '**.

4.1 Introduction

The adoption of robotic-assisted surgery (RAS) has increased worldwide in recent years which attributed to its perceived advantages over conventional surgery techniques (Maynou et al., 2021, Maynou et al., 2022, Siddaiah-Subramanya et al., 2017, George et al., 2018). However, the value of RAS compared to alternative surgical approaches is a subject of ongoing debate, primarily due to the additional cost of RAS and the equivocal evidence on surgical outcomes (Roh et al., 2018, Gkegkes et al., 2017).

In Chapter 3, where I investigate evidence of clinical effectiveness, I found RAS is better than or equivalent to open or LS across a wide range of outcomes in selected procedures. This chapter, I then further investigate evidence of cost-effectiveness.

Some evidence suggests that RAS may be cost-effective compared to conventional surgeries (Close et al., 2013, Song et al., 2022), other studies found that RAS was unlikely to be cost-effective (Hohwü et al., 2011, Teljeur et al., 2014, Morii et al., 2019). A recent consensus-based best-practice paper looking at the assessment of RAS systems, stressed the importance of including clinical perspectives (such as clinical evidence and the learning curve), economics perspectives (such as costing methods and economic analysis methods) and provider perspectives (i.e. the robotic ecosystem and hospital procedure volume). It also stressed that the assessment should consider the cross-therapeutic nature of RAS and the needs of decision-makers at all levels (Erskine et al., 2023).

Previous systematic reviews of economic evaluation methodologies used in studies of robotic surgery have highlighted inconsistencies among studies in terms of methodology employed, costs included and setting (Korsholm et al., 2018, Tandogdu et al., 2015, Turchetti et al., 2012, Bai et al., 2022). They indicated that there was insufficient economic evidence to support informed decision making on the adoption of RAS and that more work on economic evaluation in this area was required (Tandogdu et al., 2015, Turchetti et al., 2012, Bai et al., 2022).

The inconclusive findings on the cost-effectiveness of RAS may be due to the specific challenges associated with evaluating medical devices, as I explored in Chapter 2 (Drummond et al., 2009, Drummond et al., 2018, Sorenson et al., 2011). For instance, the interaction between the device and the user (e.g., the surgeon) introduces a learning curve, where the outcomes associated with a device may improve over time. The implementation of medical devices can also have significant organisational implications, requiring capital investment and training. Challenges in conducting outcomes research also result from difficulties in enrolling patients in randomised controlled trials (RCTs), leading to issues with data quality. Incremental innovation (i.e., continual small improvements) made to existing devices, or the introduction of new products, means data on costs and outcomes can become outdated very quickly and the evidence base can include studies using multiple iterations of the same technology. Pricing of medical devices can also be dynamic over time. For example, pricing may be influenced by tendering in the procurement process or the entry of competitors into the market. These challenges introduce an additional layer of complexity for the assessment of medical devices, compared with pharmaceutical interventions. Tarricone et al. (Tarricone et al., 2017a) developed a framework to help address the distinctive features of medical devices in economic evaluation. RAS constitutes a medical device which is not only associated with all of the challenges highlighted above, but also has the potential for broader organisational impact. This is because RAS may be utilised across multiple specialities and procedures. Therefore, how the capacity is used and the volume of procedures both influence cost effectiveness through cost apportionment. Healthcare providers may strategically allocate resources to ensure sufficient surgery volumes for efficiency but may also have other consideration to take into account, such as equity of access.

Therefore, in this review, I aimed to achieve three main objectives:

1. Summarise the existing evidence regarding the cost-effectiveness of RAS;
2. Identify and describe the economic evaluation methods employed in assessing RAS;
3. Identify whether and how the specific characteristics of RAS were considered in these economic evaluations.

4.2 Methods

I conducted a systematic scoping review following the *Guidance for Conducting Systematic Scoping Reviews* and the *Preferred Reporting Items for Systematic Reviews and Meta-Analysis* guidelines (Peters et al., 2015, Page et al., 2021).

4.2.1 Search strategy and selection

A search was executed in PubMed and EMBASE to identify studies which performed economic evaluations of RAS published in the English language within the period January 2015 to December 2023. I aimed to update a previous review (Tandogdu et al., 2015) to the most recent years with the additional purpose of discussing different economic evaluation methods which have been used to highlight methodological issues for RAS. My supervisors and I reviewed the previous review strategy for relevance and completeness and decided that it met our requirements. The search terms can be found in **Appendix 4 - Database search terms for the scoping** review**.**

Myself and a fellow PhD student independently conducted the initial review of all records for potential eligibility by screening the titles and abstracts using the reference management software Rayyan (Ouzzani et al., 2016). Both authors scored “include” or “exclude,” and “maybe” when there were any doubts about the potential eligibility of the article. The inclusion decision was made upon the consensus of reviewers. I then exported to Endnote X9 (Hupe, 2019) for searching the full text for inclusion. The final inclusion decision was made by consensus following discussion.

4.2.2 Criteria for inclusion of studies

All economic evaluation studies (including cost-effectiveness analysis (CEA), cost-utility analysis (CUA), cost-benefit analysis (CBA), cost-minimisation analysis (CMA), and cost-consequence analysis (CCA)) of RAS versus laparoscopic or open surgery were included in this review. Studies which were unable to report RAS separately from other minimally invasive procedures or with no comparator, the grey literature (i.e., conference abstracts, letters, and commentaries etc.), case reports, protocols and review studies, and papers not in English were excluded.

4.2.3 Data extraction and presentation

First, I extracted the key results of the study to summarise the existing evidence regarding the cost-effectiveness of RAS. In terms of determining whether RAS was considered an optimal strategy, I used narrative summary that defined the technical conclusions depending on the study design and the study authors’ conclusions. I considered an economic evaluation (ie. CUA, CEA, CBA or CCA) favourable toward RAS as determined by the study authors’ predefined goals (e.g. if an incremental cost-effectiveness ratio (ICER) was below a willingness-to-pay (WTP) threshold stated by the authors). If RAS showed favourability only under specific conditions, it was reported as neutral. In costing studies (ie. CMA), a study was considered favourable toward RAS if RAS was the least costly of the alternative surgical approaches. The rating was driven by authors’ conclusions and did not account for imprecision, or where a sensitivity analysis was undertaken. One of my supervisors (R.H.) supported the categorisation of economic evaluation methods. Second, I used the updated Consolidated Health Economic Evaluation Reporting Standards (CHEERS) 2022 (Husereau et al., 2022)to describe the methods used to undertake economic evaluations in our review. Then, I took extended CHEERS outlined by Tarricone et al. which including the additional categories relevant to medical devices (Tarricone et al., 2017a), as it is currently the best available tool for this evaluation purpose. This extended checklist contains four additional items to the original CHEERS checklist designed to capture the specific features of medical devices: learning curve, organisational impact, incremental innovation, and dynamic pricing (Tarricone et al., 2017a). For each of the four items, I identified whether they had been considered or not and, if considered, how these factors were incorporated in the analysis. In particular, whether they were measured empirically or modelled, or whether they were included only as a discussion point. They were appraised with fully considered, partially considered and not considered. The detail extraction is provided in **Appendix 5 - Characteristics of the included studies from the scoping** review.

4.3 Results

4.3.1 Summary of search and characteristics of included studies

The electronic search yielded 3,535 references, with 258 of these potentially meeting inclusion criteria. After the full-text screening, 208 studies which did not meet the inclusion criteria were excluded. As a result, a total of 50 studies were finally considered eligible for inclusion in the review. The selection process is summarised in a PRISMA flowchart at **Figure 4.3-1** (Page et al., 2021).

Among the 50 studies identified, the most common setting was Europe (n=27, 54%), of which 12% (n=6) were from the United Kingdom, followed by the United States (n=15, 30%). Urological procedures formed the largest section of studies (n=21, 42%), followed by hepato-pancreato-biliary (HPB) procedures (n=10, 20%), colorectal procedures (n=7, 14%) and gynaecological procedures (n= 3, 6%). Notably, two studies (4%) included more than one clinical field. A detailed overview of the general characteristics of the included studies, along with a summary of their results, is provided in the **Appendix 5 - Characteristics of the included studies from the scoping** review.

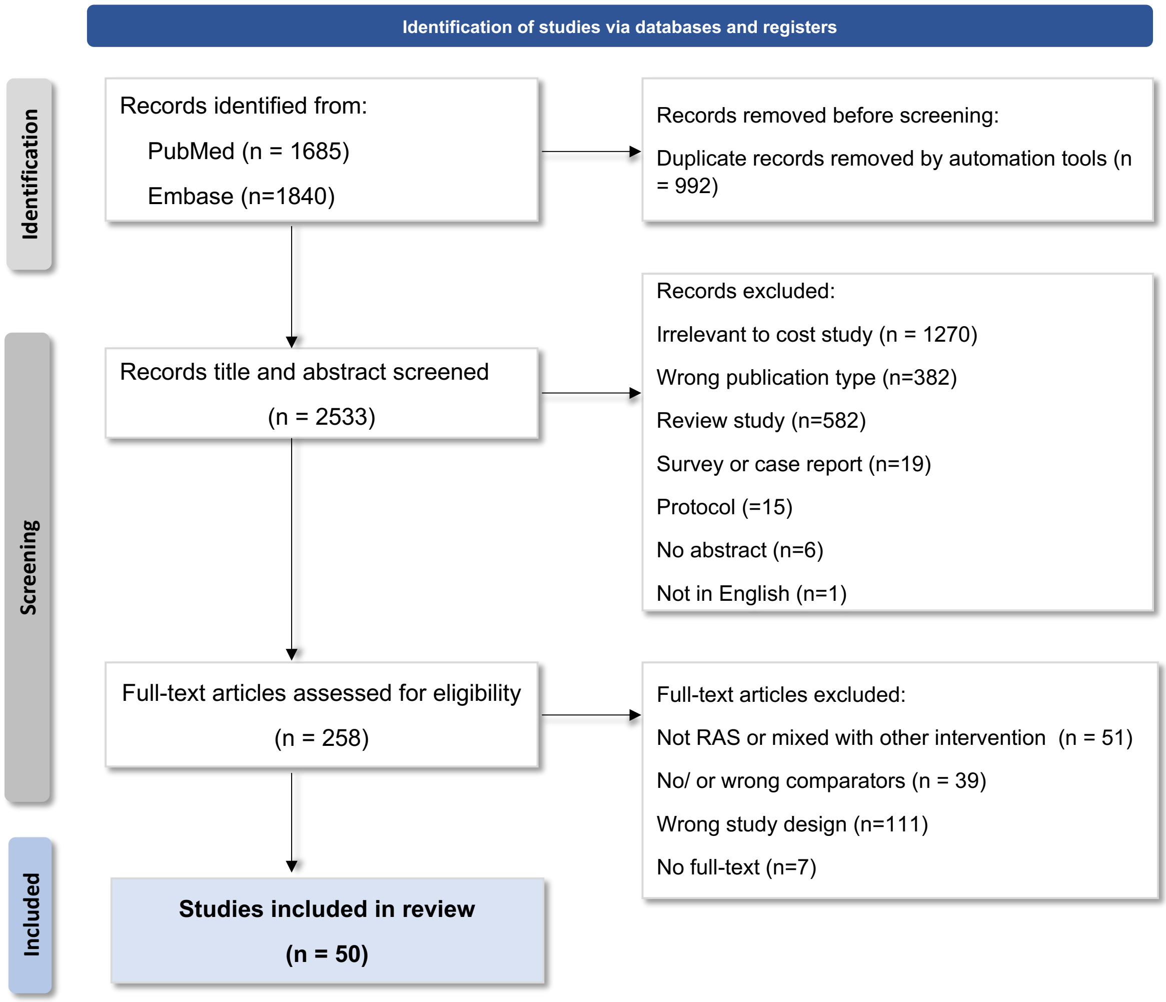


Figure 4.3-1 PRISMA 2020 flowchart of the selection process for the scoping review

4.3.2 Summary of the cost-effectiveness of RAS from included studies

Figure 4.3-2 summarises whether the results of included studies were favourable, neutral or unfavourable according to comparator and specialty. 29 out of 50 identified studies (58%) favoured RAS, nine of which compared RAS to LS, eight compared RAS to open surgery and the remaining twelve studies compared RAS to both LS and open surgery. Of the twelve studies comparing RAS to both open and LS, four studies were favourable to RAS compared to open but found that LS was the most cost-effective strategy of the three. Sixteen of the 50 studies (32%) were unfavourable towards RAS, seven studies comparing RAS to LS, seven studies comparing RAS to open surgery and two comparing RAS to both LS and open surgery. There were five studies (10%) where the findings were neutral.

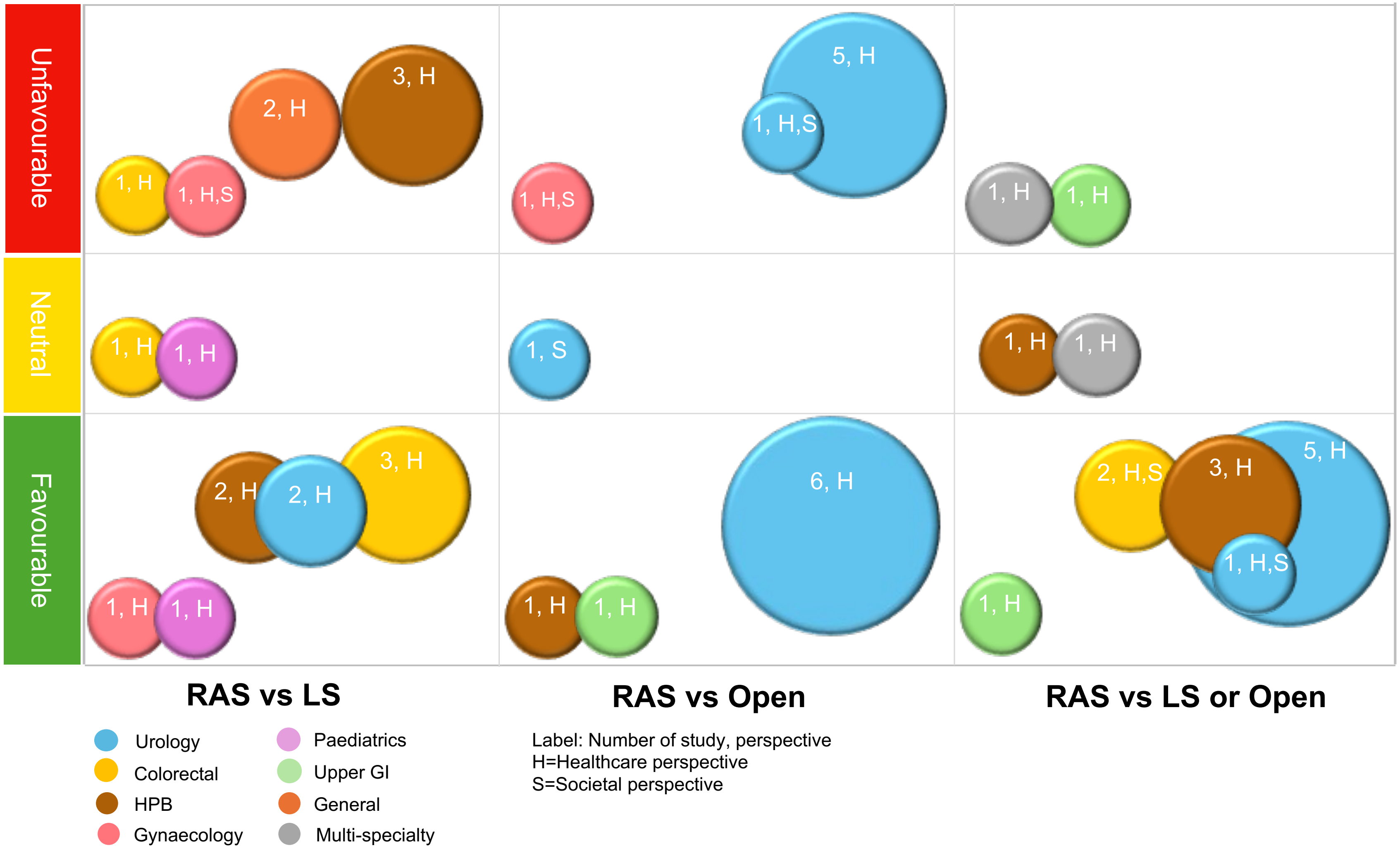


Figure 4.3-2 Summary of existing cost effectiveness evidence of RAS

4.3.3 Methods for economic evaluation used in the identified studies

A summary of the information extracted from the included studies, based on the CHEERS checklist, is provided in **Table 4.3-1**. The majority conducted their evaluations from a healthcare system perspective (n=44, 88%). Most studies considered only direct healthcare costs, including hospitalisation, medication, and diagnostic expenses, while a subset of studies (n=9, 18%) considered costs which would be included in a societal perspective such as sick leave, caregiver and travel expenses. Seventeen of the 50 studies (34%) reported the inclusion of capital costs.

The most commonly applied economic evaluation method was CUA (n=23, 46%) which estimated both the cost and quality-adjusted life years (QALYs) gained using RAS. This was followed by CCA (n=16, 32%), which assessed a wide range of costs against multiple clinical outcomes and resource usage in RAS such as complications and length of stay. In these CCAs, monetary outcomes were presented alongside clinical outcomes. Although these were not aggregated into a single metric, costs were reported separately against each outcome. Other methods utilised were CEA (n=9, 18%) which evaluated the cost, clinical outcomes (e.g. complication) and QALYs of RAS, and CMA (n=2, 4%), which estimated the cost of RAS under the explicit assumption of equal effectiveness across comparators. In the CMAs, equivalence was generally assumed based on authors' interpretation of the available evidence, rather than demonstrated formally through statistical non-inferiority analyses. For outcome measures, almost half of the studies used QALYs (n=23, 46%) while some used monetary outcomes (n=18, 36%), and some used clinical outcomes (e.g. complications, length of hospital stay, etc.) alongside QALYs (n=9, 18%). Data for outcome measures were often sourced from observational studies (n=29, 58%).

More than half of the studies undertook a model-based approach, with micro-simulation (n=16, 32%) most commonly used, followed by nine studies using a decision tree (n=9, 18%) and three using Markov models (n=3, 6%). The choice of model was only discussed in 15 (30%) of the included studies. Time horizon was reported in half of the studies. Among those that reported time horizon, both one year and the perioperative period (n=17, 34%) were frequently used. However, some studies, particularly for prostatectomy explored longer-term time horizons of up to 20 years which was appropriate given the nature of the disease (Mäkelä-Kaikkonen et al., 2019, Lindenberg et al., 2022, de Oliveira et al., 2021, Faria et al., 2022, Labban et al., 2022, Parackal et al., 2020). In studies where the time horizon exceeded one year, costs and benefits were discounted, most commonly at 3% per annum. As studies adopted alternative modelling assumptions across multiple specialities, it was not possible to say whether or not time horizon alone had a significant influence on cost-effectiveness.

Sensitivity analysis was performed to explore uncertainty in clinical parameters (e.g., length of hospital stay and operative time), health utilities, device and procedure costs, and time horizon in more than half of the studies included (n=31, 62%). The analyses were predominantly deterministic, although twelve studies (24%) conducted both deterministic and probabilistic sensitivity analysis. Heterogeneity in subgroups of patients was reported in only a few studies (n=5, 10%). The funding source was reported for 32% (n=16) of the studies included, of which 14% (n=7) were health research funding bodies and 14% (n=7) were funded by a commercial body. Eighteen studies (36%) received no funding.

Table 4.3-1 Summary results for assessments of economic evaluation of included studies

No.	Item	Value	N	%
TITLE AND ABSTRACT				
1	Title		50	100%
2	Abstract		50	100%
INTRODUCTION				
3	Background and objectives		50	100%
METHOD				
4	Form of economic evaluation (declared by the authors)			
		Cost–utility	23	46%
		Cost–consequence	16	32%
		Cost–effectiveness	9	18%
		Cost–minimisation	2	4%
5	Study population			
		Urology	21	42%
		HPB	10	20%
		Colorectal	7	14%
		Gynaecology	3	6%
		General surgery	2	4%
		Upper GI	3	6%
		Paediatrics	2	4%
		Muti–specialties	2	4%
6	Setting and location			
		Australia	2	4%
		Brazil	2	4%
		Canada	2	4%
		China	2	4%
		Finland	1	2%
		France	4	8%
		Germany	2	4%
		Italy	4	8%
		Netherlands	3	6%
		Spain	6	12%
		Sweden	1	2%
		UK	6	12%
		US	15	30%
7	Comparators			
		Laparoscopic surgery	18	36%
		Open surgery	16	32%
		Both laparoscopic surgery and open surgery	16	32%
8	Perspective			
		Healthcare	44	88%
		Societal	3	6%
		Both healthcare and societal	3	6%
9	Time horizon			

		1 year or perioperative period (90 days)	17	34%
		2 years or 5 years	5	10%
		7 years or 10 years	3	6%
		20 years	1	2%
		Not reported	24	48%
10	Discount rate			
		Yes	12	24%
		No (Not applicable)	16	32%
		Not reported	22	44%
11	Selection of outcomes			
		QALYs	23	46%
		Monetary outcome	18	36%
		Clinical outcomes and QALYs	9	18%
12	Measurement of outcomes			
		Observational study	29	58%
		Literature	9	18%
		RCTs	5	10%
		Registry	5	10%
		Non-RCTs	2	4%
13	Valuation of outcomes			
		Direct cost	41	82%
		Both direct and indirect	9	18%
14	Measurement and valuation of resources and costs			
		Yes	50	100%
		No	0	0%
15	Currency, price date, and conversion			
15a	Currency			
		Reported	50	100%
		Not reported	0	0%
15b	Price date			
		Reported	23	46%
		Not reported	27	54%
15c	Conversion			
		Reported	18	36%
		Not reported	32	64%
16	Rationale and description of model			
16a	Model design			
		Decision tree	9	18%
		Markov model	3	6%
		Micro-simulation	16	32%
		Both Decision tree and Markov model	1	2%
		Not model based	21	42%
16b	Discussion on choice of model			
		Reported	15	30%
		Not reported	35	70%
16c	Figure of model structure			

		Reported	13	26%
		Not reported	37	74%
17	Analytics and assumptions			
17a	Assumptions			
		Reported	13	26%
		Not reported	37	74%
17b	Analytical methods			
		Reported	50	100%
		Not reported	0	0%
18	Characterising heterogeneity			
		Reported	5	10%
		Not reported	45	90%
19	Characterising distributional effects			
19a	Subgroup analysis			
		Yes	2	4%
		No	48	96%
20	Characterising uncertainty			
		Deterministic sensitivity analysis	12	24%
		Probabilistic sensitivity analysis	5	10%
		Deterministic and probabilistic sensitivity analysis	10	20%
		Deterministic, probabilistic sensitivity and scenario analysis	2	4%
		Other	2	4%
		Not reported	19	38%
21	Approach to engagement with patients and others affected by the study			
		Reported	3	6%
		Not reported	47	94%
RESULT				
22	Study parameters			
		Reported	36	72%
		Not reported	14	28%
23	Summary of main results			
23a	Incremental costs and outcomes			
		Reported	31	62%
		Not reported	19	38%
23b	WTP threshold and Cost-effectiveness acceptability curves			
		Reported	20	40%
		Not reported	30	60%
23c	Technical conclusion			
	RAS vs LS			
		Favourable	9	18%
		Not favourable	7	14%
		Neutral	2	4%
	RAS vs Open			
		Favourable	8	16%

		Not favourable	7	14%
		Neutral	1	2%
	RAS vs LS or Open			
		Favourable	12	24%
		Not favourable	2	4%
		Neutral	2	4%
24	Effect of uncertainty			
		Yes	21	42%
		No	29	58%
25	Effect of engagement with patients and others affected by the study			
		Reported	0	0%
		Not reported	50	100%
DISCUSSION				
26	Study findings, limitations, generalisability, and current knowledge			
		Reported	36	72%
		Not reported	14	28%
OTHER				
27	Source of funding			
		Government	2	4%
		Academic health research	7	14%
		Industry	7	14%
		No funding	18	36%
		Not reported	16	32%
28	Conflicts of interest			
		Conflicts of interest reported	19	38%
		No conflicts of interest	28	56%
		Not reported	3	6%

Note: HPB, Hepato-Pancreato-Biliary; LS, Laparoscopic surgery; QALYs, Quality adjusted life years; RAS, Robot assisted surgery; RCTs, Randomised controlled trials; Upper GI, Upper gastrointestinal; WTP threshold, Willingness to pay threshold.

4.3.4 Specific characteristics of Robotic-Assisted Surgery

In addition to the standard methods for economic evaluation, I adopted the framework developed by Tarricone et al. to capture four additional device-specific features that are relevant to the assessment of RAS. A feature was classified as fully considered if it was explicitly modelled or measured empirically in the studies, whereas it was deemed partially considered if it was only discussed. The assessment revealed that these device-specific features were largely underexplored in economic evaluations. **Table 4.3-2** summarises the assessment across 50 identified studies. I further examined the methodologies of these studies that fully or partially considered at least one of these features, with findings presented in **Table 4.3-3**. Details on how device-specific features were considered is provided in the **Appendix 5 - Characteristics of the included studies from the scoping review.**

Table 4.3-2 Assessment for device-specific features in economic evaluations

Medical devices' distinctive features by Tarricone et al.			N	%
1	Learning curve			
		Full	5	10%
		Partial	15	30%
		Not considered	30	60%
2	Organisational impact			
		Full	7	14%
		Partial	13	26%
		Not considered	30	60%
3	Incremental innovation			
		Full	2	4%
		Partial	4	8%
		Not considered	44	88%
4	Dynamic pricing			
		Full	2	4%
		Partial	0	0%
		Not considered	48	96%

Note: Full: the items were measured empirically or modelled; and partial: the items were based on certain settings or were included only as a discussion point (see Appendix 5).

Learning Curve

Learning curve was examined in twenty of the 50 identified studies (40%), with fifteen (30%) partially considering it, and five (10%) formally incorporating it. In the studies that partially considered learning curve effects, common methods included evaluating scenarios in a high-volume hospital setting (Michels et al., 2019, Buse et al., 2016, Magge et al., 2018, Panse et al., 2023, Vasudevan et al., 2016, Miller et al., 2022, Kukreja et al., 2020, Ugliono et al., 2023, Probst et al., 2016, Bansal et al., 2018), while others specifically mentioned that the surgeons in the study had completed a sufficiently high number of surgeries so it could safely be assumed that the learning curve had been overcome (Vicente et al., 2020, Simianu et al., 2020, Simianu et al., 2021, Ferri et al., 2021, Baghli et al., 2023, Merola et al., 2020). Five of the 50 identified studies formally integrated learning curve into their economic evaluations. Three studies examined the operative time for identifying learning curve effect (Basto et al., 2016, Souche et al., 2018, Khoraki et al., 2020). The other two evaluated surgeon experience based on outcomes (Labban et al., 2022, Buse et al., 2018). Of these two, one considered the impact of surgeon experience on outcomes and efficiency through scenario analyses with varying surgical volumes as a proxy, indicating RAS annual volume and operative time each heavily impact the ICER (Labban et al., 2022). The other conducted scenario analyses using hospital costs from an early period of RAS diffusion and included a high proportion of low- and intermediate-volume centres. The study showed that RAS was not cost-effective due to higher hospital costs for RAS than for open surgery (Buse et al., 2018). Interestingly, this study included a higher cost for complications for less experienced centres (Buse et al., 2018).

Organisational Impact

Twenty of the 50 identified studies explored organisational impact to varying extents, with thirteen studies (26%) partially considering it and seven studies (14%) formally incorporating it. Some studies excluded capital cost because the surgical robot had been purchased and shared with other specialties (Caruso et al., 2022, Vicente et al., 2020, Quijano et al., 2020, De Pastena et al., 2021, Ploussard et al., 2022, Souche et al., 2018, Ferri et al., 2021, Ugliono et al., 2023, Singh et al., 2023), and one study also excluded the surgical robot's capital cost because the cost had been donated (Faria et al., 2022). Two studies conducted a scenario analysis based on the capital cost having been donated (Labban et al., 2022, HQO, 2017). The scenario analysis in one of those two studies showed that RAS became dominant over open surgery and increased its dominance over LS if capital cost was excluded (Labban et al., 2022), while, in the other scenario analysis, the inclusion of capital costs did not have an impact on cost-effectiveness (HQO, 2017). Although a donated robotic system eliminates capital costs, overhead costs, annual service fees and consumable costs still need included in any assessment (HQO, 2017). One study performed a scenario analysis with and without accounting for capital and maintenance costs (Panse et al., 2023). It reported that when the assessment included capital and maintenance costs, LS was generally more cost-effective than RAS. Another study considered two capital cost models (Bansal et al., 2018): one where the institution covered both purchase and maintenance, and another where it covered only maintenance (i.e., robot donated). This study showed that RAS was more expensive than open surgery, even when the robot was donated. One of the key drivers of this cost disparity is the high ongoing consumable equipment costs, leading to favourable results for open surgery (Bansal et al., 2018). This study also emphasised that for RAS to be preferred, annual case volumes per device must be higher than specific thresholds. These thresholds will be institution-specific and depend on the overall robotic surgical volume across several departments.

The capital cost, lifespan, and annual usage of robotic systems significantly impact allocated costs, leading to high costs per procedure when the robotic system is underutilised and unable to reach its full potential capacity. Some studies assume a robot capacity utilisation either via a certain percentage or actual volume, supported with a sensitivity analysis assuming different rates of daily usage (McCarthy et al., 2023, Panse et al., 2023, Basto et al., 2016). For example, estimating the cost per procedure by assuming three surgical procedures per day across the total number of working days or exploring different rates of daily usage such as once, twice or four times. To capture the cost per procedure, seven studies considered annual case volume per device in a capital cost calculation with the capital cost and service contract cost divided by the number of assumed cases per year and lifespan of equipment to derive a cost per case (Parackal et al., 2020, Simianu et al., 2020, Simianu et al., 2021, Bansal et al., 2018, Michels et al., 2022, Dixon et al., 2023, Labban et al., 2022).

Some of these studies also conducted sensitivity analysis to reflect the uncertainty of case volume per year ranging low to high utilisation (Parackal et al., 2020, Simianu et al., 2020, Simianu et al., 2021, Labban et al., 2022). One study considered RAS multi-specialty caseload from urology, colorectal and gynaecology (Steffens et al., 2023). Another study explored sharing a RAS platform across specialties by calculating the annual volume of procedures required for total revenue to match total costs (Tedesco et al., 2016). Higher procedure volumes improved cost-effectiveness by spreading fixed capital costs over more procedures, reducing the cost per procedure. This highlights the importance of optimising caseloads across different specialties to enhance RAS cost-effectiveness.

Incremental Innovation

Four studies (8%) in our review partially considered incremental innovation in the economic evaluation, and two studies (4%) formally included it. In studies where incremental innovation was only partially considered, the study authors only mentioned that RAS was performed using different surgical platform generations and assumed that a new generation of the technology had no impact on effectiveness (Ferri et al., 2021, Vicente et al., 2020, Merola et al., 2020, Caruso et al., 2020). For formal consideration in economic evaluations, one study undertook sensitivity analysis on effectiveness for different platform generations (Basto et al., 2016), while the other adopted the latest prices to account for incremental innovation, given the various generations of surgical systems (Labban et al., 2022).

Dynamic Pricing

There were two studies (4%) which considered dynamic pricing. One study conducted sensitivity analysis on the capital costs for different surgical robot models (Basto et al., 2016), while the other study incorporated the latest prices for various generations of the surgical system in scenario analysis (Labban et al., 2022).

Table 4.3-3 Summary of techniques used to incorporate specific features of RAS in economic evaluations

Distinctive features/ Issues	Technique used to address issues in the context of economic evaluation	References
Learning curve		
Efficiency	• Operative time for identifying learning curve effect	(Basto et al., 2016, Souche et al., 2018, Khoraki et al., 2020)
Proficiency	• Scenario of a high-volume hospital setting or settings where surgeons had completed a sufficient number of surgeries	(Michels et al., 2019, Buse et al., 2016, Magge et al., 2018, Panse et al., 2023, Vasudevan et al., 2016, Miller et al., 2022, Kukreja et al., 2020, Ugliono et al., 2023, Probst et al., 2016, Bansal et al., 2018) (Vicente et al., 2020, Simianu et al., 2020, Simianu et al., 2021, Ferri et al., 2021, Baghli et al., 2023, Merola et al., 2020)
Outcomes confounded by end-user experience	• Scenario volume analyses to evaluate the impact of surgeon experience on outcomes and efficiency	(Buse et al., 2018, Labban et al., 2022)
Organisational impact		
Initial investment	• Scenario analyses for capital cost inclusion/ exclusion • Capital cost omission due to ▪ the implementation prior to the economic evaluation ▪ platform shared with the other units or acquired via donation.	(Labban et al., 2022, HQO, 2017, Panse et al., 2023, Bansal et al., 2018) (Caruso et al., 2022, Vicente et al., 2020, Quijano et al., 2020, De Pastena et al., 2021, Ploussard et al., 2022, Souche et al., 2018, Ferri et al., 2021, Ugliono et al., 2023, Faria et al., 2022, Singh et al., 2023)
Annual usage	• Assumption on surgical volume capacity depending on the healthcare setting • Robotic platform utilisation with sensitivity analyses	(Parackal et al., 2020, Simianu et al., 2020, Simianu et al., 2021, Bansal et al., 2018, Michels et al., 2022, Dixon et al., 2023, Labban et al., 2022) (McCarthy et al., 2023, Panse et al., 2023, Basto et al., 2016)
Sharing platform	• Annual multi-specialty caseload contributed by different procedures	(Steffens et al., 2023, Tedesco et al., 2016)
Incremental Innovation		
Generations advances	• Assumption of no change in effectiveness from different platform generations • Sensitivity analysis on effectiveness for different platform generations	(Ferri et al., 2021, Vicente et al., 2020, Caruso et al., 2022, Merola et al., 2020)
Dynamic Pricing		
Generations' prices	• Scenario analysis on different generations' prices	(Basto et al., 2016, Labban et al., 2022)

4.4 Discussion

The aims of this scoping review were to summarise the existing evidence regarding the cost-effectiveness of RAS, to identify the economic approaches which have been used to evaluate RAS in practice and to discuss whether and how the specific characteristics of RAS were considered in these economic evaluations. Generally, I found the evidence on the cost-effectiveness of RAS compared to open and/or laparoscopic surgery is mixed. I identified that economic evaluations employ various methods tailored to their research aims and target audience, such as decision-makers at different levels. However, a large proportion of economic evaluations do not explicitly account for the specific characteristics of RAS, which could significantly impact the findings.

I found inconsistent evidence regarding the cost-effectiveness of RAS, with evaluations having a high degree of heterogeneity including multiple indications, outcomes, comparators, time horizons, perspectives and settings. CUA, which can capture both costs and QALYs, was the most commonly used methodology in the economic evaluation of RAS. CCA was also a popular methodology for economic evaluations. This may be because of its ability to incorporate a range of outcomes, beyond costs and QALYs, which is particularly useful when there are multiple outcomes of relevance to various stakeholders and decision makers. There were differences in the types of costs included in the analysis. For example, whether or not a study chose to include capital costs, outpatient costs, and consideration of non-health related costs (e.g., sick leave, caregiver costs) depending on the evaluation perspective and assumptions (Lindenberg et al., 2022). These findings align with those of Korsholm et al. (Korsholm et al., 2018), reinforcing the problem of heterogeneity in cost components included across current economic evaluations of RAS. This heterogeneity may be due to differences in setting as costs are highly context-driven. There is also heterogeneity in the costing methods used. Using average national data for individual procedures in economic evaluation at the national decision-making level may not be appropriate if the audience for an economic assessment is a local health region or hospital. Additionally, it may be appropriate to exclude capital cost where the robot has been donated by a charity or funded from a separate source or where the capital cost has already been incurred (i.e., RAS is already available within a hospital). In such cases, the initial capital investment does not impose a direct financial burden on the hospital or healthcare system under study. However, to provide a comprehensive evaluation of the true cost-effectiveness of RAS, I would recommend that capital costs should be included, at least as a sensitivity analysis. The consideration of capital costs for high-cost medical devices depends on their nature and the decision context. From an economics perspective, capital costs always matter due to opportunity cost, resources allocated to one technology cannot be used elsewhere. For policymakers, this means evaluating not just the upfront cost but also the long-term value and trade-offs, such as potential efficiency gains, workforce impact, and equitable access. The relevance of capital costs varies among stakeholders, but for system-level decision-making, integrating these costs ensures a more comprehensive assessment of investment priorities and sustainable technology adoption.

A previous review from Tandogdu et al (Tandogdu et al., 2015) summarised the evidence on the cost-effectiveness of RAS compared to relevant alternatives. It found that while RAS incurs higher costs, clinical effectiveness data remains limited. Only three studies conducted a full health economic evaluation using appropriate and robust methodologies. The review concluded that the evidence supporting the adoption of RAS is insufficient. My study updates this review by examining the cost-effectiveness of RAS, with a particular focus on the different economic evaluation methods used and the methodological challenges in assessing RAS. While Tandogdu et al. highlighted the limited clinical effectiveness data and the high costs of RAS, my study expands on this by incorporating a broader and more recent set of economic evaluations. Specifically, I examine how different methodological approaches have been used in cost-effectiveness analyses, identifying key gaps in assessing RAS. Additionally, I apply the framework by Tarricone et al. to systematically evaluate device-specific features, which were overlooked in previous reviews. A recent review from Bai et al. on the cost-utility of RAS compared to conventional surgeries also showed inconclusive results and indicated that more evaluation of RAS across therapeutic areas is required (Bai et al., 2022). However, it did not discuss the challenges of these evaluations and explore which characteristics may impact on economic evaluations and so should be included in an analysis (Bai et al., 2022). Clearly, there are a significant mix of approaches to key factors in the economic evaluation, including not only the context but also the distinctive features which are relevant to RAS. In contrast, my review adapted the extended CHEERS checklist outlined by Tarricone et al. (Tarricone et al., 2017a) for RAS. I explored how distinctive features such as learning curve, organisational impacts, incremental innovation and dynamic pricing have been dealt with in studies evaluating the cost-effectiveness of RAS (Drummond et al., 2009, Drummond et al., 2018, Sorenson et al., 2011). I found these distinctive features were mentioned in the economic evaluations to various degrees, but not by a substantial proportion of authors. Only 40% of the included studies considered learning curve and organisational impact and less than 12% of the included studies reflected on incremental innovation and dynamic pricing. This finding is consistent with the findings of Ciani et al (Ciani et al., 2017) which indicated the difficulty in estimating the quantitative impact of these characteristics on cost-effectiveness.

An expert panel recently set up to provide guidance on best practice for the assessment of RAS emphasised the need for specific considerations for the evaluation of RAS, including the learning curve, allocation of costs, appropriate time horizons and economic evaluation methods (Erskine et al., 2023). It recommended that cost models for RAS should consider robotic ecosystems on a multi-therapeutic area basis, with operating costs allocated based on procedure volume in hospitals. My findings echo this study and then further highlight areas for improving the economic evaluation of RAS.

One prominent factor is the learning curve, which significantly impacts outcomes. We identified studies incorporating the learning curve effect in a high-volume hospital setting (Michels et al., 2019, Buse et al., 2016, Magge et al., 2018, Panse et al., 2023, Vasudevan et al., 2016, Miller et al., 2022, Kukreja et al., 2020, Ugliono et al., 2023, Probst et al., 2016) as well as one study which considered a low-volume setting with sensitivity analyses to represent the RAS learning curve as accurately as possible (Panse et al., 2023). A previous review noted the association between the volume of RAS performed and the resulting outcomes, suggesting that higher surgical volume may contribute to improved outcomes and shorter operative times, attributed to surgeons gaining more experience and expertise (Day et al., 2022). Another previous review reported that surgeons with a higher caseload exhibited improved operative time compared to those with an average caseload (Perera et al., 2023). Other research indicated that low RAS case volumes for individual surgeons risked poor surgical outcomes and that maximising surgical volume would improve clinical outcomes (Lawrie et al., 2022, Halm et al., 2002). When selecting evidence of clinical effectiveness, analysts should be aware of the potential impact of learning curve on the evidence base and use data appropriate to their own setting in terms of surgical volume and experience with RAS. Sensitivity analysis can be used to explore the impact of alternative selections.

Another critical consideration is the organisational impact of introducing RAS. This includes both the initial investment and any reconfiguration of services in the specific setting required to optimise the utilisation of the robotic platform. In my review, I found that capital costs were typically considered as a one-time investment, where the study assumed a given surgical volume then split the costs of acquisition and maintenance across the assumed number of robotic cases. Although case volume was included within some of the studies in this review, studies rarely accounted for a surgical robot as a platform technology spanning multiple specialties. Only two studies allocated costs from different specialties based on annual usage (Steffens et al., 2023, Tedesco et al., 2016). The choice of whether to include the capital cost of high-cost medical devices like RAS in economic evaluation was dependent on the decision context and their device nature, whether the technology was already available and employed in another specialty within the hospital sharing the uses. In many settings, RAS was initially adopted for urological procedures and subsequently expanded into additional surgical specialties (Maynou et al., 2022). As RAS extends into various surgical fields, the potential for higher surgical volumes to spread out capital costs can enhance the cost-effectiveness of RAS. While the upfront costs of RAS are well-documented, the actual benefits can be uncertain, underscoring the importance of rigorous evaluation as clinical benefits may vary across specialties. The shared utilisation of RAS across specialties introduces complexities in cost allocation and operational efficiency, particularly concerning equipment use as the platform will have limited capacity. Profiling current surgical capacity approach has been recommended by some HTA agencies who indicated that planning national access programs requires the consideration of current surgical capacity to ensure optimal utilisation (Ho et al., 2013, HIQA, 2012). For example, one HTA agency assessed the capacity of a robot platform via a case-mix of different procedures such as prostatectomy and hysterectomy (HIQA, 2012). It was suggested that two surgeries per robot per day and a maximum of 10 per week was sufficient for optimal utilisation. This usage pattern would lead to reaching capacity with an annual caseload of 500 cases. A further factor which should be taken into account in assessments of cost-effectiveness of RAS is the extent to which RAS replaces open and laparoscopic procedures, particularly the current mix of these approaches in a given setting. Where RAS replaces an open approach, this increases the total proportion of patients being treated using minimally invasive approaches. Establishing the cost-effectiveness of RAS by sharing it across specialties provides an opportunity to prioritise the most cost-effective procedures to maximise robot utilisation. The focus should be on procedures with low laparoscopic surgery rates and high rates of conversion from open to RAS.

Incremental innovation brings challenges for economic evaluations of RAS. The evolution of RAS platforms, such as the da Vinci system, through multiple generations introduces new features and advancements, such as artificial intelligence(Marcus et al., 2024). Incorporating dynamic pricing into economic evaluations is another area that warrants attention. Although some studies have conducted sensitivity analyses on capital costs for different robot models, dynamic pricing, which is influenced by incremental innovation and procurement processes, is often neglected. This oversight may be due to the relatively consistent global listing price for the Da Vinci surgical robot across its generations. As a result, dynamic pricing has not been widely recognised or incorporated in RAS economic evaluations, whether for the platform itself or for consumables. New entrants into the RAS market place make price changes more likely in future and I recommend that analysts consider this possibility when planning their approach.

Generally, I suggest that analysts explore the impact of the distinctive features of RAS at least in sensitivity analyses. This approach will allow decision-makers to provide more informed recommendations regarding RAS. I provide a summary of my recommendations in the Box below.

Suggested methods to incorporate distinctive features of RAS in economic evaluations
Learning curve • Analyse clinical evidence over time to see if performance has stabilised. • Compare outcome data from low and high-volume centres (as a proxy for expert and less-experienced centres) and select outcome data appropriate to the setting. • Use sensitivity analysis to explore the impact of varying the outcome data. Organisational impact • In main analysis include capital cost if cost borne by health service provider. Assess the impact of including full capital cost in sensitivity analysis. • Choose activity levels which take both demand and surgical capacity into account. • Consider the proportions of open and laparoscopic that are likely to be replaced. • Consider cost allocation and operational efficiency of shared surgical robots. Incremental innovation • Use evidence appropriate to the generation of platform which is being assessed. Dynamic pricing • Conduct sensitivity analyses for changes in consumable prices (assuming cost of platform will be known).

My recommendations should allow for a comprehensive economic evaluation of RAS, providing a realistic assessment for decision-makers at all levels, and enhancing the optimal utilisation of a robotic platform in clinical practice. Although economic evaluation may not be widely used in supporting decisions to acquire robotic platforms, I recommend that it is used to optimise use post-acquisition. Unlike many forms of economic evaluation, this optimisation process involves consideration of multiple procedures across different specialties and necessitates a careful examination of contextual factors, such as capacity and workforce proficiency. Economic evaluation at this post-acquisition stage needs to be more embedded in the management and planning decision-making framework than for other types of technology such as drugs and implantable devices.

The strength of this scoping review is that I not only summarise the existing evidence regarding the cost-effectiveness of RAS regardless of anatomy or disease but also explore the distinctive features of RAS which may impact on economic evaluations. However, there are some limitations to our scoping review that are worth noting. Scoping reviews inherently focus on providing breadth rather than depth of information on a particular topic. I limited my included studies to those published in English, potentially missing key studies published in other languages.

Innovative devices require substantial financial investment, making a thorough evaluation of their cost-effectiveness essential. However, RAS has unique characteristics that complicate assessment as discussed in Chapter 2. In Chapter 4, I identify these challenges, highlight key gaps, and propose a methodological approach to address RAS-specific issues, including operational issues like shared capacity across specialties. Careful planning is essential to maximise its value. By incorporating these distinctive features, economic evaluations can provide decision-makers with a more realistic assessment of the cost-effectiveness of RAS, ensuring its optimal use in clinical practice. We especially need to consider multi-indication evaluation at the platform level to reflect real world usage. It requires a holistic approach to value proposition acknowledging the modelling challenges. Therefore, the next chapter I will showcase an example of how economic evaluation support to a post-acquisition stage, incorporating these distinctive features in order to advise decision-makers on the optimum use of an expensive surgical robot.

Chapter 5 Optimal Utilisation of Robotic-Assisted Surgery

In Chapter 5, I aim to answer the research questions (3)

- What can economic evaluation contribute to decisions on how to optimise utilisation of RAS?

5.1 Introduction

Following the Scottish Government's investment in RAS in 2021, its use has expanded across NHS Scotland. However, ensuring that this investment translates into meaningful health system value requires careful planning and optimisation. A key challenge lies not only in acquiring the technology, but in making strategic decisions about its utilisation across different procedures and settings to deliver clinical benefit and justify the substantial costs involved. Chapters 3 and 4 laid the foundation for understanding this challenge. Chapter 3 examined the clinical effectiveness of RAS, establishing that any expanded use should be underpinned by evidence of safety and at least comparable outcomes to conventional methods. Chapter 4 then explored the current landscape of economic evaluations, identifying methodological limitations and a lack of system-level perspectives in assessing cost-effectiveness.

Building on these insights, this chapter presents the development of a system-level economic evaluation model. The aim is to explore how economic analysis can inform optimal utilisation strategies for RAS and support resource allocation decisions in real-world NHS contexts.

Economic evaluation stands as a prominent method utilised to address this question of healthcare resource allocation (Hjelmgren et al., 2001). It aims to assess the efficiency of healthcare interventions, maximising health gains from finite resources. In HTA, economic evaluations involve the comparative analysis of alternative courses of action, providing a structured approach to measuring and comparing the health outcomes and costs of competing interventions over time and across populations (Richardson and Schlander, 2019).

Efficiency in healthcare refers to the optimal use of resources to achieve the best possible health outcomes (Palmer and Torgerson, 1999). For instance, in pursuing efficiency within the healthcare sector, emphasis is placed on prioritising treatments that offer the highest benefit per unit of cost. This involves balancing costs against intermediate outputs (e.g., number of patients treated, waiting times) and final health outcomes (e.g., lives saved, quality-adjusted life years gained) to maximise health outcomes from the allocated resources.

Health economics emphasises different concepts when evaluating efficiency for healthcare resource allocation. According to Palmer and Torgerson (Palmer and Torgerson, 1999), productive efficiency is about achieving the maximum health benefit for a given cost or minimising the cost for a given health outcome. This involves comparing different interventions to identify which produces the desired health outcomes at the lowest cost. Healthcare providers use productive efficiency to compare treatments or interventions yielding similar health outcomes, such as comparing the cost-effectiveness of two screening methods for Down's syndrome (maternal age screening vs. biochemical screening). Allocative efficiency occurs when resources are distributed in a way that maximises the overall welfare of the community. This concept extends beyond productive efficiency by considering not just the cost-effectiveness of interventions but also how these outcomes are distributed among the population. Allocative efficiency is achieved when the allocation of resources results in the highest possible welfare, meaning that no other allocation could make someone better off without making someone else worse off.

Cost-benefit analysis (CBA) expresses both costs and benefits in monetary terms, allowing comparisons across sectors and interventions with different outcomes. It aims to maximise allocative efficiency by identifying interventions that yield the greatest net social benefit (Robinson, 1993, YHEC, 2016a). However, CBA's application in healthcare is limited due to challenges in assigning monetary value to health or life. These limitations have led to more cautious use of CBA in routine health technology assessments.

Cost-utility analysis (CUA), by contrast, incorporates utility-based measures, most notably quality-adjusted life years (QALYs), to enable comparison across diverse interventions to assess productive efficiency using an incremental cost-utility ratio

(ICUR). It facilitates comparisons across interventions with diverse clinical aims by translating outcomes into a common unit that reflects both quality and quantity of life. However, it cannot fully address allocative efficiency since it does not express outcomes in monetary terms and cannot easily compare health with non-health investments. While cost-utility analysis (CUA) incorporates qualitative health aspects like quality-adjusted life years (QALYs), cost-effectiveness analysis (CEA) measures health benefits in natural units (e.g. life years saved or improvements in functional status) (McIntosh and Luengo-Fernandez, 2006).

CEA assesses interventions based on their cost-effectiveness ratio, focusing on productive efficiency in terms of health outcomes gained per cost incurred. Incremental cost-effectiveness ratio (ICER) is usually the main output or result of an economic evaluation. An ICER is calculated by dividing the difference in total costs (incremental cost) by the difference in the chosen measure of health outcome or effect (incremental effect) to provide a ratio of 'extra cost per extra unit of health effect (YHEC, 2016b). ICER and ICUR are typically used interchangeably. Decision-making in the results of CUA involves selecting interventions with the lowest incremental cost-utility ratios, defining a maximum acceptable cost per unit of effectiveness. The results guide decision makers towards interventions that could improve the return on resources expended in health care. Therefore, decision makers must also consider trade-offs between effectiveness and cost. These trade-offs' acceptability amidst competing priorities remains a central concern for decision makers (Palmer et al., 1999, McIntosh and Luengo-Fernandez, 2006).

To tackle the issue of adopting a novel and costly intervention, one should ideally apply an economic evaluation to guide the decision to invest, for instance, to purchase a surgical robot. An economic evaluation would compare RAS with LS and conventional open surgery from the decision-maker perspective, identifying cost-effective procedures. This ensures that the introduction of robotic technology is justified. This comprehensive analysis should ideally precede the purchase to ensure informed decision-making.

When using an ICER to evaluate RAS, several key assumptions underpin its interpretation, particularly around divisibility and scale. The ICER assumes that the intervention can be scaled or adjusted marginally, and that costs and outcomes change proportionally with usage. However, in the case of RAS, these assumptions are problematic. Surgical robotic systems represent indivisible, high-capital investments with significant fixed costs, meaning that cost-effectiveness is heavily dependent on scale (i.e. high procedure volumes to amortise costs). This challenges the standard marginal interpretation of the ICER and requires economic evaluations to move beyond simple comparisons of average costs and outcomes.

Additionally, the use of RAS has grown drastically in clinical practice, meaning robotic surgical platforms have already been implemented. The investment decision was often made despite the uncertainties regarding the clinical and cost-effectiveness of RAS, and often influenced by political, surgeon, patient, and manufacturer pressures, leading to acquisitions for reasons beyond cost-effectiveness. Despite the irreversible purchasing decision, evaluating the cost-effectiveness of RAS for procedures can no longer influence decisions to purchase but may influence decisions on how they are used.

Traditional cost-effectiveness analysis assumes constant costs and effects per patient regardless of scale. However, this assumption does not hold for platform technologies like RAS (or any other intervention which requires upfront capital cost), where costs per procedure can decline with increased utilisation due to economies of scale. Additionally, clinical outcomes, such as QALYs, may improve over time as surgical teams move along the learning curve. Other organisational factors, such as infrastructure use and staff training, can introduce non-linearities in both cost and effectiveness. These scale-dependent dynamics are not fully captured by standard ICER approaches. This highlights the need for a complementary system-level evaluation approach (such as considering capital cost dilution, volume thresholds, and capacity constraints), identified in Chapter 2 and 4, to inform how best to optimise the utilisation of the robotic asset and ensure the efficient deployment of this high-cost technology. Take NHS Scotland as an example; the decision has been made, and the surgical robots are being used. In early adoption or low-volume centres, the per-patient cost is much higher than in high-volume centres. Decision-makers are facing difficulties establishing an evidence-based approach for the use of RAS, particularly in how to maintain caseload and cost-efficiency. Therefore, it requires further analyses to guide decision-makers to optimise the utilisation of RAS, especially at post-acquisition stage. Economic evaluations are crucial not only for the initial purchase decision of novel interventions like surgical robots but also likely can be helpful on guiding the optimisation of their utilisation once acquired.

Implementing surgical robotics requires careful planning to maximise its value which means optimal utilisation. This involves not only assessing cost-effectiveness but also considering wider organisational manner to ensure that this technology is able to achieve its full potential in relation to costs and patient outcomes. Thus, the purpose of this section is to use an economic evaluation to guide decision-makers on how to optimise the utilisation of the robotic system, especially on cost-efficient healthcare delivery. In the pursuit of the overarching goal of optimising and enhancing the adoption of RAS, this chapter sets out to accomplish the following aims:

(1) Embed aspects of importance identified in the scoping review in Chapter 4.

(2) Develop a system-level model to assess cost-effectiveness and explore optimising the initial investment and potential expansion routes and to maximise the technology's potential and improve healthcare delivery efficiency.

5.2 Methods

This study followed the guidelines of the International Society of Pharmacoeconomics and Outcomes Research-Society of Medical Decision Making (ISPOR-SMDM) Modelling Good Research Practices Task Force-2 (Roberts et al., 2012). This framework outlines consensus-based best practices for model conceptualisation in medical decision-making and resource allocation. Therefore, there are two key components of modelling processes developed accordingly in this study. First, is the conceptualisation of the problem, which involves translating healthcare issues into a clear representation of the problem. The second is model conceptualisation, a sequential process that determines the appropriate modelling types and their attributes to represent the defined problem, along with the data and parameters used, and includes ensuring the model's transparency.

5.2.1 Conceptualising the problem

As ISPOR-SMDM stated, it is important to consult widely and refine the problem definition early in model development. This study started with consulting experts. Stakeholder engagement is an iterative process of actively seeking input including knowledge, experience, judgment and values from a diverse group of individuals who represent direct interests in a specific issue (Deverka et al., 2012). Stakeholder engagement is being increasingly promoted across the board by health research funding organisations, and indeed by many researchers themselves, as an important tool to closing the gap between research production and research use (Boaz et al., 2018). While evidence generated from health economic models is being used routinely in HTA, it is suggested that actively engaging with multiple stakeholder groups throughout the model development process may result in models more widely accepted by decision makers. It is indicated that stakeholder engagement approach has the potential to improve HTA adoption (Xie et al., 2021).

Therefore, stakeholder consultations were held in order to conceptualise the problem. This expert-focused consultation developed organically through the research period, and included essential clinical, academic and RAS industry stakeholders. Three surgeons were all from a single hospital, one of the surgeons was also the chair of the Clinical Reference Group from NHS Scotland National Planning Board. There were three representatives from the RAS industry. Ideally, I would have also included policymakers in Scotland perspectives, and indeed had attempted to include stakeholders from the Scottish Health Technologies Group, however, we have not been able to finalise a date for interview with at the time of writing this thesis. The NHS Scotland National planning framework document (NHSScotland, 2021a) was used instead.

Based upon these consultations, there were five general themes identified as crucial for decision problem, and they have implications for economic evaluation in terms of assessing the use of RAS.

Firstly, uncertain evidence base. There remains little robust evidence to suggest that RAS are superior to existing open or minimally invasive (e.g. laparoscopic) approaches. From the consultation, one surgeon indicated the difficulty in following the clinical effectiveness evidence. This may be related to the challenge of establishing RCTs, particularly establishing equipoise for phase III trials. Meaning, timing of conducting RCTs and their evaluation matters as conducting RCTs requires a delicate balance. In the early period, there may be insufficient surgical innovation diffusion that recruiting an adequate number of participants with the requisite statistical power becomes problematic. Additionally, the da Vinci robotic device for example, obtained FDA approval through a premarket approval pathway, US FDA "510(k) procedure" that the manufacturer only had to submit the substantial equivalent of the new product research. The regulatory pathways do not incentivise evidence generation and a limited number of clinical studies are required for approval (Broholm et al., 2016, Dahm et al., 2014). This means innovators often omit stages in evidence generation with a lack of RCT studies. However, once RAS becomes widely adopted which means it has diffused, conducting RCTs becomes less feasible due to the pervasiveness of the technology. It also has the difficulty of facing the preferences from patients and surgeons, unwillingness to accept randomisation, and difficulties in concealing allocation (Paul et al., 2013). I have discussed these issues in Chapter 2 (session 2.2.1 and 2.2.3). A previous article stressed that most studies suggesting benefits of RAS are small and lack rigorous controls, providing limited robust evidence that it is superior to open or laparoscopic approaches (Sheetz and Dimick, 2019a). This article indicated that the FDA urged research institutions, clinical societies, and device manufacturers to collaborate on better safety data and encouraged open discussions between patients and surgeons about the risks and benefits of RAS. Based upon the discussions, the analyst should be aware of issues caused by the source of the evidence and be prepared to address the uncertainties in sensitivity analysis in model developing for economic evaluation of RAS.

Secondly, the issue of economic factor, meaning high capital cost. In this research context, the Scottish early RAS implementation was realised in procurement. Some hospitals obtained the surgical robots via charity donation. Decision-makers are interested in how to achieve the best value for money for their investment. This implies the financial framework for utilising and maintaining RAS at the

Health Board level focused on running costs rather than implementation costs. In this case, it may be appropriate for economic evaluation to not include capital cost in cost-effectiveness analysis. Increasing the use of surgical robots could lead to better cost-efficiency that cost per procedure can be reduced when the surgical volume is high. This might be true when considering fixed costs, such as the initial investment in the robots themselves. This implies that the value-for-money of RAS is more significant in high-volume surgeries, such as urology, colorectal, and gynaecology. However, it is important to consider the variable costs (i.e. disposable equipment used) which may not yield greater savings from economies of scale (Sheetz and Dimick, 2019b). However, the surgical robotics manufacturer indicated that training and proficiency could reduce consumable consumption. Additionally, the company currently offers different funding model to access the robotic surgical platform, such as up-front purchasing, leasing and pay-per-use models. It depends on individual institution’s demand.

Thirdly, there is the issue of platform utilisation. RAS represents a platform technology applicable to various procedures across different medical specialties. This raises two important considerations: cost allocation and capacity. As surgical robots can be shared among different procedures, increased utilisation leads to lower costs per procedure. A platform implies it has limited capacity, scheduling the sharing framework is crucial which may increase its operational efficiency. There is a risk associated with underutilisation of a surgical platform, potentially undermining the initial investment justification. This situation may prompt the expansion of RAS to procedures with marginal clinical benefits. An indication creep may not be based on clinical evidence. Therefore, profiling capacity and the case-mixed of different procedures are required to ensure optimal utilisation. In most settings, the various alternative options like LS and open surgery co-exist. In the development process of economic evaluation modelling for optimal utilisation, it is beneficial to consider capital cost allocation, platform capacity and the proportion to replacement to ensure optimal utilisation and its cost-effectiveness.

Fourth, surgeon and workforce factors. This relates to training new surgeons and the learning curve which is an unavoidable process for all surgical innovation. However, a critical article indicated that current credentialing for RAS often grants surgeons broad privileges after minimal training, which can be problematic because it does not account for the specific procedures or learning curves involved. Hospitals should instead ensure that surgeons are credentialed only for a narrow range of robotic procedures in which they have demonstrated proficiency (Sheetz and Dimick, 2019a). However, the availability of RAS can potentially address ongoing concerns related to staff and surgeon shortages, backlog, and limited capacity in the health system as it is expected to attract surgeons. The advantage of a surgical robot includes offering better ergonomics for surgeons. Some difficult surgeries such as large size patients or complex anatomical features may cause subsequent impacts and consequences of surgeon musculoskeletal injuries or discomfort. Availability of RAS gives an opportunity to ease the pressure of surgeon recruitment and retention to address staff shortages. This may be an interesting operational issue for hospital management in terms of efficiency.

The final theme is public expectation. Investment in surgical robots by hospitals is often driven by public expectations, as they seek to attract top-tier surgeons, trainees, and enhance their reputation in the healthcare market. This motivation stems from the desire to expand their customer base and remain competitive within the industry. This finding is corresponded to the previous research that hospitals may invest in equipment such as RAS device prior to determining which procedures it will be utilised for, with some acquisitions motivated by the desire to enhance hospital reputation or attract top-tier surgeons and trainees (Abrishami et al., 2014, Abrishami et al., 2020). However, such investments have raised concerns about equality of access, particularly in cases where only a selected few hospitals have access to this technology through donations, as seen in the Scottish national investment scenario. Patients may prefer to be treated by innovations. The availability of surgical robots is also expected to address the equity of access for surgeons, particularly for complex surgeries. Often public expectation like in jurisdictions where hospitals prioritise maximising their customer base and competing with one another cannot be capture in an economic evaluation modelling. It is probably more nuanced than this. Buying the robot may be a business decision based on the reputation of the hospital and its ability to attract patients, rather than being based on the most cost-effective way to provide care.

This key stakeholder engagement highlights some crucial factors that can be incorporated into health economic evaluation models to demonstrate cost-efficient implementation of RAS. More detail information of this consultation is at **Appendix 6 - Discussions with key stakeholder and Appendix 7 - Summary of the stakeholder** interviews**.**

5.2.2 Defining the scope and objective

This expert consultation reinforces the conclusions drawn from my review of economic evaluations in Chapter 4, guiding me to include theses specific factors in my modelling exercise.

Decision problem and modelling objective

The adoption of RAS requires significant investment, yet its clinical effectiveness varies across specialties, creating uncertainty in its cost-effectiveness. The diffusion has occurred despite persistent uncertainties regarding its clinical and cost-effectiveness. It initially adopted in urology, particularly for robotic-assisted radical prostatectomy, and now expanding into other surgical specialties (Maynou et al., 2021, Maynou et al., 2022). However, this expansion may not be an evidence-based decision.

In the NHS, many hospitals have already acquired robotic systems, supported by national investments such as the Scottish Government's funding for RAS expansion (NHSScotland, 2021b) and NHS England's surgical robotics strategy (NHSEngland, 2025). The central policy challenge is no longer whether to invest, but how to ensure these technologies are used efficiently, equitably, and in ways that deliver value across the health system.

As identified through stakeholder consultation and the review of economic evaluations (Chapter 4), a key challenge is operational considerations for platform technology that determine whether the caseload of cost-effective procedures justifies the investment and how to prioritise clinical applications (Chapter 3) for optimal utilisation.

Against this backdrop, this modelling exercise aims to develop and test an experimental approach to explore how RAS could optimally be configured within the NHS to guide system-level implementation. The focus is on resource allocation, procedural prioritisation, and the organisational impact of RAS as a platform technology across multiple specialties, providing a structured framework to inform strategic planning, rather than a single point estimate of cost-effectiveness.

Scope of the model

In practice, the decision-making pathway begins with assessing the suitability of MIS based on the patient's condition and surgical requirements. When MIS is appropriate, the choice between RAS and LS depends on factors such as hospital resources, surgeon expertise, and patient preference. Where MIS is not feasible or contraindicated, open surgery remains the fallback option. In most clinical contexts, LS is already established as the preferred approach over open surgery. Open surgery is reserved for cases where MIS is not technically feasible, such as anatomically complex or intracavity procedures. This decision pathway was informed by consultation with clinical experts during model conceptualisation. Therefore, the analysis focuses on whether RAS can act as a viable alternative to conventional approaches, particularly as a means of increasing the overall proportion of procedures performed as MIS, as discussed in Chapter 3. The relevant decision questions concern: (i) whether RAS offers a better and more widely accessible MIS option compared with LS, and (ii) whether RAS can reduce reliance on open surgery by extending MIS to patients who might otherwise require open procedures.

Reflecting real-world practice that three surgical modalities co-exist; therefore, the model adopted an incremental analysis structure (RAS vs LS vs open), but focusing on decision space of RAS comparing to conventional approaches and robotic platforms service planning in health systems. (A frontier method was not involved). Pairwise comparison approach allows the model to assess how RAS displaces or complements existing methods, using cost-effectiveness to guide procedural prioritisation of RAS across specialties. In this way, the model provides decision-makers with a structured framework to evaluate both the economic feasibility and the system-level integration of RAS.

The application of RAS in selected procedures is supported by the clinical evidence synthesised in Chapter 3, particularly for colorectal resection (colorectal surgery), hysterectomy (gynaecology), and pancreaticoduodenectomy (Hepato-Pancreato-Biliary, HPB). While prostatectomy in urology is already widely adopted in clinical practice and often serves as a reference point for RAS utilisation, there remains a need to account for RAS-naïve hospital settings in a comprehensive economic evaluation. This economic evaluation therefore focused on these four procedures across different specialties where substantial clinical evidence exists (see **Figure 3.3-2**). These procedures also align with the priority areas identified by the Scottish National planning Robotic Review Group under NHS Scotland, making them particularly relevant for this PhD research, which takes Scotland as a case study context.

5.2.3 Conceptualising the model

To address the evaluation challenges highlighted in Chapter 4 and by Erskine et al (Erskine et al., 2023), this approach was specifically tailored to reflect the unique characteristics of RAS, including its high capital cost, variable clinical benefit across procedures, and its nature as a shared platform technology. A two-level structure was needed to reflect both vertical and horizontal decision dimensions:

- Procedure-level cost-effectiveness to inform prioritisation, and
- Platform-level optimisation to guide the strategic allocation of RAS across specialties.

A single simple model would not have been sufficient to address both the clinical effectiveness of RAS at the procedure level and the broader operational planning concerning system-level resource allocation.

This structure enables decision-makers to move beyond binary adoption decisions toward strategic planning that considers capacity, utilisation, and clinical priorities. It also provides a foundation for tailoring RAS implementation to local contexts, acknowledging that cost-effectiveness is influenced not only by the choice of procedures, but also by how the technology is deployed across the system.

Prior to constructing this experimental model in health economic evaluation, I conceptualised the possible patient care pathways to reflect the clinical decisions according to the consultation with clinician. **Figure 5.2-1** presents the conceptual model that shows possible patient pathways to reflect the clinical decisions, as the advantages of using a visual simplification to present decision routes in economic evaluation (Tappenden, 2014). The procedure for a patient is decided by surgeons. Patients may have experienced an intraoperative complication, and then operating surgeons will decide if a conversion is necessary. However, conversions may be done in anticipation of a potential issue rather than the result of a complication. This is presented by a dotted arrow to intraoperative complication and a two-way arrow between conversion and intraoperative complication. Patients can have an intraoperative complication in the conversion or before the conversion. After the surgery, patients may have postoperative complications which require medical actions. Hospital recourse includes action to complications and hospital stays. The choice of surgery, conversion and postoperative complication are related to hospital resource. For example, the choice of surgery requires different surgical equipment and operation theatre setup. A conversion requires another surgery with a whole new set of surgical equipment.

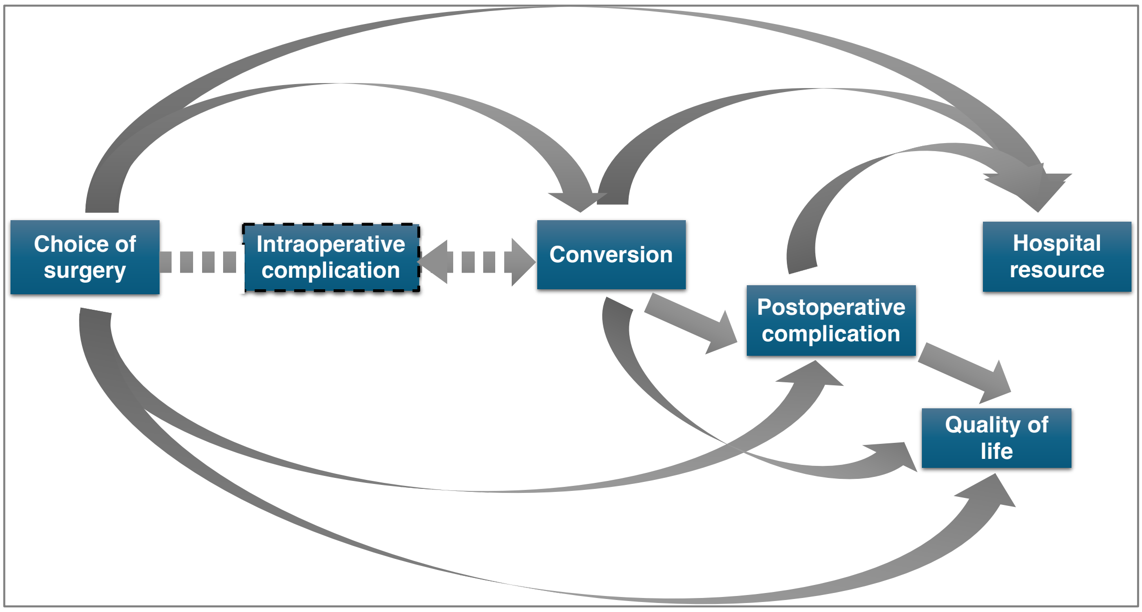


Figure 5.2-1 A conceptual clinical care pathway for patients

5.2.4 Model structure and type

To capture the complexities of RAS, a two-stage economic evaluation framework was developed to address procedure-specific value and system-level utilisation and resource allocation.

Stage 1: Cost-Utility Analysis

The first stage model aimed to evaluate the relative clinical and economic value of RAS compared to laparoscopic and open surgery for specific indications in incremental analysis. Decision-analytic models were constructed to conduct cost-utility analysis (CUA) for the following procedures: robotic-assisted prostatectomy, colorectal resection, hysterectomy, and pancreaticoduodenectomy. Each model estimated the incremental costs and quality-adjusted life years (QALYs) of RAS compared to laparoscopic and open surgical approaches over a one-year perioperative time horizon. The purpose of these analyses was to provide a foundation for understanding the relative value of RAS within each surgical domain and to generate input parameters for system-level analysis.

A standardised decision tree structure was applied across all models to ensure comparability and facilitate integration into the stage-two platform model. This conceptualised unified structure reflects a generalised surgical care pathway, incorporating common health states such as intraoperative complications, conversion, postoperative complications, and recovery. The approach was informed by the clinical effectiveness review (Chapter 3), which identified a common and consistent set of outcome measures across surgical interventions (operative time, length of stay, complications, conversion). These common drivers of cost and utility support the use of a shared model structure. While disease-specific models may provide greater granularity for individual pathways, the objective here was to inform system-level implementation decisions for a shared robotic platform. A unified structure was therefore considered both appropriate and necessary to maintain consistency and integrability across the two-stage framework.

Figure 5.2-2 show the unified decision tree skeleton used in the stage-one modelling. In each model, patients begin with one of three surgical approaches: robotic, laparoscopic, or open surgery, with risks of intraoperative complications and, where relevant, conversion to open surgery. Following surgery, patients may experience an uncomplicated recovery or postoperative complications. This structure allowed consistent estimation of costs and utilities across comparisons, reflecting the decision space of evaluating RAS relative to current alternatives. Conversions were treated the same as open surgery in terms of utility, cost, and postoperative course because, clinically, once a robotic procedure is converted, the remainder of the operation proceeds as an open surgery. This requires a new setup and the use of open surgical resources, and patients are then exposed to the same risks, recovery pathway, and outcomes as standard open procedures. An additional cost was incorporated to reflect the extra resource burden associated with conversion. This assumption was confirmed through consultation with clinical experts.

A one-year time horizon was adopted in the stage-one modelling to capture the immediate perioperative outcomes of surgery, such as operative time, complications, and length of stay. Longer-term implications, including survival, recurrence, or metastasis, are difficult to attribute directly to the surgical approach, as they are heavily influenced by underlying disease progression (ie.

tumour biology and stage) and subsequent treatments (Al-Madhi et al., 2025, Mullens et al., 2025). For this reason, a short-term horizon was considered the most appropriate for isolating and reflecting outcomes directly attributable to the surgical intervention. Mortality was not explicitly modelled in this analysis. Although surgical mortality can occur, perioperative death rates for the included procedures are extremely low in high-income settings (ie. NHS) due to advances in anaesthesia and perioperative care (NELA, 2025). Additionally, these mortality rates vary widely depending on surgical complexity, patient selection, centre volume, and procedure type. Where deaths do occur, they are often multifactorial and difficult to attribute solely to the surgical approach, being influenced by underlying comorbidities, or disease severity (Cutti et al., 2020). Given the one-year time horizon and the model's focus on perioperative outcomes directly attributable to surgery, mortality was treated as negligible and not separately modelled.

The model was constructed from the perspective of the publicly-funded health care system in Scotland. Only direct medical costs (i.e. fixed and variable medical costs associated with health system) were included. All health benefits accruing to individuals are included in the assessment of outcomes. Indirect costs (e.g. decreased productivity due to disease or death) associated with RAS were excluded from the evaluation.

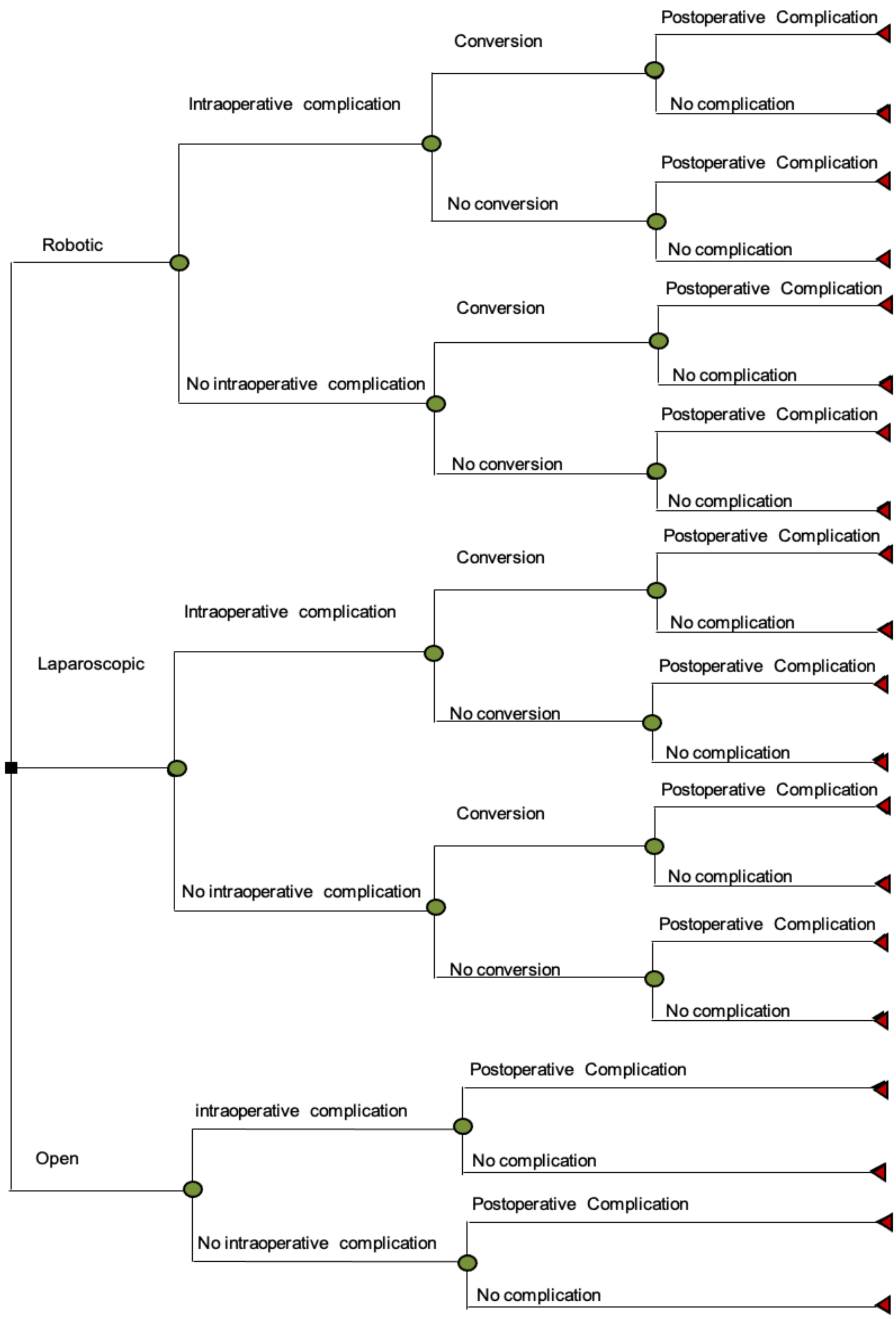


Figure 5.2-2 Overview of decision tree skeleton for the stage-one modelling

Stage 2: System-Level Utilisation Model

The second stage integrated outputs from the procedure-level models into a unified platform model. This system-level tool estimates total incremental costs and QALYs across user-defined scenarios that reflect local surgical capacity and service delivery. To accommodate variability across different hospital settings, an interactive interface was developed as part of the stage-two model. This allows users to tailor the analysis by adjusting key parameters in three steps: (1) defining the annual caseload, (2) allocate case-mix proportions across the four procedures, and (3) adjust replacement levels of open and laparoscopic surgeries with RAS. This structure enables dynamic scenario testing, offering decision-makers the ability to tailor cost-effective adoption strategies to local surgical capacity, demand, and workforce constraints.

The first step, designing for the annual caseload input. Three annual caseload scenarios: 150, 250, and 350 cases per robot. The 150 cases per system align with the minimum volume requirement by the National Institute for Health and Care Excellence (NICE) (NICE, 2014b, Dasgupta et al., 2019). The 250 cases scenario corresponds to a RAS schedule of one operation per day, Monday to Friday, throughout the year. The 350 cases scenario reflects a RAS schedule of once to twice per day, Monday to Friday, over the year. The second step, the proportions for the four selected procedures. Users can reference the outcomes from stage-one to determine the case-mix combination strategy. They can also input their parameters given institutional resource settings. The third step, users specify the replacement proportion for conventional surgeries.

By linking cost-effectiveness at the procedure level with strategic planning at the system level, this two-stage framework supports more informed decisions on optimising value for money and health system performance. **Figure 5.2-3** illustrates the conceptual design.

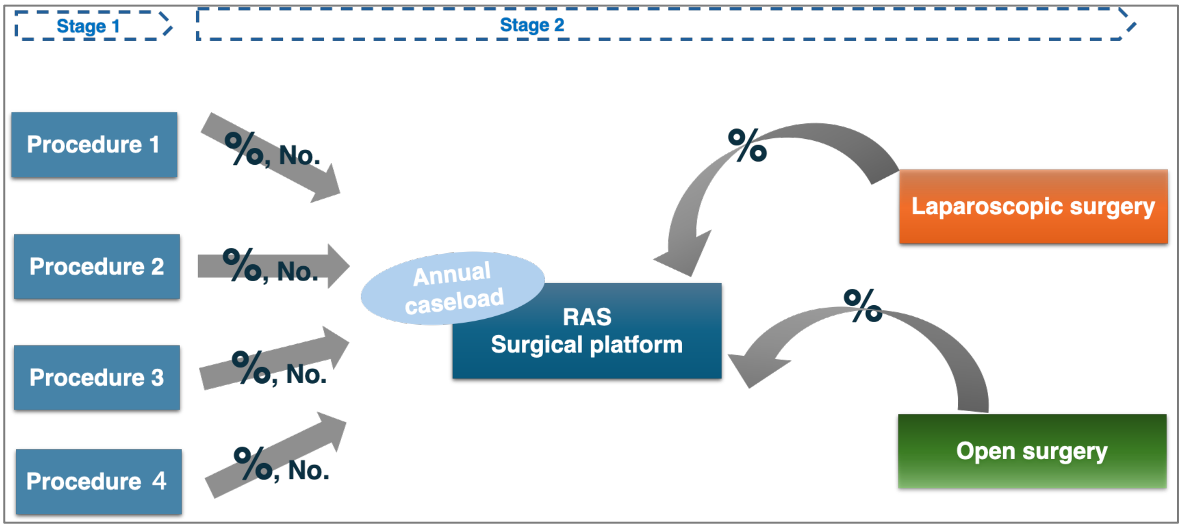


Figure 5.2-3 Schematic diagram of the two-stage modelling framework

5.2.5 Model parameters

The clinical parameters for the four selected procedures in the decision model were primarily informed by the clinical effectiveness overview presented in Chapter 3.

In developing the model parameters, an initial attempt was made to draw upon real-world data (RWD) collected at Glasgow Royal Infirmary (NHSGGC) to build on discussions in Chapter 2. These data contained procedure-level information on robotic-assisted, laparoscopic, and open cases, with the potential to inform operative time, length of stay, and short-term complication rates. However, at the time of analysis, the data were not sufficiently mature for robust model parameterisation. Specifically, they were restricted to a single specialty and one hospital, with limited follow-up and incomplete outcome recording, which introduced risks of bias and limited generalisability. Additionally, the data reflected the first year of robotic system availability, when surgeons were still within their learning curve. Consequently, the observed outcomes may not represent steady-state performance and could underestimate the benefits of RAS.

Given these limitations, the scope of available variables was not adequate for the requirements of a system-level model, particularly when considering the need for comparability across multiple surgical specialties. Parameterisation in this study therefore relied on evidence identified through the systematic clinical review (Chapter 3) and the scoping review of economic evaluations (Chapter 4).

While this ensured consistency and transparency, it also highlights an important limitation: the lack of integrated RWD to strengthen external validity. Had the NHSGGC dataset been of sufficient quality, maturity, and breadth, its use could have complemented trial and literature-based estimates, particularly for modelling resource use patterns in the Scottish NHS context. It is important to note, however, that the primary aim of this study was not to generate definitive "best" estimates of cost-effectiveness, but rather to develop and test an experimental system-level modelling approach for exploring the optimal utilisation of robotic-assisted surgery. Within this framework, the reliance on literature-based inputs was considered sufficient to demonstrate the structure, feasibility, and application of the model, while highlighting the potential value of incorporating high-quality RWD in future iterations.

Clinical Inputs and Use of Health Care Resources

Central input values for the four selected procedures (e.g. medians, weighted means, or base-case estimates) were extracted from the most robust available studies based on the literature following the hierarchy of evidence (Burns et al., 2011). Network meta-analysis (NMA) of three-arm comparison were prioritised over individual randomised controlled trials (RCTs) and observational studies with appropriate covariate adjustment. Studies were selected to align with the model's incremental structure (i.e. RAS vs laparoscopic vs open surgery). More recent publications were favoured over older sources to reflect current surgical practice. Hospital resource use (e.g. length of stay and operative time) prioritised UK-based studies where available, to improve the relevance of estimates to NHS settings.

For rate-based parameters such as odds ratios (ORs), effect sizes were primarily taken from published meta-analyses, ensuring that comparative treatment effects between RAS and comparator groups were incorporated directly into the model. Where necessary, reported 95% confidence intervals were used to derive standard errors (SEs), with log-transformation applied when ORs were presented. For continuous variables (e.g. length of stay, operative time), meta-analyses often reported mean differences rather than absolute values. In these cases, a UK-based study (where available) was used to provide baseline estimates, and the pooled mean difference from the meta-analysis was applied to derive the corresponding value for open surgery, thereby anchoring relative effects to a relevant baseline. Where meta-analyses reported means and 95% confidence intervals, standard deviations (SDs) were calculated to estimate SEs. In cases where only medians and interquartile ranges (IQRs) or ranges were available, either using lognormal or the method developed by Wan et al. (Wan et al., 2014) to approximate mean and SD values, which accounts for sample size and distributional assumptions. These derivation methods ensured consistency, transparency, and completeness across all parameter inputs for subsequent modelling. All clinical input parameters and their corresponding uncertainty ranges are summarised in **Appendix 8 - Clinical outcomes, utilities and costs inputs.**

Utility inputs

Health-related quality-of-life inputs were drawn from previously published studies using preference-based measures, primarily EQ-5D. Where direct utility estimates were unavailable, data from validated instruments such as the EORTC QLQ-C30 were mapped to EQ-5D values using established algorithms (Longworth et al., 2014). Base-case utility values were applied to the terminal health states in the decision model and multiplied by a one-year duration to calculate QALYs. In line with common practice, it was assumed that quality-of-life stabilises after postoperative recovery and remains constant throughout the one-year time horizon. As such, the QALY estimates reflect short-term quality-of-life differences between surgical approaches, rather than long-term health outcomes. Uncertainty ranges were derived using beta distributions based on reported means and standard errors. All utility parameters are presented in in **Appendix 8 - Clinical outcomes, utilities and costs inputs**.

Costs

Cost inputs were derived from a combination of published literature, NHS sources, manufacturer data, and expert opinion where necessary. Capital cost estimates were required for RAS and LS, since they involve medical devices, the surgical robotic system and a laparoscopic tower. Capital costs were annualised using the equivalent annual cost method, following the approach recommended in Drummond et al. (2015) as shown in **Figure 5.2-4**. This method converts the one-off acquisition cost into a stream of equal annual payments over the expected useful life of the equipment, applying a discount rate to reflect the opportunity cost of capital. An annual maintenance charge was then added to obtain the total annual cost. This annual cost was subsequently divided by the number of procedures performed per year to calculate the per-procedure capital cost, ensuring that utilisation effects (i.e. economies of scale) were explicitly captured. This method has been used in previous surgical robotic research (Sejal et al., 2021). For RAS, this was based on alternative annual case volumes (150, 250, or 350), allowing the model to reflect site-specific utilisation and economies of scale. This setting was necessary to address the central aim of the analysis, exploring the optimal utilisation of a high-cost surgical platform. Under these scenarios, the annualised per-procedure costs of RAS were £2,466, £1,480, and £1,057, respectively. In contrast, LS was modelled with a fixed annual caseload of 200 procedures, reflecting a mature technology where laparoscopic towers are already purchased and embedded in routine surgical practice. Unlike RAS, the marginal capital cost of LS is minimal, so varying its throughput would not materially affect per-procedure costs (£315.3). This differential treatment does not imply any inherent throughput advantage for RAS; rather, it reflects the different capital cost structures of the two technologies. While LS equipment costs are largely sunk within existing infrastructure, RAS involves substantial new acquisition and maintenance costs, making utilisation rates a critical determinant of cost-effectiveness. Explicitly modelling RAS volumes was therefore essential to explore the optimal use of a high-cost surgical platform.

Total annual capital cost

$$= \frac{device\ aqusition\ cost}{annual\ factor} + maintenance\ cost$$

$$= \frac{device\ aqusition\ cost}{\frac{1}{R} * 1 - 1/(1+R)^n} + maintenance\ cost$$

Note: R means discount interest rate

Figure 5.2-4 Formula of annual capital cost calculation

Per-case variable costs, primarily disposable instruments and accessories were informed by manufacturer reports for RAS and assumption-based estimates for LS and open surgery. Additional hospital-related costs, such as operating theatre time, inpatient stay, and complication management, were sourced from NHS reference costs and assumptions (see **Table 5.2-2**). These resource use costs were linked to clinical outcomes in the stage-one model and aggregated in stage two to estimate total system-level cost. All cost values used in the model are presented in **Appendix 8 - Clinical outcomes, utilities and costs inputs**. Given the one-year time horizon, discounting was not applied. Cost inputs were assigned gamma distributions for use in sensitivity analyses.

Table 5.2-1 Cost profile per case of different surgical approaches across specialties

Variables	value	Source
Costs of operating room per minute	£ 23	Information Services Division 2019, adjusted with NHSCII (2023/24)
Cost per hospital day	£ 467	NHS reference cost 2019, adjusted with NHSCII (2023/24)
Cost for conversion	£2,112	NSF report
Costs for postoperative complication	£8,000	Assumption based on NSF report
Costs for intraoperative complication	£2,000	Assumption based on NSF report
Da Vinci surgical platform	£ 1,500,000	Listing price
Useful life in year	7	Assumption
Annual interest rate	4%	Assumption
Da Vinci annual maintenance	£120,000	Listing price
Laparoscopic tower	£250,000	Assumption based on (Simianu et al., 2020)

Laparoscopic tower maintenance	£21,400	Assumption based on (Simianu et al., 2020)
Capital cost per case		
RAS		
Caseload of 150	£ 2,466	Calculation
Caseload of 250	£ 1,480	Calculation
Caseload of 350	£ 1,057	Calculation
LS		
fixed	£ 315	Calculation
Disposable cost per case		
Colorectal		
RAS	£ 1,300	Scotland data from Intuitive Surgical
LS	£ 700	Assumption
Open	£ 550	Assumption
Gynaecology		
RAS	£ 1,008	Scotland data from Intuitive Surgical
LS	£ 550	Assumption
Open	£ 450	Assumption
General		
RAS	£ 1,268	Scotland data from Intuitive Surgical
LS	£ 650	Assumption
Open	£ 500	Assumption
Urology		
RAS	£ 885	Scotland data from Intuitive Surgical
LS	£ 550	Assumption
Open	£ 400	Assumption

Note: NHSCII, NHS Cost Inflation Index.

Direct medical costs included costs of operating room, surgical instruments and hospitalisation as well as treatments for complications. The average annual cost per theatre is £1.7 million with an average usage of 27 hours per week based on theatre running costs in NHS Scotland from the Information Services Division (ISD) Theatre Service 2019 (Note: no data were collected from 2020-2022 due to COVID-19). The cost of operating room (OR) time was estimated at £23 per minute. The estimated cost per hospital day is £467. This information was sourced from the NHS National Schedule of Reference Costs and used in the RAS National Strategic Framework (NSF) report of 2020 and adjusted with NHSCII (2023/24). Costs for disposable instruments of RAS were from the manufacture internal data and of LS and open surgery estimates were based on assumption based on previous research estimate (Sejal et al., 2021). Costs for conversion is £2,112 based on NSF report. Costs for postoperative complication is £8,000 and intraoperative complication is £2,000 which are assumptions based on previous research estimate (Sejal et al.,

2021) and NSF report. All costs are presented in pound sterling, and no discounting was applied as the analysis timeframe was 1 year.

5.2.6 Analytical Approach

Base case analysis

The base-case analysis estimated the total costs, quality-adjusted life years (QALYs), and incremental cost-effectiveness ratios (ICERs) for RAS compared with LS and with open surgery across the selected procedures. Capital costs were incorporated as device cost per procedure for both RAS and LS in base-case and RAS set at 150 procedures annual caseload.

For each operative approach, the models estimated the 1-year mean total cost and QALYs per patient, including both fixed and variable costs. Incremental cost-effectiveness ratios (ICERs) were calculated to assess the additional cost per QALY gained of RAS compared with LS and with open surgery. If a surgical approach was associated with higher effectiveness and lower cost, it was considered dominant. Where a surgery was more effective but more costly, the ICER was compared to the willingness-to-pay (WTP) threshold used by the National Institute for Health and Care Excellence (NICE). The reference case threshold is £20,000 per QALY, with values up to £30,000 per QALY considered in specific circumstances. In this analysis, the £20,000 threshold was applied as the base case.

Sensitivity analysis

To assess the robustness of the model results, both deterministic sensitivity analysis (DSA) and probabilistic sensitivity analysis (PSA) were conducted.

In the stage 1 decision-analytic models, Deterministic sensitivity analysis (DSA), specifically one-way sensitivity analysis (OWSA), was used to vary individual parameters within their plausible ranges. Utility values were modelled using beta distributions fitted from published means and standard errors; the 2.5th and

97.5th percentiles were used to define the lower and upper bounds for the analysis. For complication probabilities derived from meta-analysis, beta distributions were parameterised using event counts, with alpha (α) equal to the number of events plus one and beta (β) equal to the number of non-events plus one (where possible). These percentiles were also used as bounds in the deterministic analysis. Results were visualised using tornado diagrams to identify influential drivers. To capture joint parameter uncertainty, a PSA was performed using 1,000 Monte Carlo simulations. Probability and utility inputs were sampled from beta distributions, and cost parameters from gamma distributions. Relative effect sizes were incorporated wherever possible. Outputs from the PSA were used to construct cost-effectiveness acceptability curves (CEACs) and estimate net monetary benefit (NMB) across a range of willingness-to-pay (WTP) thresholds. Together, DSA and PSA provided a comprehensive assessment of parameter uncertainty and its influence on the cost-effectiveness conclusions.

Scenario analysis

The scenario analysis considered alternative funding pathways and procurement conditions that may affect the economic profile of RAS. Specifically, it assumed that hospitals may acquire robotic platforms through donations, public-private partnerships, or centralised funding mechanisms, in which case the capital investment, comprising both purchase and maintenance costs, has already been incurred and would not be borne by individual procedures. This reflects a plausible real-world situation, especially in NHS settings where major equipment may be procured through separate infrastructure budgets.

Similarly, given that many hospitals already own laparoscopic systems, a parallel assumption was made to exclude the capital costs of LS for consistency. This scenario isolates the operational or variable costs of each surgical approach, allowing a clearer comparison of ongoing resource use and health outcomes, such as consumables and operating time.

Importantly, RAS uniquely incurs substantial per-case costs for proprietary disposable instruments and accessories. These were retained in the scenario analysis to reflect the fact that hospitals are still responsible for covering disposable costs, which depend on usage and manufacturer pricing. This ensures that procedural cost differences were not underestimated. This approach allows the analysis to capture a realistic and policy-relevant view of ongoing costs, even when capital investments are excluded.

Threshold and case-mix analysis in system-level model

To explore the optimal utilisation of RAS following adoption, two scenario-based analyses were conducted at the second-stage system-level model.

First, a threshold analysis for RAS replaced proportion was conducted to evaluate the impact of varying the proportions of conventional surgical approaches displaced by RAS. This analysis calculated the ICER for each of the four procedures (colorectal resection, hysterectomy, pancreaticoduodenectomy, and prostatectomy) based on the stage one modelling outcomes. The analysis systematically varied the proportion of open surgery and LS replaced by RAS, starting from 0% open surgery and 100% LS, and incrementally increasing the proportion of open surgery by 10% up to 100% open surgery and 0% LS. This approach allowed us to identify the cost-effectiveness of RAS across different replacement proportion scenarios.

To further explore the optimal expansion of RAS utilisation from a system-level perspective, additional threshold analyses were conducted to identify the most cost-effective mix of procedures across specialties, informed by stage-one outcomes and the prioritisation derived from the replacement proportion scenarios. Following this prioritisation framework and the identified expansion strategy, twenty different case-mix combinations were developed to incrementally distribute RAS capacity across the four surgical specialties. Each scenario tested different percentage allocations of RAS use, reflecting a practical and stepwise expansion of robotic surgery applications in real-world clinical practice. The ICER for each of these twenty case-mix combinations was calculated to identify the most cost-effective configurations and to determine the optimal balance of RAS utilisation across specialties. However, it should be noted that this stage-two platform model is designed as a flexible package that allows users to input their own parameters based on specific preferences and local contexts. The threshold analyses presented here merely demonstrate the concept of a two-stage linked model for optimising RAS utilisation and service planning.

5.3 Results of the economic models

5.3.1 Base case analysis results

Table 5.3-1 presents the results of the base case deterministic incremental cost-effectiveness analysis comparing RAS with LS and open surgery across four procedures: prostatectomy, colorectal resection, hysterectomy, and pancreaticoduodenectomy.

Prostatectomy was the only procedure where RAS was found to be cost-effective compared with open surgery. The ICER was £12,700/QALY, indicating a positive net benefit at the £20,000 threshold. However, LS dominated RAS, offering greater effectiveness at lower cost. Both LS and RAS were cost-effective compared to open surgery (ICERs of £6,156/QALY and £12,700/QALY, respectively).

In the colorectal model, RAS was not cost-effective compared with either LS or open surgery. The ICERs for RAS versus LS and RAS versus open were £156,127/QALY and £101,149/QALY, respectively, both substantially exceeding the £20,000/QALY threshold. For hysterectomy, RAS was similarly not cost-effective when compared to LS (ICER: £71,551/QALY) or open surgery (ICER: £37,512/QALY). In contrast, LS dominated open surgery, offering a small QALY gain at lower cost, with a positive INMB. For pancreaticoduodenectomy, RAS generated higher QALYs than LS and open surgery but at substantially greater cost, resulting in ICERs above the £20,000 threshold and negative INMBs.

Table 5.3-1 Base case results of incremental cost-effectiveness analysis for RAS vs LS vs open

Comparison	Incremental Cost (£)	Incremental QALYs	ICER (£/QALY)	INMB @£20k	Conclusion
Prostatectomy					
RAS vs LS	£ 409	-0.005	£ -85,696/QALY	£ -505	dominated
RAS vs Open	£ 851	0.067	£ 12,700/QALY	£ 489	CE
LS vs Open	£ 442	0.072	£ 6156/QALY	£ 994	CE
Colorectal Resection					
RAS vs LS	£ 1,838	0.012	£ 156,127/QALY	£ -1602	Not CE
RAS vs Open	£ 3,137	0.031	£ 101,149/QALY	£ -2519	Not CE
LS vs Open	£ 1,300	0.019	£ 67,896/QALY	£ -917	Not CE
Hysterectomy					
RAS vs LS	£ 1,411	0.020	£ 71,551/QALY	£ -1016	Not CE
RAS vs Open	£ 776	0.021	£ 37,512/QALY	£ -362	Not CE
LS vs Open	£ -635	0.001	£ -661,146/QALY	£ 645	LS dominant
Pancreaticoduodenectomy					
RAS vs LS	£ 2,738	0.107	£ 25,470/QALY	£ -588	Not CE
RAS vs Open	£ 3,057	0.075	£ 40,940/QALY	£ -1564	Not CE
LS vs Open	£ 320	-0.033	£ -9746/QALY	£ -976	dominated

Note: NMB used WTP of £20,000 per QALY.
Abbreviations: CE, Cost-effective; ICER, incremental cost-effectiveness ratios; NMB, net monetary benefit; LS, laparoscopic surgery; QALY, quality-adjusted life years, RAS, robotic-assisted surgery. WTP, willingness-to-pay.

5.3.2 Scenario analysis results

Scenario analyses excluding capital costs were conducted to evaluate situations where these costs have already been incurred. The results of these analyses are summarised in **Table 5.3-2**, demonstrated a more favourable profile.

For prostatectomy, RAS was cost-effective compared with open surgery but not with LS, where it was less costly and less effective (south-west quadrant). For colorectal resection, RAS dominated LS but was not cost-effective compared with open surgery. For hysterectomy, RAS dominated both LS and open surgery. For pancreaticoduodenectomy, RAS was cost-effective against both LS and open surgery, with ICERs well below the £20,000/QALY threshold. Overall, RAS offered value relative to open surgery in most procedures but remained less favourable when compared directly with LS. These findings suggest that when capital costs are excluded, the cost-effectiveness profile of RAS improves significantly, particularly when replacing open surgery.

Table 5.3-2 Scenario case results of incremental cost-effectiveness analysis for RAS vs LS vs open

Comparison	Incremental Cost (£)	Incremental QALYs	ICER (£/QALY)	INMB @£20k	Conclusion
Prostatectomy					
RAS vs LS	£ -1,742	-0.005	£ 364,829/QALY	£ 1,646	CE
RAS vs Open	£ -1,615	0.0067	£ -24,102/QALY	£ 2,955	RAS dominant
LS vs Open	£ 127	0.0072	£ 1,764/QALY	£ 1,309	CE
Colorectal Resection					
RAS vs LS	£ -313	0.031	£ -26,611/QALY	£ 549	RAS dominant
RAS vs Open	£ 671	0.031	£ 21,713/QALY	£ -53	Not CE
LS vs Open	£ 984	0.019	£ 51,427/QALY	£ -602	Not CE
Hysterectomy					
RAS vs LS	£ -740	0.020	£ -37,533/QALY	£ 1,131	RAS dominant
RAS vs Open	£ -1,690	0.021	£ -81,750/QALY	£ 2,104	RAS dominant
LS vs Open	£ -950	0.001	£ -989,333/QALY	£970	LS dominant
Pancreaticoduodenectomy					
RAS vs LS	£ 587	0.107	£ 5,460/QALY	£ 1,563	CE
RAS vs Open	£ 591	0.075	£ 7,918/QALY	£ 902	CE
LS vs Open	£ 4	-0.033	£ -136/QALY	£ -661	dominated

Note: NMB used WTP of £20,000 per QALY.
Abbreviations: CE, Cost-effective; ICER, incremental cost-effectiveness ratios; NMB, net monetary benefit; LS, laparoscopic surgery; QALY, quality-adjusted life years, RAS, robotic-assisted surgery. WTP, willingness-to-pay.

5.3.3 Sensitivity analysis results

One-way deterministic sensitivity analyses were performed to identify the parameters driving incremental net monetary benefit (INMB). Tornado diagrams (**Figures 5.3-1** to **Figure 5.3-4**) illustrate key drivers by procedure and comparator.

For prostatectomy, results were most sensitive to assumptions around LS length of stay and operative time in the RAS vs LS comparison, and to postoperative complication rates and RAS length of stay in the RAS vs open surgery. In both cases, RAS remained less cost-effective than LS but consistently cost-effective compared with open surgery. For colorectal resection, the main drivers were RAS length of stay, quality of life, and postoperative complication rates; however, INMB values remained negative across all parameters, indicating that RAS was not cost-effective against either comparator. For hysterectomy, cost-effectiveness results were most influenced by operative time, length of stay, and quality of life parameters for both RAS and open surgery. Despite this variation, INMB remained negative, confirming that RAS was not cost-effective compared with LS or open surgery. Finally, for pancreaticoduodenectomy, results were highly sensitive to assumptions about quality of life and length of stay for both RAS and open surgery, as well as postoperative complications, but INMB consistently remained negative, showing that RAS was not cost-effective in any scenario. Overall, while different parameters emerged as influential across procedures, the OWSA confirmed the robustness of the base case results: RAS was only consistently cost-effective compared with open surgery in prostatectomy, whereas LS remained the more economically favourable option in other indications.

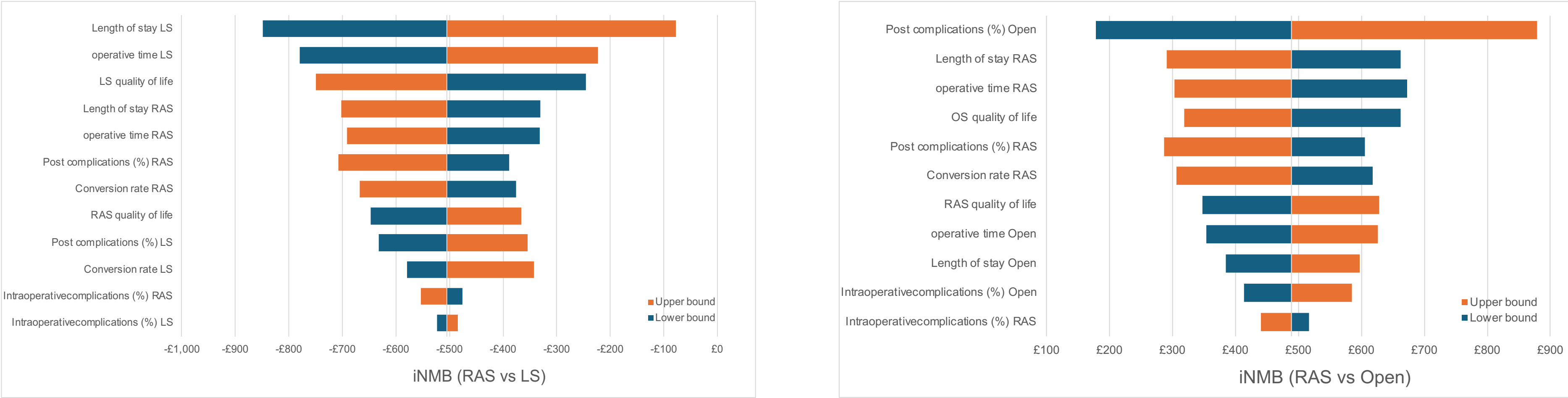


Figure 5.3-1 Tornado Diagram of one-way sensitivity analysis comparing RAS with LS and Open in prostatectomy

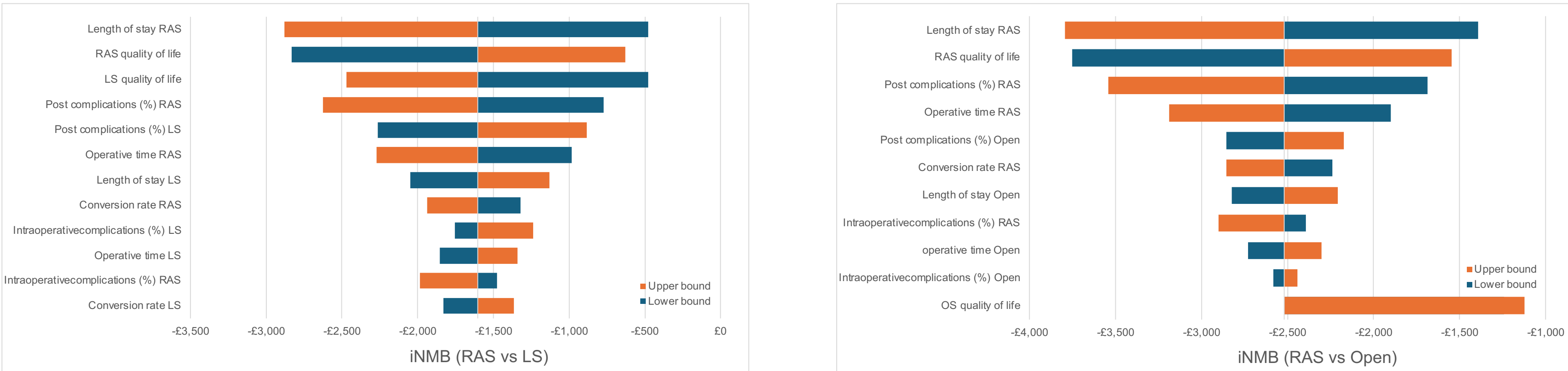


Figure 5.3-2 Tornado Diagram of one-way sensitivity analysis comparing RAS with LS and Open in colorectal resection

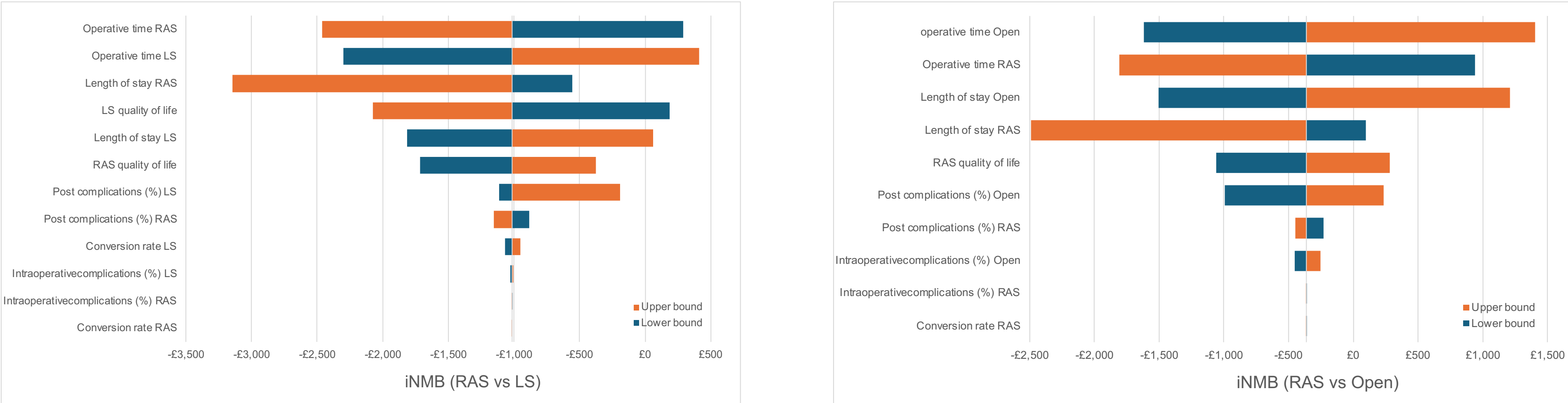


Figure 5.3-3 Tornado Diagram of one-way sensitivity analysis comparing RAS with LS and Open in hysterectomy

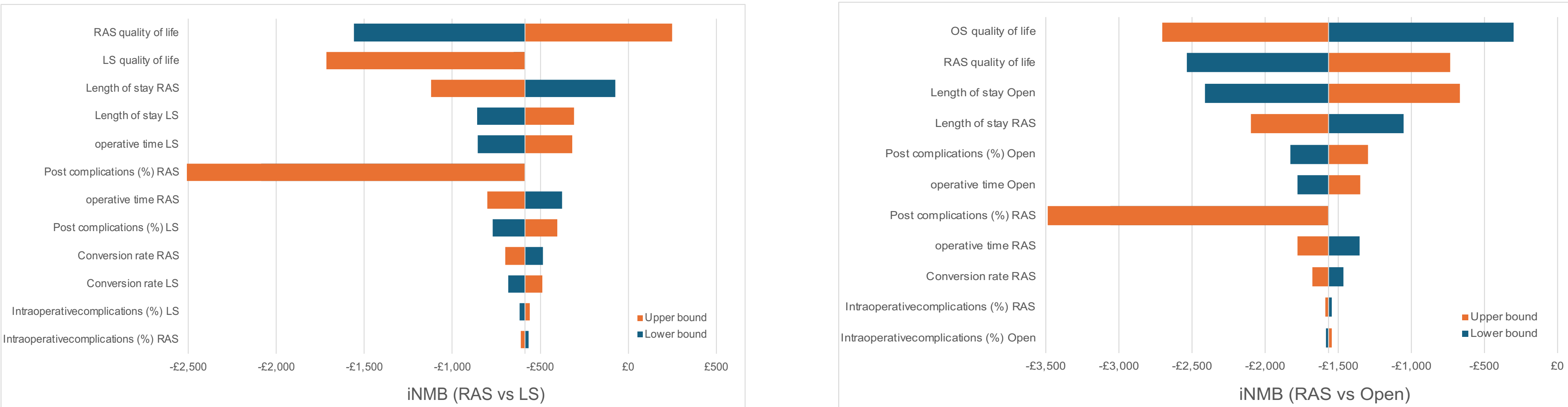


Figure 5.3-4 Tornado Diagram of one-way sensitivity analysis comparing RAS with LS and Open in pancreaticoduodenectomy

To evaluate decision uncertainty, a PSA was conducted, and cost-effectiveness acceptability curves (CEACs) were generated to illustrate the probability of RAS being cost-effective compared with LS and open surgery across WTP thresholds (**Figures 5.3-5**). For prostatectomy, RAS demonstrated a high probability of being cost-effective compared with open surgery, reaching nearly 100% at a willingness-to-pay (WTP) threshold of £20,000 per QALY, while the probability of RAS being cost-effective compared with LS remained close to zero across all thresholds. For colorectal resection, the probability of RAS being cost-effective against either comparator was consistently low (<15%) across the full range of thresholds, reflecting its unfavourable incremental cost-effectiveness ratios. For hysterectomy, the probability of RAS being cost-effective was modest, reaching around 30–40% at £30,000/QALY compared with both LS and open surgery, indicating substantial decision uncertainty. In pancreaticoduodenectomy, the probability of RAS being cost-effective increased with higher thresholds, reaching around 90% versus LS and 25% versus open surgery at £30,000/QALY, although neither comparison crossed conventional UK thresholds at £20,000 per QALY.

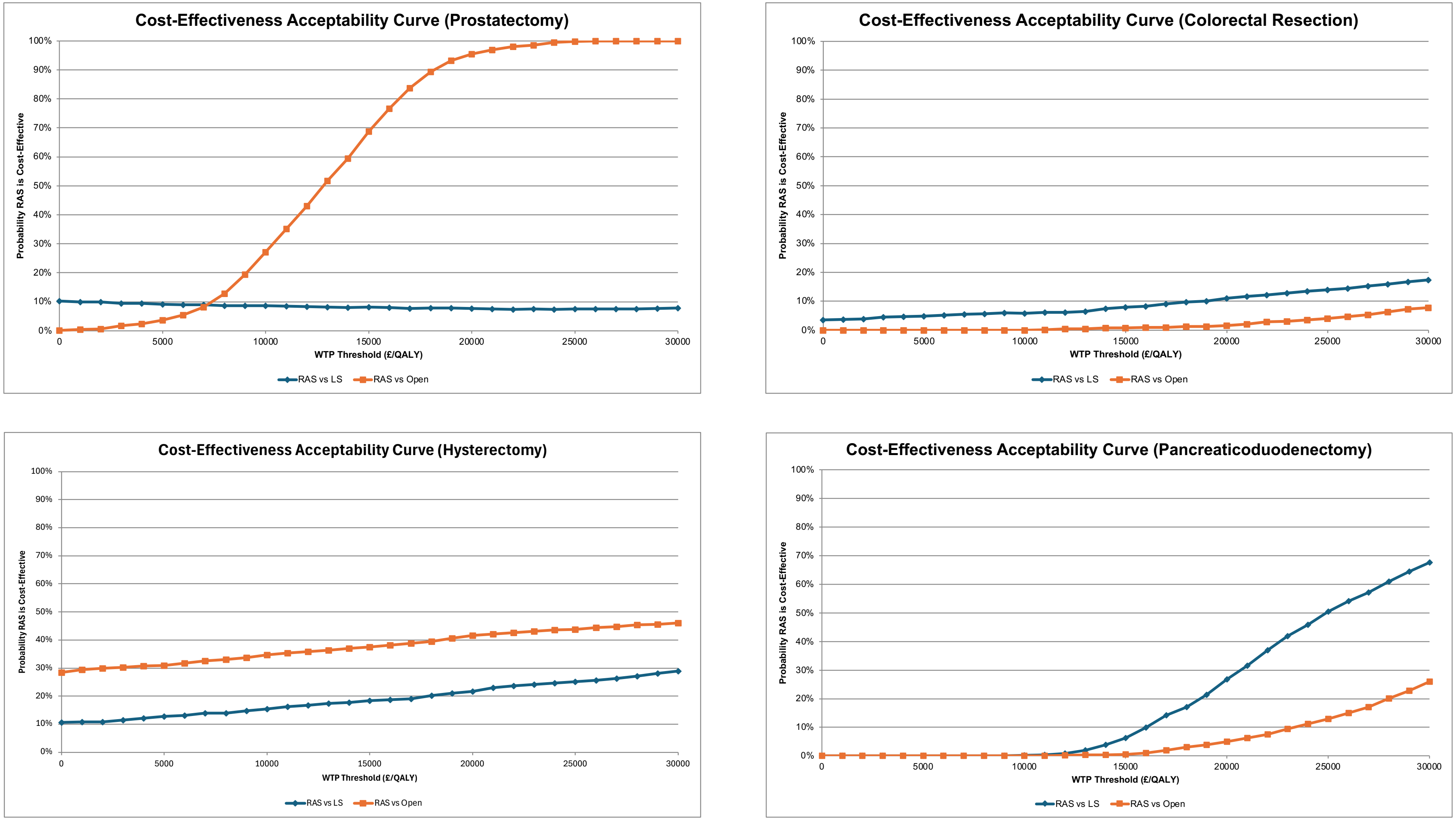


Figure 5.3-5 Cost-effectiveness acceptability curves for RAS vs LS and RAS vs open surgery in four procedures

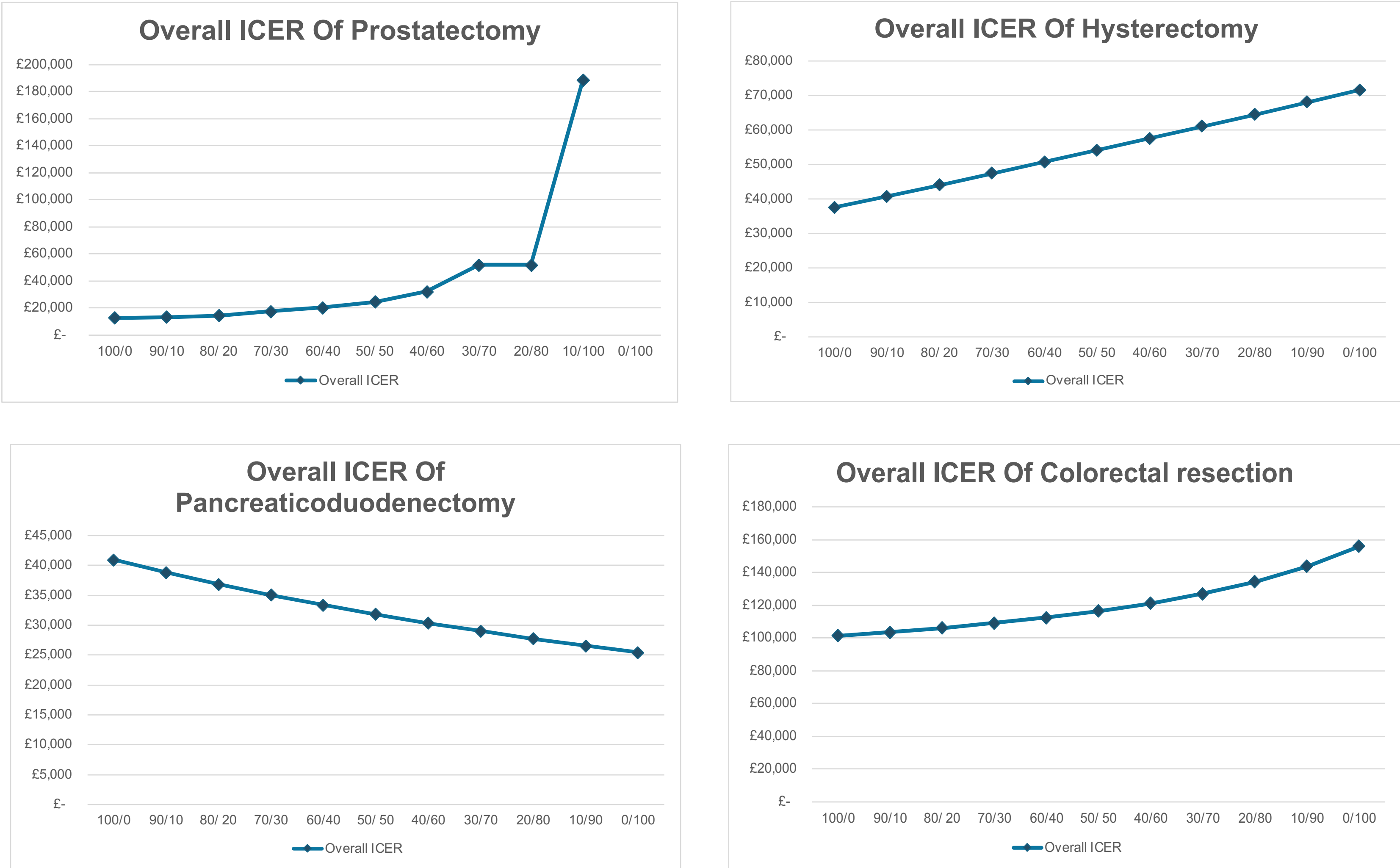
5.3.4 Threshold and case-mix analysis

A threshold analyses examined the cost-effectiveness of RAS under varying replacement proportions of LS and open surgery, while case-mix analyses assessed the various case-mix allocations across four procedures under different annual caseload scenarios. A series of replacement scenarios evaluated the cost-effectiveness of RAS as it incrementally displaced LS and open surgery. Across procedures, the threshold analyses demonstrated distinct patterns in the cost-effectiveness of RAS depending on the proportion of open versus LS replaced, reflecting higher utility gains and potential cost offsets from replacing more invasive approaches (**Table 5.3-3** and **Figures 5.3-6**). For prostatectomy, RAS was cost-effective when primarily replacing open surgery, with ICERs below £20,000/QALY for scenarios from 100/0 to 70/30, but lost efficiency as more LS was substituted, exceeding the threshold beyond a 60/40 mix and reaching £188,535/QALY when replacing only LS. For hysterectomy, RAS was not cost-effective under any scenario, indicating declining efficiency with greater LS substitution. In pancreaticoduodenectomy, ICERs remained consistently above the £20,000 threshold across all scenarios, although efficiency improved as replacing LS rather than open surgery. For colorectal resection, ICERs were also substantially above threshold.

This suggests that RAS adoption is more economically favourable in indications where it displaces a greater share of open surgeries, except pancreaticoduodenectomy. These findings informed the preliminary prioritisation strategies applied in the system-level case-mix model. The following strategies were tested: prostatectomy (70% open, 30% LS), pancreaticoduodenectomy (30% open, 70% LS), and hysterectomy and colorectal resection (both 90% open, 10% LS). These strategies were taken to support the design of case-mix strategies tested in stage-two modelling.

Table 5.3-3 ICERs of threshold analyses results in four procedures

	RAS replaced proportion for conventional surgeries			
	Prostatectomy	**Hysterectomy**	**Pancreaticoduoden e-ctomy**	**Colorectal resection**
OS vs LS (%)	**Overall ICER**			
100/0	£ 12,700/QALYs	£ 37,512/QALYs	£ 40,940/QALYs	£ 101,491/QALYs
90/10	£ 13,485/QALYs	£ 40,773/QALYs	£ 38,807/QALYs	£ 103,708/QALYs
80/ 20	£ 14,484/QALYs	£ 44,065/QALYs	£ 36,847/QALYs	£ 106,239/QALYs
70/30	£ 17,606/QALYs	£ 47,387/QALYs	£ 35,038/QALYs	£ 109,156/QALYs
60/40	£ 20,248/QALYs	£ 50,741/QALYs	£ 33,365/QALYs	£ 112,552/QALYs
50/ 50	£ 24,473/QALYs	£ 54,127/QALYs	£ 31,812/QALYs	£ 116,557/QALYs
40/60	£ 32,318/QALYs	£ 57,545/QALYs	£ 30,367/QALYs	£ 121,352/QALYs
30/70	£ 51,916/QALYs	£ 60,996/QALYs	£ 29,019/QALYs	£ 127,195/QALYs
20/80	£ 51,916/QALYs	£ 64,480/QALYs	£ 27,759/QALYs	£ 134,472/QALYs
10/90	£ 188,535/QALYs	£ 67,998/QALYs	£ 26,578/QALYs	£ 143,785/QALYs
0/100	LS dominant	£ 71,551/QALYs	£ 25,470/QALYs	£ 156,127/QALYs



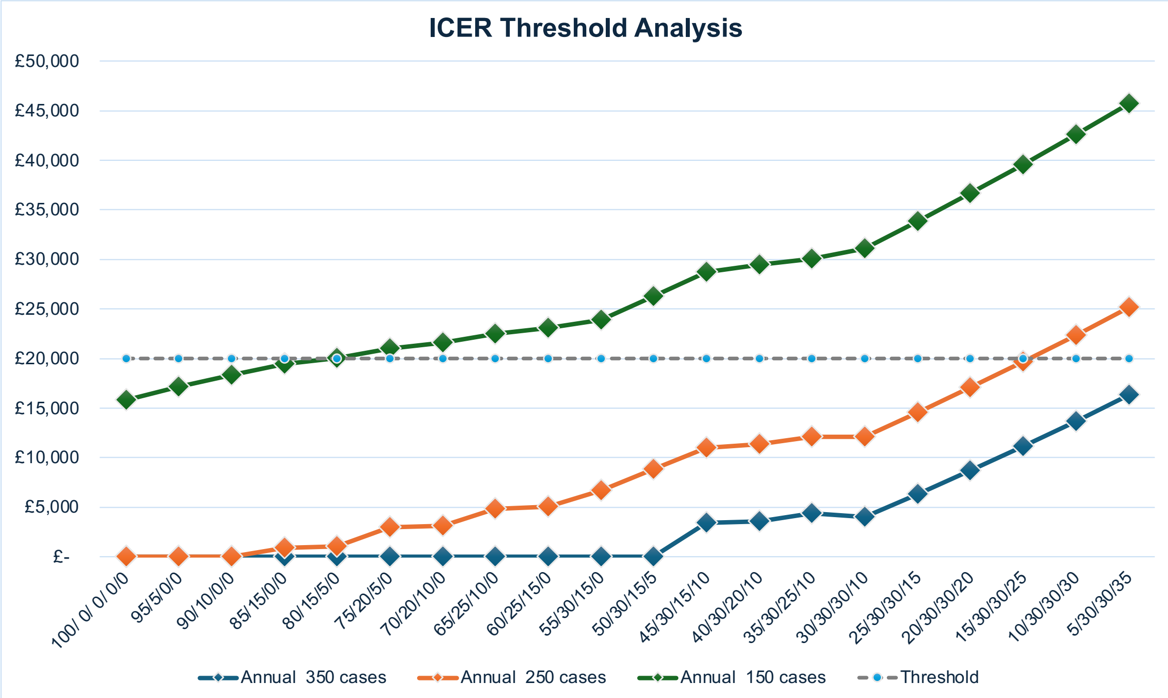
Note: X axis refers to proportions for open surgery vs LS

Figure 5.3-6 ICERs of RAS replacing different mixed proportions in four procedures

This prioritisation was not intended as a definitive ranking or proportion, but rather to guide the allocation of RAS procedures across specialties when exploring cost-effectiveness under different utilisation scenarios. The case-mix strategies of four procedures were then tested in further threshold analyses to identify the most cost-effective scenarios. A total of twenty case-mix strategies, distributing RAS use across the four procedures, were evaluated to estimate their overall ICERs. Additionally, the effect of varying annual case volumes of 150, 250, and 350 cases was examined to understand how scale influences cost-effectiveness outcomes.

Figure 5.3-7 presents the results of the threshold analysis evaluating the overall ICER of twenty different allocative strategies (%) for RAS utilisation for prostatectomy, pancreaticoduodenectomy, hysterectomy, colorectal resection respectively, under three annual case volume scenarios (150, 250, and 350 cases).

At 150 cases annually, RAS was cost-effective only in strategies heavily weighted towards prostatectomy, with ICERs rising sharply as other procedures were included. At a moderate caseload of 250 cases, RAS remained cost-effective in most strategies but exceeded the threshold when pancreaticoduodenectomy, hysterectomy, or colorectal resection accounted for more than 20–30% of the mix. At a high caseload of 350 cases, RAS was consistently cost-effective, dominating conventional surgery in all strategies up to a mix of 50% prostatectomy, 30% pancreaticoduodenectomy, 15% hysterectomy, and 5% colorectal resection. Beyond this allocation, ICERs rose progressively but remained below the £20,000/QALY threshold.



Note: X axis refers to allocative proportions (%) for prostatectomy, pancreaticoduodenectomy, hysterectomy, colorectal resection respectively; y axis refers to incremental cost-effectiveness ratios

Figure 5.3-7 The ICER values across 20 allocative strategies by different annual volumes

5.4 Discussion

This research aimed to guide decision-makers in optimising the utilisation of surgical robotic systems, focusing not only on their initial cost-effectiveness but also on their broader integration into health systems to maximise value, especially when investment decisions are being made. To accomplish this, A two-stage modelling framework was developed. The first stage estimated the cost-effectiveness of RAS compared with LS and open surgery across four high-interest procedures. The second stage explored how case-mix strategies and annual procedural volume affect the overall economic viability of adopting RAS at the system level to achieve cost-efficient healthcare delivery in the NHS setting.

Stage one compared RAS with LS and open surgery across four procedures. RAS generally delivered higher QALYs but at higher cost, yielding heterogeneous ICERs. It was cost-effective only in prostatectomy comparing to open surgery, while not cost-effective comparing to LS across procedures. Colorectal resection had the least favourable ICERs. The scenario analyses, which excluded capital costs to reflect situations where these costs have already been incurred or a donation setting, revealed a notable improvement in the cost-effectiveness profile of RAS across all procedures. In particular, RAS became cost-effective (or dominant) in hysterectomy and pancreaticoduodenectomy, remained cost-effective comparing to open in prostatectomy. As discussed in Chapter 4, investing surgical robotics has opportunity cost. Although consideration of capital costs varies among stakeholders, for the national decision-making, integrating these costs ensures a more comprehensive assessment. Importantly, the inclusion of capital costs raises questions not only of affordability but also of economic accountability.

Uncertainty around input parameters was explored through sensitivity analyses. Deterministic analyses showed cost-effectiveness is most sensitive to length of stay, operative time, postoperative complications, and health-related quality of life. The PSA revealed important differences in the likelihood of RAS being cost-effective across procedures and comparators, reflecting the underlying uncertainty in clinical and economic parameters. CEACs showed higher probabilities of cost-effectiveness for RAS versus open surgery, but low probabilities compared to LS. This reflects the higher marginal utility gains and potential cost offsets achievable in replacing open surgery. In contrast, replacing

LS with RAS resulted in smaller incremental benefits, making it more difficult to justify the higher cost of robotic systems. These findings highlight that the value case for RAS becomes more favourable when it is used to replace open surgery, where the incremental clinical benefit is more pronounced. This is particular reinforced by threshold analyses. It indicates that directing RAS to displace open consistently reduced ICERs, whereas using RAS to replace LS would increase ICERs. This highlights the economic value of RAS in displacing more invasive techniques and as well as demonstrates its scalability in expanding access to minimally invasive surgery.

Stage two model demonstrated most strategies achieved cost-effectiveness at higher volumes (≥350 cases/year), while at lower volumes, only mixes concentrated on higher-impact indications remained below threshold. This highlights the importance of economies of scale and strategic Robotic surgery service planning in achieving value for money. RAS is most economically viable when deployed at sufficient volume and in procedures, prioritised to procedures with larger incremental benefits, and used primarily to replace open rather than LS. In such contexts, the system-level framework presented in this study offers a valuable tool to support ongoing strategic planning and efficient use of RAS.

My cost-effective analysis result on the use of RAS in prostatectomy is consistent with previous study (Close et al., 2013), which concluded that robot-assisted radical prostatectomy (RARP) could be a cost-effective alternative to open surgery, particularly in high-volume centres performing at least 150 cases annually. Their analysis informed NICE's guideline (NICE, 2014b), which recommended that urology services consider offering robotic surgery for localised prostate cancer and identified ≥150 RARP procedures per centre per year as a benchmark for cost-effectiveness. They employed a lifetime Markov model that captured long-term outcomes, including postoperative continence and erectile dysfunction, thereby reflecting differences in health-related quality of life over time. My analysis presents a pragmatic, short-term evaluation tailored to NHS investment decisions, using a one-year decision tree model focused on perioperative outcomes and immediate resource use.

Managing RAS-specific features

As suggested in Chapter 4, RAS presents several distinctive features that should, at a minimum, be explored through sensitivity analysis. This study aimed to address the broader organisational implications of RAS adoption by developing a two-stage, system-level economic model. This approach provides insights for decision-makers on how to allocate robotic surgical resources across different specialties and determine the optimal proportion of RAS replacement for existing surgical methods, ensuring the most cost-effective utilisation of the robotic platform.

To account for the learning curve effect, synthesised clinical evidence was used to inform baseline inputs for clinical outcomes, representing performance levels closer to the expected norm once initial training and familiarisation have been achieved. While surgical proficiency improves with case volume, it also depends on factors such as team coordination, institutional experience, and support infrastructure, which can vary considerably across settings (Day et al., 2022). The second-stage model incorporated different annual case volumes to reflect variations in service scale and maturity. Although higher volumes are associated with reduced operative time and lower costs, thus enhancing cost-effectiveness, conservative estimates were used to avoid overstating potential benefits. These assumptions were tested through sensitivity analysis. A previous clinical trial for RAS of colorectal resection also shown the outcomes were confounded by learning curve effect (Corrigan et al., 2018). Clinical outcomes can be improved with increased surgeon experience, thereby potentially impacting cost-effectiveness. This is by no means universal. Yet it may be only in certain procedures since every procedure has different natures in terms of technical complexity.

Another important feature of RAS relates to its pricing dynamics, which may be affected by incremental technological innovation (e.g. successive generations of robotic systems) and variations in procurement processes. While the capital cost of robotic platforms, such as the Da Vinci system, is relatively consistent across global markets due to standardised list pricing, other cost components are more variable and may influence economic evaluations. In particular, RAS requires proprietary disposable instruments and accessories that are typically more expensive than those used in laparoscopic or open surgery (Sheetz and Dimick, 2019b). These consumables are often bundled into package deals, with pricing structures that differ by manufacturer, institution, or procurement contract. Although dynamic pricing of the robotic system itself may not drastically affect per-case costs in the short term, the recurring cost of disposable instruments represents a substantial proportion of the total cost per procedure. Therefore, in this study, the costs of RAS-specific disposable instruments were explicitly incorporated, considering various disposable instruments consumption across different specialties. This inclusion ensures that the model captures a more realistic and comprehensive view of cost drivers associated with RAS.

This study provides timely insights for NHS policy on the adoption and strategic deployment of surgical robotic systems, especially for Scotland that investment decision has been made and still in early adoption, where surgical volumes may still be limited and services are expanding. A system-level model complements this by supporting ongoing optimisation decisions post-adoption, where immediate costs, utilisation patterns, and operational efficiency are central concerns. At present, the expansion of robotic platforms across multiple specialties is often driven by practical considerations such as capital cost-sharing rather than evidence-based assessments of value for money. While platform sharing may reduce upfront investment, it does not necessarily align with procedure-specific cost-effectiveness. This analysis highlights the importance of strategically placing robotic systems to improve economic viability, not only through high-volume centres but also by prioritising procedures where RAS delivers significant gains over open surgery in terms of patient outcomes and resource use.

My findings are highly relevant to broader NHS goals to reduce waiting times and bed pressures by showing that robotic surgery can reduce hospital stays in some procedures. They also correspond with the NHS Long Term Plan’s commitment to surgical innovation, including recent announcements of further investment in RAS technologies (NHS, 2025). Moreover, my two-stage model suggests that considerations in theatre scheduling and capacity that relevant to volumes is critical to cost-effectiveness, reinforcing the potential of this framework to support regional service reconfiguration and surgical hub planning. A previous study investigated current issues and future directions for RAS in the UK, noting fragmented RAS provision, spread across low-volume centres. (Lawrie et al., 2022). While centralised high-volume hubs may facilitate platform sharing, my findings show that economic efficiency ultimately depends on case-mix and strategic deployment, not utilisation alone. As the NHS expands surgical hubs to help reduce waiting lists for planned operations, this model provides practical tool to support key decisions, such as which procedures are most suitable for robotic surgery, where to place robotic systems, and how to use resources most efficiently. Centralised service planning and targeted implementation strategies, particularly in early-adopting regions like Scotland where volumes are still developing, may offer a path toward more efficient service delivery. This indicates that there is considerable space for the application of this holistic model. However, centralisation may come at the cost of reduced local access, highlighting the need for balanced policy decisions that consider both economic efficiency and equitable access.

Strengths, Contributions, and Limitations

In this study, I introduce a novel, system-level economic modelling approach that highlights organisational and operational considerations to guide the adoption and optimal use of within the NHS. A key methodological contribution lies in its two-stage modelling approach, which extends beyond conventional cost-effective analyses by addressing both productive and allocative efficiency, features particularly important for evaluating capital-intensive technologies like RAS. Additionally, this study is the incorporation of stakeholder perspectives during the model conceptualisation process. Active engagement with key stakeholders throughout development enhances the model's relevance and acceptability, increasing the likelihood of uptake by decision-makers. This stakeholder-informed approach strengthens the credibility of the health economic model. To my knowledge, this is the first study to develop an interactive, Excel-based model that enables users to simulate site-specific strategies by incorporating surgical volumes, allocation ratios, and case-mix assumptions at system level perspective. The model is designed for real-world, post-adoption decision-making, offering flexibility for clinicians, hospital managers, and service planners to explore the local feasibility of RAS under operational and institutional constraints. While cost-effectiveness provides a foundation for evidence-based expansion, actual adoption decisions may also reflect broader considerations, such as maintaining local access, supporting training, or balancing service distribution. For instance, a hospital may choose to adopt a less cost-effective procedure to maintain local access, provide training opportunities, or balance service distribution. Conversely, even a cost-effective strategy may be impractical if there is insufficient surgical capacity or a lack of trained personnel. This experimental modelling is flexible and can be responsive to new evidence and service change. The strength of this model is it offers a pragmatic, adaptable framework to support decision-making throughout the technology lifecycle, from upfront investment decisions to dynamic resource planning. This enhances its utility as a planning tool beyond academic research, facilitating dynamic assessment during implementation in varied NHS settings. Overall, this system-level framework provides actionable insight for hospitals and health systems seeking to maximise the value of surgical robotics. It offers practical guidance for strategic planning, with the potential to support more efficient service delivery and a broader adoption of minimally invasive surgery in clinical practice.

Despite its contributions, some limitations of this model should be noted. First, the one-year time horizon captured perioperative outcomes and short-term healthcare use but did not reflect longer-term benefits such as functional recovery, chronic complications, or cancer recurrence. Second, a uniform decision tree structure was applied across all procedures to enable cross-specialty comparison and maintain consistency and policy relevant, but this inevitably sacrificed some clinical granularity. These modelling choices were deliberate, reflecting the system-level objective of informing early-stage service investment and utilisation planning from a policy perspective. Third, clinical parameters were informed by current available and relevant evidence, but the quality and consistency of the underlying evidence varied. The analysis could have been strengthened by incorporating mature real-world data (RWD), had such data been available, to provide more robust and generalisable estimates of outcomes in routine NHS practice. Fourth, mortality was excluded due to low incidence and attribution challenges, which may understate potential harms in high-risk groups. Fifth, capital cost scenarios in this model were limited to a setting in which hospitals bear both purchase and maintenance costs. It did not explore alternative funding mechanisms in detail (e.g. leasing). Additionally, there is an issue of generalisability. This model was based on data from a single robotic platform (da Vinci), whereas current NICE guidance conditionally recommends five systems for soft tissue procedures (NICE, 2025). These platforms differ in procurement costs and operational functionality, including ease of use and adaptability. Such differences affect training needs, workflow, and learning curves, not just for surgeons but for the entire team, dependent on institutional readiness and team support, affecting transferability (Randell et al., 2019). Cost, usability, and learning curves may vary across platforms and these may impact on cost-effectiveness. Lastly, this model focused solely on patient-related outcomes relevant to healthcare resource utilisation to address efficiency issue, without incorporating workforce impacts, such as staff well-being or ergonomic strain. These factors may have downstream implications for staff turnover and absenteeism and should be considered in future research as data become available. However, I have not identified any quantitative evidence which would allow me to incorporate it in the economic evaluation. If impacts such as agility or work burnout could be quantified, they could possibly be included in an economic evaluation in future research. Nevertheless, the model was designed to be adaptable; it does not aim to provide a single base-case estimate but rather offers a flexible framework for sensitivity testing and customisation based on local inputs. The model illustrates an approach to guide utilisation rather than provides any clear tool for best estimation at present. Nonetheless, this study provides a methodological foundation for incorporating the distinctive features of RAS into economic evaluations, enabling flexible, evidence-informed decision-making in both local and national contexts.

Chapter 6 Discussion and Conclusion

6.1 Introduction

When I started my PhD in 2020, I was very much interested in medical device evaluation methodology. I explored the methodological differences in evaluating medical devices and identified some issues via literature. However, I needed a good solid case study to research in more depth. This passion was ignited when I learned of a Scottish hospital getting some donated surgical robots, which sparked my curiosity. Subsequently, the announcement of Scotland's national investment in Robotic-Assisted Surgery (RAS) in 2021 further piqued my interest. This is because it was a bold move from the government to make this decision, given the uncertainty in the evidence base. There has been plenty of research on RAS, but controversy still surrounds its use. There is still a lot of debate among the researchers and policy makers about whether it is a good thing, and whether it is worth investing. This inspired me to focus my thesis on this question: How can Health Technology Assessment (HTA) support high-cost devices like RAS are used in the best possible way while being adopted? I am excited to find out if it is really not too late for HTA to make a difference and whether implementing an HTA approach can improve this adoption process.

Health innovations often diffuse quickly but also raise concerns among stakeholders about evidence, safety, high costs, and the benefits of the innovation. The use of RAS grew rapidly largely in the absence of evaluation which incorporated the specific characteristic of medical devices. The characteristics of high-cost innovative devices like RAS pose extra challenges to assessments and may require wider consideration including considering context, involvement of stakeholders, identifying uncertainties, economic factors, transparent regulation process, and evidence generation that I have mentioned in Chapter 2.

In Scotland, a national investment in surgical robots has been made. Decision-makers made decisions given an awareness of evidence controversies and now they face the challenge of expanding RAS services amidst these uncertainties. Given the ongoing adoption and expansion of RAS in Scotland, this thesis proposes there could be a role for HTA methodology in addressing the associated issues.

Therefore, the aim of this thesis was to demonstrate the role that HTA can play in supporting the optimal use and implementation decisions for high-cost devices by taking a case study of RAS. Furthermore, I illustrated how HTA can guide expansion decisions and future investment, ultimately informing strategies for integrating innovative technologies into healthcare systems effectively.

6.2 Main findings of the thesis

This thesis adopted a multidisciplinary HTA approach using a multi-step process to demonstrate how HTA can support evidence-informed decision-making for high-cost, platform technologies such as surgical robotics. The work focused on not only assessing initial cost-effectiveness, but also on optimising the broader utilisation of RAS within the health system, particularly post-investment.

This study began by overviewing the clinical effectiveness of RAS related to intra-cavity procedures compared to LS and open surgery where evidence is still in equipoise. The review covered four specialties, six procedures, and included 165 systematic reviews. A range of clinical outcomes was explored, including surgical, postoperative, oncological, and long-term endpoints. Overall, the findings suggest that RAS demonstrates either neutral or favourable outcomes across most domains, with the exception of operative time, which was typically longer. The evidence was generally more favourable when comparing RAS to open surgery than to LS. This means that the use of RAS can focus on procedures with low LS uptake rates and high potential for conversion from open to RAS to enhance the proportion of MIS. This study shows a key insight that RAS can serve as a means to increase the overall proportion of MIS, contributing to greater scalability and equity in access to MIS techniques. This finding gives robust evidence to support Scottish national strategy of shifting to MIS and its plan to extend the use of RAS to more intracavity procedures. A key novelty of this study is establishing an evidence spectrum to show where uncertainty lies, and how fragmented and incremental evidence can still yield actionable signals and navigate complex decision spaces. The study contributes to the field of RAS utilisation by enhancing evidence transparency and usability for decision-makers.

Building on these findings and insights, I then investigated the economic evaluation of RAS, recognising that its adoption remains contested due to its high cost and variable clinical effectiveness. I particularly explored the methods and challenges of economic evaluation and what opportunities there are to improve methods of economic evaluation. While some studies considered RAS-specific features, such as the learning curve or device costs, many lacked systematic treatment of organisational impact, dynamic pricing, and the platform nature of RAS. This review proposed a framework for incorporating these distinctive features into future evaluations and emphasised the need for sensitivity analyses to assess uncertainty. Moreover, the wider organisational implications of RAS, as a shared surgical platform, demand special consideration. Compared to conventional devices, RAS presents a more complex implementation profile, requiring capital-intensive investment, trained multidisciplinary teams, and operational coordination. These factors directly influence cost allocation, scheduling, and efficiency, and should be integrated into model structures where relevant. The novelty of this scoping review not only synthesises the existing evidence on the cost-effectiveness of RAS but also highlights methodological gaps and proposes practical, context-sensitive recommendations for improving the robustness of evaluations. The key insights developed in this review stress the need for more realistic, operationally grounded assessments for guiding investment decisions and optimising the utilisation of complex medical technologies in clinical practice.

The clinical evidence synthesis from Chapter 3 presented the use of RAS in specific specialties. I found that RAS has positive clinical outcomes compared to open surgery. This highlights the potential of RAS to enhance MIS uptake, particularly for procedures where LS is underutilised. The methodological scoping review from Chapter 4 further demonstrated that existing economic evaluations often fail to reflect the unique features and organisational implications of RAS, despite their impact on cost-effectiveness outcomes. These two studies provided the evidence base and conceptual foundation for the final study at Chapter 5, which developed a holistic, two-stage economic model.

Chapter 5, my third study, which develops a holistic de novo modelling framework, begins with the conceptualisation of the model. The model conceptualisation process is guided by a review of existing economic evaluations and refined through expert consultation. This consultation reinforced the methodological insights from Chapter 4 and provided direct input into the inclusion of key factors, such as learning curve effects, organisational impact, and resource constraints, ensuring that the model reflects real-world conditions and decision-making priorities. This model integrated procedure-level cost-effectiveness (Stage one) with platform-level planning (Stage two), enabling the exploration of case-mix strategies and annual volume thresholds across colorectal, gynaecology, HPB, and urology. These procedures were chosen based on clinical promise (Chapter 3) and alignment with national priorities, including those of the Scottish National Planning Robotic Review Group.

The model results show that RAS generally delivered higher QALYs but at higher cost, yielding heterogeneous ICERs. It was cost-effective only in prostatectomy comparing to open surgery. Scenario analyses excluding capital costs, reflecting settings where robots were donated or funded externally, substantially improved the cost-effectiveness of RAS. However, even in such scenarios, the opportunity cost of the robotic platform must be considered from a national investment perspective, as the resource could have been allocated to alternative uses within the health system. Sensitivity analyses identified utility values, length of hospital stay, and operative time as key drivers of cost-effectiveness. These factors help explain the threshold analysis findings, which showed that increasing the proportion of open surgery replaced by RAS consistently reduced ICERs. This trend is likely due to the high fixed capital cost of RAS devices, the per-procedure cost of disposable instruments, and the greater marginal benefit of RAS over open surgery in terms of reduced hospital stays and improved utility. In stage two, 20 case-mix scenarios were tested across annual volumes. Strategies which allocated more RAS to procedures with greater marginal benefit were more likely to fall below the £20,000/QALY threshold. Higher annual volumes allowed capital costs to be spread across more cases, improving cost-effectiveness in several scenarios, indicating that economies of scale play an important role. These findings conclude that RAS can be cost-effective when strategically implemented in high-volume or high-benefit procedures.

This study in Chapter 5 contributes a novel approach by developing a de novo two-stage, system-level model that explicitly considers the scale-dependent, organisational, and technological complexities of RAS. It goes beyond conventional cost-effectiveness analyses by addressing real-world operational constraints, supporting more cost-efficient delivery of RAS. The two-stage model captures both productive efficiency (procedure-level cost-effectiveness) and allocative efficiency (strategic service deployment across specialties), offering a flexible and practical tool to support decision-making for both hospital- and system-level stakeholders. The flexible design of the model allows dynamic scenario testing to guide local configuration, resource allocation, and national service planning. For hospitals, the model helps prioritise procedures based on cost-effectiveness and local capacity; for national systems such as NHS Scotland, it supports investment justification and efficiency optimisation during RAS scale-up.

Stage-one results confirmed the patterns observed in Chapter 3: RAS consistently delivered higher QALYs but at greater cost, with more favourable ICERs when compared with open surgery than with LS. Stage-two then addressed the organisational and system-level issues raised in Chapter 4 by explicitly modelling the role of procedure mix, annual case volume, and capital cost allocation. This demonstrated that while cost-effectiveness is highly variable at the procedure level, strategic allocation of RAS to high-benefit or high-volume applications can improve value for money and enhance equity in MIS provision. Together, the three chapters provide a cohesive picture: RAS offers limited incremental benefit over LS but clear advantages over open surgery, and its economic viability depends critically on system-level factors of utilisation and case-mix strategy.

6.3 Contribution of HTA to high-cost devices

High-cost medical technologies, such as surgical robotic systems, pose complex challenges for healthcare decision-makers due to their substantial investment requirements, cross-specialty applications, and system-wide implications. Surgical robotics, in particular, combine characteristics of medical devices, surgical innovation, platform technologies, and complex interventions. This thesis applied a multidisciplinary HTA approach to demonstrate how HTA methods can support more informed, context-sensitive decisions, both at the point of adoption and throughout a technology's lifecycle.

The case of RAS exemplifies many of the key issues faced with high-cost platform technologies. Unlike traditional interventions, decisions to adopt RAS are often shaped by a combination of clinical aspirations, institutional ambition, and political influence, sometimes occurring in the absence of conclusive evidence. Capital investment in RAS can occur at different levels, hospital, regional, or national, and may be funded through internal budgets, government initiatives, or external donations. These varied pathways complicate both economic accountability and the timing of cost-effectiveness assessments.

It is important to place such capital investment decisions of high-cost devices in an economic context, particularly by distinguishing between recoverable and irrecoverable costs. For example, surgical robotic platforms, even when leased or donated, can, in principle, be resold or transferred, making them potentially recoverable investments. In contrast, associated infrastructure changes, such as theatre renovations, reinforced flooring, or bespoke operating layouts, are often irrecoverable. These sunk costs become embedded within institutional operations, limiting flexibility and elevating the importance of optimising utilisation after adoption. Furthermore, when robotic systems are acquired to meet surgical demand in established clinical areas (e.g., prostatectomy), the capital costs may be effectively sunk, and HTA becomes especially important for informing optimisation and utilisation rather than adoption decisions. Therefore, the applicability and usefulness of my two-stage can play a significant role.

The organisational impact of RAS extends beyond economics, influencing workforce planning and institutional reputation(Abrishami et al., 2020, Abrishami et al., 2014). National strategies, such as Scotland's national investment ambitions and NHS England's 2025 plan to expand RAS, highlight its perceived value in reducing waiting times and attracting skilled surgeons. Lawrie et al. (Lawrie et al., 2022) reported stakeholder optimism about RAS due to its benefits but noted concerns around training, equity, and procedural volume, especially in low-use centres. Randell et al similarly emphasised the need for institutional support, dedicated teams, and adequate caseloads to ensure safe and effective RAS delivery (Randell et al., 2019). The stakeholder engagement in this thesis not only focused on practical factors to inform economic modelling but also identifying the factors beyond economics, such as workforce issues (see **Appendix 6 - Discussions with key stakeholder**).

These challenges are not unique to RAS. Similar complexities arise with other hight-costs shared platform technologies, such as advanced imaging equipment or innovative MIS devices, where value depends not just on the purchase price, but on sustained, coordinated use across departments. In this context, HTA is uniquely positioned to address such complexities by integrating clinical, economic, organisational, and contextual factors into a structured evaluation. The three interlinked studies in this thesis exemplify this integrated approach.

First, a narrative evidence synthesis was conducted to assess the clinical effectiveness of RAS across multiple intra-cavity procedures. This approach aligns with HTA's core aim of informing accountable healthcare decisions with the best available evidence. It was particularly valuable in the RAS context, where evidence is fragmented, incremental, and often inconsistent. The synthesis helped clarify where RAS offers benefit, especially in replacing open surgery, and extracted actionable signals for decision-maker. This approach is equally applicable to other high-cost technologies, such as advanced imaging systems or precision radiotherapy platforms, where evidence may be dispersed across indications or evolve rapidly with technological innovation.

Second, a scoping review examined methodological gaps in existing economic evaluations of RAS. It found that key features, including learning curve dynamics, organisational impact, incremental innovation, and dynamic pricing were often neglected. These limitations undermine the realism of many current models. The review offered practical improvements to strengthen the relevance of evaluations for system-level decision-making. It also highlighted broader adoption challenges common to high-cost technologies: unique characteristic of devices, variability in funding arrangements, shared use across specialties, and non-economic considerations such as workforce attraction, reputational value, and training needs. This review contributes to more comprehensive and realistic HTA methods for evaluating complex technologies with systemic implications.

Third, building on these insights, a two-stage, system-level economic model was developed and applied to the NHS Scotland context. The model assessed procedure-specific cost-effectiveness and platform-level optimisation strategies by varying case-mix of procedures, annual volume, and replacement proportions. Developed through expert consultation, the model was grounded in real-world policy questions, particularly for systems where RAS has already been acquired and the key challenge lies in optimising its use. The modelling approach illustrates how HTA can address not only adoption decisions, but also efficiency and resource allocation after investment. It provides a flexible, dynamic framework for decision-makers to test local scenarios and inform policy aligned with operational constraints. This approach is transferable to other capital-intensive technologies, such as proton beam therapy or diagnostic imaging suites, where effective deployment depends on case selection, throughput, and interdepartmental coordination. Tailoring such models to different device types enables health systems to maximise value from existing infrastructure while supporting scalable, evidence-informed service planning.

Together, these studies demonstrate how HTA can provide decision support across the full lifecycle of a technology, from pre-adoption appraisal to post-investment optimisation. This thesis contributes to the HTA field by showing how evaluation methods can be adapted for complex, high-cost, platform-based interventions. By integrating clinical evidence, economic reasoning, and operational planning, this research reinforces the importance of HTA as a practical and flexible tool for improving the governance, implementation, and sustainability of advanced technologies in healthcare.

6.4 Limitations

While this thesis offers several contributions to the field of HTA for high-cost surgical technologies, some limitations must be acknowledged.

First, in Chapter 3, an evidence synthesis was conducted to review the clinical effectiveness of RAS across multiple intra-cavity procedures where evidence maybe still equipoise. Although the narrative synthesis approach provided a structured and comprehensive overview, it did not involve a formal meta-analysis or quantitative pooling of effect estimates. As such, the heterogeneity in study designs, and outcomes reported, included may limit the generalisability of findings. In particular, the counting approach used to summarise the direction of findings across studies does not account for differences in study quality, giving equal weight to all studies regardless of methodological rigour. This may lead to overinterpretation, especially where publication bias results in the overrepresentation of positive findings.

Second, Chapter 4 employed a scoping review to examine the methods and limitations of existing economic evaluations of RAS. Given the review's aim to map the field and identify methodological gaps, formal quality appraisal was not undertaken, nor did I attempt to calculate statistical precision across heterogeneous studies. This limits the ability to assess the robustness of individual study conclusions but remains appropriate for the review's objective, which was to inform modelling development rather than provide definitive cost-effectiveness estimates.

Third, in Chapter 5, expert consultation was used to support model conceptualisation and ensure alignment with real-world decision-making needs. While this engagement added valuable contextual insights, the sample was small and purposively selected. As this was not a formal qualitative study and no identifiable patient data or real-world datasets were used, formal ethics approval was not required under the prevailing university guideline. Nevertheless, the scope of stakeholder input could be expanded in future work through broader, more systematically recruited engagement processes.

Finally, the modelling framework itself carries several limitations. The one-year time horizon captured perioperative outcomes and short-term healthcare use but did not reflect longer-term consequences such as functional recovery, chronic complications, or cancer recurrence. A uniform decision-tree structure was applied across procedures to enable cross-specialty comparison and maintain consistency and policy relevant. However, while this structure enhances adaptability for my system-level model and ease of implementation across settings, it also reduces flexibility in capturing procedure-specific clinical pathways, cost components, and outcome differences. This simplification may lead to the omission of important costs and effects, particularly those unique to individual procedures. These modelling choices were intentional, reflecting the system-level objective of informing early-stage service investment and utilisation planning from a policy perspective. Clinical parameters were informed by the best available evidence, though quality and consistency varied. The model would have been strengthened by incorporating mature real-world data, had these been available. Mortality was excluded due to low incidence and attribution challenges, which may understate harms in high-risk groups. Capital cost scenarios were limited to settings in which hospitals bear both purchase and maintenance costs and did not explore alternative procurement mechanisms (e.g. leasing model). Generalisability is further constrained by reliance on a single robotic platform (da Vinci), despite current NICE guidance recommending multiple systems with different costs and operational characteristics (NICE, 2025). These differences, such as ease of use, training requirements, and workflow integration, may affect cost-effectiveness and transferability (Randell et al., 2019). Lastly, the model focused on patient-related outcomes and healthcare utilisation, without incorporating workforce impacts such as ergonomic strain or staff well-being, for which quantifiable evidence was lacking. Despite these limitations, the model is intended as an adaptable decision-support framework, capable of sensitivity testing and local customisation, rather than a definitive cost-effectiveness analysis for all settings.

6.5 Implications

The findings of this thesis stress the vital role of HTA in supporting the responsible integration of high-cost, complex technologies like RAS into healthcare systems. As health services face growing pressure to adopt cutting-edge innovations amidst budgetary and operational constraints, HTA provides a structured, multidisciplinary framework to guide evidence-based and context-sensitive decision-making. This research highlights how HTA and economic evaluation can play a valuable role in informing the ongoing use and optimisation of technologies post-implementation, supporting more efficient and context-sensitive resource allocation throughout a technology's lifecycle.

The three interlinked studies in this thesis demonstrate how HTA methods can be applied across multiple stages of a technology's lifecycle. This work aligns with NICE's evolving lifecycle approach, supporting timely, evidence-based decisions from early assessment to post-adoption optimisation. It complements NICE's Early Value Assessment (HTE21) (NICE, 2025) by highlighting the importance of strategic planning and operational efficiency once RAS enters clinical use. I am pleased that some of the findings from this thesis (Chapters 3 and 4) were referenced at the 2025 NICE Conference on surgical robotics, indicating its relevance and contribution to ongoing national policy discussions. This study anticipates and supports its direction by identifying key evidence gaps and proposing a structured modelling framework to support future implementation practices. The model is designed to incorporate NHS data as it becomes available, providing a practical foundation for guiding RAS-related decisions—including surgical hub planning and resource allocation—in early-adopting regions such as Scotland.

This thesis provides practical insights and methodological novelty that extend how HTA can support the adoption and optimisation of high-cost technologies like RAS.

1. **Making sense of noisy evidence:** The first study maps the fragmented and often conflicting clinical evidence base for RAS. By establishing an evidence spectrum, it shows how uncertainty can be navigated constructively, enabling decision-makers to extract actionable signals. A key implication is that RAS may hold value not only in terms of clinical outcomes, but as a strategic enabler to expand the overall share of minimally invasive surgery,

improving access and scalability. This approach highlights HTA not only as an assessor, but as a navigator through complex, imperfect evidence landscapes.

2. **Strengthening how economic evaluations are designed for high-cost medical devices:** The second study highlights that existing economic evaluations of RAS tend to be siloed within single specialties and often neglect features unique to high-cost, multi-use platforms—such as shared infrastructure, learning curves, and interdependencies across services. This work identifies key methodological gaps and proposes a more holistic, system-level perspective. A practical implication is the need to align evaluations with real-world operational planning, especially when assessing technologies that cut across surgical specialties and organisational boundaries.

3. **Shifting from static analysis to strategic modelling**: The third study develops a novel two-stage modelling framework that responds to real-world NHS policy questions. Rather than focusing solely on whether RAS is cost-effective in isolation, the model addresses how robotic systems can be deployed most efficiently once adopted. It explores key system-level drivers—such as case-mix, platform sharing, annual surgical volumes, and capital cost structures—enabling scenario-based planning around resource allocation and service configuration (e.g. surgical hub models). A key contribution of this work is the advancement of HTA as an iterative process. Economic considerations are embedded early and designed to evolve, rather than being treated as a one-off appraisal. The framework is flexible and adaptable to local contexts, allowing for refinement as new data or operational insights become available. This positions economic modelling not simply as a retrospective evaluation tool, but as a forward-looking, responsive instrument to support both initial investment decisions and ongoing optimisation throughout a technology's lifecycle.

6.6 Conclusion

This thesis set out to explore how HTA methods can be applied to inform the adoption and utilisation of high-cost technologies, using RAS as a case study. Through three interlinked studies, a narrative evidence synthesis, a scoping review of economic evaluations, and the development of a novel two-stage system-level economic model. This research has demonstrated how HTA can provide comprehensive, context-sensitive, and actionable decision support across the lifecycle of a complex medical technology.

The evidence synthesis clarified the clinical effectiveness of RAS across intra-cavity procedures, identifying where it offers the greatest benefit and where uncertainties persist. The scoping review highlighted key methodological gaps in current economic evaluations, such as the limited management of organisational impacts, learning curves, and pricing dynamics, while proposing ways forward for more realistic evaluations of high-cost devices. Building on these insights, the modelling study introduced an adoptable, decision-oriented framework that supports both strategic investment planning and efficient platform utilisation, grounded in real-world constraints and stakeholder input. The HTA method used in this thesis are generalisable to high-cost devices generally and could potentially be applied to other high-cost device in the future. Together, these studies demonstrate the value of HTA not only at the point of adoption, but also in guiding post-investment optimisation. The research aligns closely with current frameworks and emerging HTA practice, including IDEAL Robotic Colloquium, complex interventions and NICE's lifecycle approach, offering practical insights for how HTA can evolve to better support platform technologies like RAS.

By integrating clinical evidence, economic reasoning, and operational realities, this thesis contributes both methodological innovations and applied tools to the HTA field. It reinforces the idea that HTA is not a one-off activity but a flexible, iterative process that can inform decisions at multiple levels and stages. Ultimately, this work underlines the potential of HTA to support the responsible, efficient, and equitable integration of high-cost technologies into healthcare systems. Therefore, it is never too late for HTA to play a role in the assessment of high-cost devices adoption.

6.7 Recommendations for future research

This thesis has advanced the application of HTA methods for high-cost technologies, using RAS as a case study. However, several avenues for further research are recommended to address the limitations identified and build upon the contributions made.

1. **Real-world evidence integration (including workforce and system-level benefits):** A key priority for future research is the integration of high-quality real-world data (RWD) into this system-level modelling framework. As discussed in Section 5.2.5, exploratory analyses using NHSGGC data highlighted both the potential and the limitations of early local datasets. At the time of collection, the data were restricted to a single specialty and hospital, with limited follow-up, and captured the first year of robotic system availability when surgeons were still within their learning curve. These constraints limited their suitability for robust model parameterisation. Future research should focus on applying the RAS evaluation model within real-world decision-making contexts, such as the NHS healthcare system, using locally sourced and clinically relevant data. While current datasets remain limited, initiatives such as the REINFORCE study(NIHR, 2022)—a national in-situ evaluation of robotic surgery in the NHS—are beginning to address this evidence gap. As these data infrastructures mature, they offer opportunities to capture a broader range of outcomes across multiple levels: patient-level (e.g. quality of life, complications), surgeon/team-level (e.g. precision, surgical workload), organisation-level (e.g. equipment failure, service efficiency, cost-effectiveness), and population-level (e.g. equity of access). Incorporating these real-world insights would allow for validation and refinement of the model, improving both its accuracy and its contextual relevance. In particular, linking the model to workforce and operational data could help capture system-level impacts, supporting more holistic and adaptive decision-making around high-cost technologies.

2. **Real-World application and implementation**: In parallel, implementation research should explore how decision-makers interact with the model in operational settings. This includes assessing its usability, perceived value,

and influence on decisions related to planning, resource allocation, or technology adoption. A dedicated implementation study could involve hospital managers, clinical leads, and policymakers to identify both the facilitators and barriers to using the model, such as stakeholder buy-in, institutional readiness, or data availability. Understanding these dynamics will be essential for tailoring the model to fit different organisational contexts and ensuring that it supports not only theoretical evaluation but also practical service planning and policy development.

3. **Broader HTA application to high-cost devices**: This thesis used RAS as a case study to illustrate how HTA can be applied to complex, high-cost platform technologies. Many emerging innovations, such as AI-enabled diagnostic tools, robotic imaging systems, and advanced radiotherapy platforms, face similar challenges in terms of substantial capital costs, system-wide impact, and cross-specialty use. The framework developed in this research could be adapted to these technologies to assess its transferability and strengthen its generalisability.

   For instance, the recent NICE pilot evaluations of AI-based diagnostic tools (under the Early Value Assessment programme) have demonstrated the need for flexible, context-aware economic models that incorporate uncertainty, workflow change, and implementation barriers. Similarly, national efforts to expand advanced imaging infrastructure, such as AI-supported MRI or CT interpretation systems, highlight the importance of evaluating shared, capital-intensive platforms with long-term service implications. Adapting this HTA framework to such technologies would help promote consistent, scalable evaluation standards and support the development of adaptable HTA methodologies tailored to next-generation innovations. Ultimately, this broader application could enable more timely and evidence-informed decision-making for a wide range of high-cost medical technologies across health systems.

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List of appendices

Appendix 1 - Database search terms for the overview review

Database search record		
Database:	**Saved search strategy name**	**Search strategy** (inc. limits and filters)
Cochrane Library	Robotic surgery Dec 2023	Date Run: 18/12/2023 ID Search Hits #1 MeSH descriptor: [Robotic Surgical Procedures] this term only 711 #2 ((robot* near/3 (surger* or surgical* or transplant* or laparoscop*))):ti,ab,kw 3135 #3 (("robot-assisted" or "robotically-assisted") near/3 (surger* or surgical* or transplant* or laparoscop*)):ti,ab,kw 1487 #4 (#1 or #2 or #3) in Cochrane Reviews 17
Ovid Medline	Robotic surgery Medline Dec 2023	Systematic reviews Database: Ovid MEDLINE(R) ALL <1946 to Dec 18, 2023> Search Strategy: -- 1 Robotic Surgical Procedures/ (17146) 2 (robot* adj3 (surger* or surgical* or transplant* or laparoscop*)).tw. (21673) 3 (("robot-assisted" or "robotically-assisted") adj3 (surger* or surgical* or transplant* or laparoscop*)).tw. (6280) 4 or/1-3 (30099) 5 Meta-Analysis as Topic/ (23602) 6 meta analy$.tw. (288688) 7 metaanaly$.tw. (2650) 8 Meta-Analysis/ (192167) 9 (systematic adj (review$1 or overview$1)).tw. (312303) 10 exp Review Literature as Topic/ (24187) 11 5 or 6 or 7 or 8 or 9 or 10 (481996) 12 cochrane.ab. (142735) 13 embase.ab. (164555) 14 (psychlit or psyclit).ab. (918) 15 (psychinfo or psycinfo).ab. (62138) 16 (cinahl or cinhal).ab. (49085) 17 science citation index.ab. (3884)

		18 bids.ab. (705) 19 cancerlit.ab. (639) 20 12 or 13 or 14 or 15 or 16 or 17 or 18 or 19 (261525) 21 reference list$.ab. (22756) 22 bibliograph$.ab. (23298) 23 hand-search$.ab. (8799) 24 relevant journals.ab. (1374) 25 manual search$.ab. (6335) 26 21 or 22 or 23 or 24 or 25 (56223) 27 selection criteria.ab. (37067) 28 data extraction.ab. (34536) 29 27 or 28 (68859) 30 Review/ (3257314) 31 29 and 30 (36342) 32 Comment/ (1028567) 33 Letter/ (1239422) 34 Editorial/ (677045) 35 animal/ (7365147) 36 human/ (21674355) 37 35 not (35 and 36) (5147329) 38 32 or 33 or 34 or 37 (7288093) 39 11 or 20 or 26 or 31 (575393) 40 39 not 38 (548388) 41 4 and 40 (1882) 42 limit 41 to (english language and yr="2017 - 2023") (1426)
Ovid Embase	Robotic surgery Embase Dec 2023	**Systematic reviews** Database: Embase <1974 to 2023 Dec 18> Search Strategy: -- 1 robot assisted surgery/ (24536) 2 (robot* adj3 (surger* or surgical* or transplant* or laparoscop*)).tw. (38463) 3 (("robot-assisted" or "robotically-assisted") adj3 (surger* or surgical* or transplant* or laparoscop*)).tw. (10035) 4 or/1-3 (50153) 5 exp Meta Analysis/ (303011) 6 ((meta adj analy$) or metaanalys$).tw. (368652)

		7 (systematic adj (review$1 or overview$1)).tw. (375813) 8 5 or 6 or 7 (602549) 9 cancerlit.ab. (757) 10 cochrane.ab. (180054) 11 embase.ab. (203939) 12 (psychlit or psyclit).ab. (1011) 13 (psychinfo or psycinfo).ab. (59100) 14 (cinahl or cinhal).ab. (57034) 15 science citation index.ab. (4448) 16 bids.ab. (895) 17 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16 (310979) 18 reference lists.ab. (24314) 19 bibliograph$.ab. (33883) 20 hand-search$.ab. (10741) 21 manual search$.ab. (7396) 22 relevant journals.ab. (1628) 23 18 or 19 or 20 or 21 or 22 (70842) 24 data extraction.ab. (41739) 25 selection criteria.ab. (46133) 26 24 or 25 (85120) 27 review.pt. (3211610) 28 26 and 27 (39123) 29 letter.pt. (1302410) 30 editorial.pt. (791130) 31 animal/ (2142249) 32 human/ (27182511) 33 31 not (31 and 32) (1624637) 34 29 or 30 or 33 (3699510) 35 8 or 17 or 23 or 28 (714138) 36 35 not 34 (696659) 37 4 and 36 (2500) 38 limit 37 to (english language and yr="2017 - 2023") 1920

Appendix 2 - Characteristics of included reviews and quality assessment from the overview review

Table A2-1 Characteristics of included reviews and quality assessment for colorectal oncology surgery

Review	Year	Studies included, n			Population	Intervention vs Comparator	Risk of bias tool	Critically flawed domains	Quality assessed by author (TJ LAI)
		Total	RCT	Non-RCT					
Li (Li, 2017a)	2017	17	-	17	patients with rectal cancer	RTME vs LTME	-	9, 11, 15	Critically low
Xu (Xu, 2017)	2017	9	-	9	patients with anus-preserving rectal cancer	RTME vs LTME	MINORS	13	Low
Lee (Lee, 2018)	2018	5		5	patients with low rectal adenocarcinoma	Robotic vs laparoscopic ISR	RoBANS	15	Low
Jones (Jones, 2018)	2018	28	1	27	patients with rectal cancer	RTME vs LTME	-	9, 13	Critically low
Holmer (Holmer, 2018)	2018	13	2	11	patients with rectal cancer	RTME vs TME or open TME	No meta was performed	9, 13	Critically low
Ohtani (Ohtani, 2018)	2018	23	-	23	patients with rectal cancer	RTME vs LTME	MINORS	13, 15	Critically low
Pezzolla (Pezzolla, 2018)	2018	5	5	-	patients with rectal cancer	RTME vs LTME	Cochrane risk of bias tool	15	Low
Sheng (Sheng, 2018)	2018	40			patient with colorectal cancer	RAS vs LS vs open surgery	Cochrane risk of bias tool	11, 13, 15	Critically low
Tang (Tang, 2018)	2018	6	2	4	patients with rectal cancer	RTME vs LTME	NOS, Cochrane Collaboration tool		High
Milone (Milone, 2019)	2019	12	1	11	patients with rectal cancer	RTME vs LTME	Cochrane Collaboration tool		Moderate
Ma (Ma, 2019)	2019	13	1	12	patient with colon cancer	Robotic-assisted vs laparoscopic right colectomy	-	13	Low
Simillis (Simillis, 2019)	2019	37	29	8	patients with rectal cancer	RTME vs LTME or TaTME	Cochrane risk of bias tool	15	Low
Grass (Grass, 2019)	2019	64	2	62	patients with rectal cancer	taTME or RTME vs LTME	No meta was performed	9, 13	Critically low
Liao (Liao, 2019a)	2019	7	7	-	patients with rectal cancer	RTME vs LTME	Cochrane risk of bias tool		High
Li (Li, 2019)	2019	7	7	-	patients with rectal cancer	RTME vs LTME	Jadad scale	15	Low
Ng (Ng, 2019)	2019	73	6	67	patient with colorectal cancer	RTME vs LTME	Cochrane risk of bias tool, NOS	15	Low
Huang (Huang, 2019)	2019	8	8	0	patients with rectal cancer	RTME vs LTME	Cochrane risk of bias tool	15	Low
Phan (Phan, 2019)	2019	11	6	5	patients with rectal cancer	Robotic vs. laparoscopic rectal cancer surgery	Cochrane Collaboration tool	15	Low

Rausa (Rausa, 2019)	2019	48	5	43	patient with colonic neoplasms	Robotic hemicolectomy vs open vs Laparoscopic-assisted vs Total laparoscopic hemicolectomy	Cochrane risk of bias tool, NOS	15	Low
Rubinkiewicz (Rubinkiewicz, 2019)	2019	6	-	6	patients with rectal cancer	RAS vs LS	NOS	7, 15	Critically low
Sun (Sun, 2019)	2019	6	2	4	patients with rectal cancer	RTME vs LTME	NOS	15	Low
Eltair (Eltair, 2020)	2020	9	9	-	patients with rectal cancer	RTME vs LTME	Cochrane risk of bias tool	11	Low
Gavriilidis (Gavriilidis, 2020b)	2020	25	3	22	patients with rectal cancer	RTME vs LTME	NOS	15	Low
Tejedor (Tejedor, 2020)	2020	4	-	4	patients with rectal cancer	RTME vs LTME	-	9, 13, 14	Critically low
Wang (Wang, 2020b)	2020	20		20	patients with rectal cancer	RTME vs LTME	-	9, 13, 15	Critically low
Waters (Waters, 2020)	2020	15	1	14	patients with rectal cancer	Robotic vs laparoscopic hemicolectomy	Cochrane risk of bias tool, NOS		Moderate
Qiu (Qiu, 2020)	2020	7		7	patients with rectal cancer	RTME vs LTME	MINORS	13, 15	Critically low
Guo (Guo, 2021)	2021	14		14	patients with rectal cancer	RAS vs open rectal surgery	Jadad scale, NOS		High
Hoshino (Hoshino, 2021)	2021	59	7	52	patients with rectal cancer	RTME vs LTME	-	9, 11,13, 15	Critically low
Fleming (Fleming et al., 2021)	2021	10	3	7	patients with rectal cancer	RTME vs LTME	NOS	11	Low
Ryan (Ryan, 2021)	2021		30		patients with rectal cancer	RTME vs LTME	-	9, 13, 15	Critically low
Tang (Tang, 2021)	2021	7	7		patients with rectal cancer	RTME vs LTME	Cochrane risk of bias tool, Jadad scale		High
Butterworth(Butterworth et al., 2021)	2021	62	-	62	patients with low rectal adenocarcinoma	RTME vs TaTME	Cochrane Collaboration Tool		High
Chen (Chen et al., 2021)	2021	6	-	6	patient with rectal cancer	RTME vs TaTME	-	9, 13	Critically low
Genova(Genova et al., 2021)	2021	37	1	36	patient with colon cancer	Robotic-assisted vs laparoscopic right colectomy			High
Kowalewski (Kowalewski et al., 2021)	2021	48	3	45	patient with colon cancer	Robotic vs. laparoscopic rectal cancer surgery	NOS	9	Low
Liu (Liu et al., 2021)	2021	15	2	13	patients with rectal cancer	Robotic vs. laparoscopic rectal cancer surgery	NOS		High
Safiejko (Safiejko et al., 2021)	2021	42	3	39	patient with colon cancer	Robotic TME, APR, LAR, Hartman, ISR vs laparoscopic TME APR, LAR, Hartman, ISR	RoB2 tool for RCT and ROBINS-I bias for nRCT		High
Wee (Wee et al., 2021)	2021	39	-	39	patient with colon cancer	Robotic-assisted vs laparoscopic resection	Cochrane risk-of-bias tool		Moderate

Zhang (Zhang et al., 2021a)	2021	5	-	5	patients with low rectal cancer	Robotic vs laparoscopic ISR	NOS	9, 13	Critically low
Zhu (Zhu et al., 2021)	2021	10	-	10	patient with right colon tumor	Robotic vs laparoscopic right colectomy	NOS	9, 13, 15	Critically low
An (An et al., 2022)	2022	19	19	-	patient with colon cancer	Robotic vs laparoscopic colectomy	Cochrane risk of bias tool	15	Low
Ravindra(Ravindra et al., 2022)	2022	16	2	14	patients with colorectal cancer	Robotic vs laparoscopic APR	Cochrane risk of bias tool		Moderate
Sandlas (Sandlas et al., 2022)	2022	12	-	12	patients with rectal cancer	RTME vs LTME	-	7,9,13,15	Critically low
Solaini (Solaini et al., 2022)	2022	11	-	11	patients with rectal cancer	Robotic vs laparoscopic left colectomy	NOS	9, 13	Critically low
Tschann (Tschann et al., 2022)	2022	25	1	24	patients with colorectal cancer	Robotic vs laparoscopic right colectomy	NOS	9, 13, 15	Critically low
Cuk (Cuk et al., 2023)	2023	55	3	52	patient with colonic cancer	Robotic vs laparoscopic CME	Cochrane risk of bias tool		High
Flynn (Flynn et al., 2023)	2023	50	3	47	patient with rectal cancer	Robotic vs laparoscopic colectomy	-	9, 13, 15	Critically low
Khajeh (Khajeh et al., 2023)	2023	26	RAS vs Open, N=5; RAS vs LAS, n=24		patients with colorectal cancer	Robotic vs laparoscopic vs Open colectomy	-	9, 15	Critically low
Huang (Huang et al., 2023c)	2023	11	11	-	patients with rectal cancer	Robotic vs laparoscopic colectomy	Cochrane risk of bias tool		High
Kim (Kim et al., 2023)	2023	5	-	5	patients right colon cancer	robotic vs laparoscopic right colectomy	MINORS	9, 13, 15	Critically low
Kyrochristou (Kyrochristou et al., 2023)	2023	16	-	16	patient with colonic cancer	Robotic vs laparoscopic CME	-	9, 13	Critically low
Oweira (Oweira et al., 2023)	2023	7	-	7	patient with colonic cancer	Robotic vs laparoscopic CME	-	9, 13, 15	Critically low
Seow (Seow et al., 2023)	2023	47	32	15	patients with rectal cancer	RTME vs TaTME	RoB2		High
Xu (Xu et al., 2023)	2023	7	4	3	patient with colonic cancer	Robotic vs laparoscopic CME	Cochrane risk of bias tool		Moderate
Yang (Yang and Zhou, 2023)	2023	11	2	9	patient with rectal cancer	Robotic vs laparoscopic colectomy	NOS		High
Yang (Yang et al., 2023)	2023	6	6	-	patient with colonic cancer	Robotic vs laparoscopic colectomy	Cochrane risk of bias tool		High
Yao (Yao et al., 2023)	2023	8	-	8	Patient with mid–low rectal cancer	RTME vs LTME	NOS	9	Low
Zheng (Zheng et al., 2023a)	2023	42	1	41	patient with colonic cancer	robotic vs laparoscopic right colectomy	NOS	9	Low

Zheng (Zheng et al., 2023b)	2023	15	-	15	patient with colonic cancer	robotic vs laparoscopic right colectomy	NOS	9	Low

APR abdominoperineal resection; CME, complete mesorectal excision; LS, laparoscopic surgery; LTME, laparoscopic Total Mesorectal Excision; ISR=intersphincteric resection; RAS=Robotic Assisted Surgery; RTME=Robotic Assisted Total Mesorectal Excision; TaTME= Transanal Total Mesorectal Excision; TME=Total Mesorectal Excision. MINORS, methodological index for non-randomized studies; NOS, Newcastle–Ottawa scale; RCT, randomized controlled trial; RoB, risk of bias.
Domain 2, protocol registration; 4, adequacy of the literature search; 7, justification for excluding studies; 9, risk of bias assessment for included studies; 11, appropriateness of methods used for meta-analysis; 13, consideration of risk of bias; 15, assessment of publication bias.

Table A2-2 Characteristics of included reviews and quality assessment for hysterectomy

Review	Year	Studies included, n			Population	Intervention vs Comparator	Risk of bias tool	Critically flawed domains	Quality assessed by author (TJ LAI)
		Total	RCT	Non-RCT					
Li (Li, 2017b)	2017	19	-	19	women with cervical cancer	RH vs LH vs OH	-		High
Laios (Laios, 2017)	2017	36	1	35	patients with endometrial cancer	RH vs LH	-	9, 13, 15	Critically low
Nevis (Nevis, 2017)	2017	35	-	35	patients with endometrial and cervical cancers	RH vs OH	-		Moderate
Park (Park, 2017)	2017	22	-	22	patients with cervical cancer	RH vs LH vs OH	RoB 2.0	15	Low
Jin (Jin, 2018)	2018	17	17	-	patients with cervical cancer	RH vs LH vs OH	PEDro	13, 15	Critically low
Behbehani (Behbehani, 2019)	2019	21	1	20	patients with gynecologic oncology conditions	RH vs LH	NOS, Cochrane risk of bias	13, 15	Critically low
Cusimano (Cusimano, 2019)	2019	51	-	51	patient with early-stage endometrial cancer	RH vs LH	NOS	15	Low
Lawrie (Lawrie, 2019)	2019	12	12	-	women with malignant/ benign gynaecological disease	RH vs LH vs OH	Cochrane risk of bias tool		High
Marra (Marra, 2019)	2019	50	5	45	patients with benign uterine disease/ endometrial cancer/ cervical cancer	RH vs LH	-	9, 13	Critically low
Shi (Shi, 2019)	2019	8	-	8	patients with ovarinan cancer	RH vs LH vs OH	MINORS		High
Zhang (Zhang, 2019)	2019	13	-	13	patients with cervical cancer	RH vs LH	modified MINORS, NOS		Moderate
Behbehani (Behbehani, 2020)	2020	65	5	60	patients with benign gynecologic conditions	RH vs LH	NOS, Cochrane risk of bias tool	13, 15	Critically low
Prodromidou (Prodromidou, 2020)	2020	6	-	6	patients with benign or early-stage malignant gynecological conditions	RH vs LH	MINORS	15	Low
Wang (Wang, 2020a)	2020	27	1	26	patients with endometrial cancer	RH vs LH vs OH	NOS, Cochrane risk of bias		High
Hwang (Hwang, 2020)	2020	23		23	patients with benign gynecologic conditions	RH vs LH	-	9, 13	Critically low
Alshowaikh (Alshowaikh et al.,	2021	25	2	23		RH vs LH	NOS	7, 9	Critically low

2021)									
Kampers (Kampers et al., 2022)	2022	27	2	25	patients with early cervical cancer	RH vs LH	RoB 2.0	15	Low
Huang (Huang et al., 2023b)	2023	6	-	-	patients with early cervical cancer	RH vs LH	Cochrane risk of bias		High
Hwang (Hwang and Kim, 2023a)	2023	20	-	-	patients with early cervical cancer	RH vs LH		9	Low
Hwang (Hwang and Kim, 2023b)	2023	19	-	-	patients with early cervical cancer	RH vs LH		9, 11,13	Critically low
Marchand (Marchand et al., 2023a)	2023	35	-	35	patients with early cervical cancer	RH vs OH		9, 13, 15	Critically low
Marchand (Marchand et al., 2023b)	2023	33	-	33	patients with early cervical cancer	RH vs LH	Cochrane risk of bias	15	Low
Lenfant (Lenfant et al., 2023)	2023					RH vs LH RH vs OH			

LH, laparoscopic hysterectomy; OH, open hysterectomy; RH robotic hysterectomy; MINORS, methodological index for non-randomized studies; NOS, Newcastle–Ottawa scale; RCT, randomized controlled trial; RoB, risk of bias. Domain 2, protocol registration; 4, adequacy of the literature search; 7, justification for excluding studies; 9, risk of bias assessment for included studies; 11, appropriateness of methods used for meta-analysis; 13, consideration of risk of bias; 15, assessment of publication bias.

Table A2-3 Characteristics of included reviews and quality assessment for hepatopancreaticobiliary surgeries

Review	Year	Studies included, n			Population	Intervention vs Comparator	Risk of bias tool	Critically flawed domains	Quality assessed by author (TJ LAI)
		Total	RCT	Non-RCT					
Lauretta (Lauretta, 2017)	2017	10		10	patient with pancreatic body-tail tumors	RDP vs LDP	NOS		Moderate
Kornaropoulos (Kornaropoulos, 2017)	2017	13		-	patients with cancerous tumors of the head of the pancreas, malignant periampullary tumors	RPD vs LPD	-		Moderate
Peng (Peng, 2017)	2017	7	-	7	patients with tumors of pancreatic head, distal bile duct, duodenal or ampullary carcinomas	RPD vs OPD	NOS	13	Low
Shin (Shin, 2017)	2017	5		5	patient with periampullary neoplasms	RPD vs LPD vs OPD	NOS	13	Low
Hu (Hu, 2018)	2018	17	-	17	patients with liver neoplasms	RLR vs LLR	NOS, GRADE	15	Low
Zhao (Zhao, 2018)	2018	15		15	patient with pancreatic adenocarcinoma	RAS vs Open	NOS	13, 15	Critical low
Machairas (Machairas, 2019)	2019	10	-	10	patient with malignant and benign hepatic tumors	RLR vs OLR	MINORS	15	Low
Wong (Wong, 2019)	2019	7	-	7	patient with liver disease	RLR vs OLR	NOS	15	Low
Gavriilidis (Gavriilidis, 2019)	2019	36	-	36	patients with pancreatic adenocarcinoma	RDP vs LDP vs ODP	NOS	15	Low
Guan (Guan, 2019)	2019	13	-	13	patient with liver malignancies	RLR vs LLR	NOS	9	Low
Kamarajah (Kamarajah, 2019)	2019	20	-	20	patient with pancreatic benign and malignant condictiones	RDP vs LDP	NOS		High
Niu (Niu, 2019)	2019	17	-	17	patients with pancreatic lesion	RDP vs LDP vs ODP	NOS, GRADE		High
Ciria (Ciria, 2020)	2020	150	-	150	patient with liver malignancies	RLR vs LLR	NOS	13	Low
Gavriilidis (Gavriilidis, 2020a)	2020	79	1	78	Patient with hepatocellular carcinoma	RLR vs LLR vs OLR	NOS	15	Low
Kamarajah (Kamarajah, 2020b)	2020	26	-	26	patient with liver malignancies	RLR vs LLR vs OLR	NOS, Cochrane Risk of Bias Tool	9	Low
Zhang (Zhang, 2020)	2020	28	-	28	patient with liver malignancies	RLR vs LLR	NOS	13	Low
Zhao (Zhao, 2020)	2020	31	-	31	patients had benign and malignant liver conditions	RLR vs LLR vs OLR	NOS	13	Low

Lyu (Lyu, 2020)	2020	46	-	46	patient with pancreatic benign and malignant tumors of the pancreatic body and tail	RDP vs LDP vs ODP	NOS		High
Mavrovounis (Mavrovounis, 2020)	2020	22	-	22	patients with pancreatic pathology	RDP vs LDP	NOS		Moderate
Zhou (Zhou, 2020)	2020	7	-	7	patient with pancreatic benign and malignant conditions	RDP vs ODP	NOS	13, 15	Critical low
Aiolfi (Aiolfi, 2020)	2020	41	3	39	patient with pancreatic head neoplasms	RPD vs LPD vs OPD	ROBINSI	15	Low
Kamarajah (Kamarajah, 2020a)	2020	44	-	44	patient with benign and malignant conditions	RPD vs LPD	NOS, the Cochrane Risk of Bias Tool		High
Podda (Podda, 2020)	2020	18	-	18	patients with benign and malignant periampullary disease	RPD vs OPD	ROBINS-I, GRADE		High
Yan (Yan, 2020)	2020	12		12	patient with malignant lesions of the pancreatic head, distal common bile duct, and duodenum	RPD vs OPD	NOS	13	Low
Coletta (Coletta, 2021)	2021	8	-	8	patient with liver malignancies	RLR vs LLR	ROBINS-I, GRADE		Moderate
Coco (Coco, 2020)	2020	16	-	16	patient with liver cancer	RLR vs LLR	-		Moderate
Hu (Hu, 2021)	2021	6		6	patient with liver malignancies	RLR vs LLR	NOS	13	Low
Ziogas (Ziogas, 2021)	2021	7	-	7	patient with liver disease	RLR vs LLR	NOS	13	Low
Wang (Wang, 2021)	2021	12	-	12	patient with liver disease	RLR vs LLR	NOS	9	Low
Da Dong (Da Dong et al., 2021)	2021	24	-	24	patient with pancreatic head neoplasms	RPD vs OPD	ROBINS-I		Moderate
Zhang (Zhang et al., 2021b)	2021	18	-	18	patient with pancreatic head neoplasms	RPD vs OPD	NOS	9	Low
Di Martino (Di Martino et al., 2021)	2021	11	-	11	patient with pancreatic benign and malignant conditions	RDP vs LDP		9, 13, 15	Critical low
Feng (Feng et al., 2021a)	2021	6	-	6	patient with pancreatic benign and malignant conditions	RDP vs LDP	NOS	9, 13	Critically low
Rompianesi (Rompianesi et al., 2021)	2021	11	-	11	patient with pancreatic benign and malignant conditions	RDP vs LDP	NOS	9	Low
Aboudou (Aboudou et al., 2022)	2022	19	-	19	patient with liver disease	RLR vs LLR	NOS	9, 13	Critical low
Hajibandeh (Hajibandeh et al., 2022)	2022	7	-	7	patient with liver disease	RLR vs LLR	ROBINS-I	9, 11	Critical low
Fu (Fu et al., 2022)	2022	21	-	21	patient with pancreatic cancer	RPD vs OPD	NOS	15	Low

Lincango (Lincango Naranjo et al., 2022)	2022	4	-	4	patient with liver disease	RLR vs LLR	CLARITY tool		Moderate
Murtha-Lemekhova (Murtha-Lemekhova et al., 2022)	2022	8	-	8	patient with liver disease	RLR vs LLR	ROBINS-I	15	Low
Rahimli (Rahimli et al., 2022)	2022	14	-	14	patient with liver disease	RLR vs LLR	NOS	9, 13, 15	Critical low
Yeow (Yeow et al., 2022)	2022	19	-	19	living donor right hepatectomy	RLR vs LLR vs OLR		9	Low
Kabir (Kabir et al., 2022)	2022	27	4	23	patient with pancreatic head neoplasms	RPD vs LPD vs OPD	Cochrane Risk of Bias tool/ NOS		Moderate
Ouyang (Ouyang et al., 2022)	2022	9	-	9	patient with pancreatic head neoplasms	RPD vs LPD	NOS	9, 13	Critical low
Gao (Gao et al., 2023)	2023	22	-	22	patient with liver disease	RLR vs LLR vs OLR	NOS	9, 13	Critical low
Long (Long et al., 2023)	2023	5	-	5	patient with liver disease	RLR vs LLR	NOS	9, 13	Critical low
Mao (Mao et al., 2023)	2023	12			patient with liver disease	RLR vs LLR	NOS	9, 13	Critical low
Papadopoulou (Papadopoulou et al., 2023)	2023	14	-	14	patient with liver disease	RLR vs OLR	MINORS	9, 13, 15	Critical low
Xuea (Xuea et al., 2023)	2023	8	-	8	patient with liver disease	RLR vs OLR	NOS	9, 13	Critical low
Ziogas (Ziogas et al., 2023)	2023	31	-	31	patient with liver disease	RLR vs OLR	NOS	9	Low
Chaouch (Chaouch et al., 2023)	2023	4	4 (open label)	-	patient with pancreatic benign and malignant conditions	RDP vs ODP	MINORS/ NOS/RoB2	15	Low
Li (Li et al., 2023)	2023	34	-	34	patient with pancreatic benign and malignant conditions	RDP vs LDP	NOS	9	Low
van Ramshorst (van Ramshorst et al., 2023)	2023	43	-	43	patient with pancreatic benign and malignant conditions	RDP vs LDP	RoB		High
Wang (Wang et al., 2023)	2023	65	3	62	patient with benign and malignant conditions	RPD vs LPD vs OPD		9, 13	Critical low

LDP, laparoscopic distal pancreatectomy; ODP, open distal pancreatectomy; RDP, robotic distal pancreatectomy; LLR, laparoscopic liver resection; OLP, open liver resection; RLR robotic liver resection; LPD, laparoscopic pancreaticoduodenectomy, OPD open pancreaticoduodenectomy; RPD robotic pancreaticoduodenectomy; MINORS, methodological index for non-randomized studies; NOS, Newcastle–Ottawa scale; RCT, randomized controlled trial; RoB, risk of bias.

Domain 2, protocol registration; 4, adequacy of the literature search; 7, justification for excluding studies; 9, risk of bias assessment for included studies; 11, appropriateness of methods used for meta-analysis; 13, consideration of risk of bias; 15, assessment of publication bias.

Table A2-4 Characteristics of included reviews and quality assessment for gastrointestinal oncology surgery

Review	Year	Studies included, n			Population	Intervention vs Comparator	Risk of bias tool	Critically flawed domains	Quality assessed by author (TJ LAI)
		Total	RCT	Non-RCT					
Caruso (Caruso, 2017)	2017	6	1	5	patients with gastric cancer	RG vs LG vs OG	NOS, Jadad's scoring system		Moderate
Chen (Chen, 2017)	2017	19	-	19	patients with gastric cancer	RG vs LG	NOS	9	Low
Pan (Pan, 2017)	2017	5	-	5	patients with gastric cancer	RG vs LG	MINORS		Moderate
Magouliotis (Magouliotis, 2017)	2017				patients with gastric cancer				
Wang (Wang, 2017a)	2017	12	-	12	patients with gastric cancer	RG vs LG	MINORS		Moderate
Wang (Wang, 2017b)	2017	3	-	3	patients with gastric cancer	RG vs LG	Cochrane risk of bias tool	13, 15	Critically low
Yang (Yang, 2017)	2017	7	-	7	patients with gastric cancer	RG vs OG	NOS		Moderate
Ai (Ai, 2019)	2019	24	-	24	patients with gastric cancer	RG vs LG	NOS, GRADE	15	Low
Zheng (Bobo, 2019)	2019	16	-	16	patients with gastric cancer	RG vs LG	NOS, GRADE		High
Liao (Liao, 2019b)	2019	8	-	8	patients with gastric cancer	RG vs LG	NOS		Moderate
Guerrini (Guerrini, 2020)	2020	40	-	40	patients with gastric cancer	RG vs LG	MINORS		Moderate
Ma (Ma, 2020)	2020	19	-	19	patients with gastric cancer	RG vs LG	NOS		Moderate
Solaini (Solaini, 2020)	2020	10	-	10	patients with gastric cancer	RG vs LG vs OG	NOS	15	Low
Aiolfi (Aiolfi et al., 2021b)	2021	17	17	-	patients with gastric cancer	RDG vs LDG vs ODG	Cochrane risk of bias tool	15	Low
Feng (Feng et al., 2021b)	2021	20	1	19	patients with gastric cancer	RDG vs LDG	NOS	9	Low
Wu (Wu et al., 2021)	2021	11	-	11	patients with gastric cancer	RDG vs LDG	MINORS	9, 13	Critically low
Zhang (Zhang et al., 2021c)	2021	12	-	12	patients with gastric cancer	RDG vs LDG		9, 13	Critically low

Zhang (Zhang et al., 2021d)	2021	12	-	12	patients with gastric cancer	RDG vs LDG	NOS	9, 13	Critically low
Ali (Ali et al., 2022)	2022	32	-	32	patients with gastric cancer	RDG vs LDG	MINORS	9, 13	Critically low
Baral (Baral et al., 2022)	2022	48	-	48	patients with gastric cancer	RDG vs LDG	MINORS	9, 13	Critically low
Chen (Chen et al., 2022)	2022	11	-	11	patients with gastric cancer	RDG vs LDG	NOS	9, 13	Critically low
Gong (Gong et al., 2022)	2022	22	-	22	patients with gastric cancer	RDG vs LDG	ROBINS-I		High
Jin (Jin et al., 2022)	2022	31	1	30	patients with gastric cancer	RDG vs LDG	NOS	13	Low
Sun (Sun et al., 2022)	2022	8	1	7	patients with gastric cancer	RDG vs LDG	ROBINS-I		High
Davey (Davey et al., 2023)	2023	22	22	-	patients with gastric cancer	RDG vs LDG		15	Low
Lacovazzo (Iacovazzo et al., 2023)	2023	15			patients with gastric cancer	RDG vs LDG		9, 15	Critically low
Multani (Multani et al., 2023)	2023	29	-	29	patients with Situs Inversus Totalis	RDG vs LDG	JBI critical appraisal	9, 15	Critically low
Shibasaki (Shibasaki et al., 2023)	2023	33	-	33	patients with gastric cancer	RDG vs LDG		9, 13, 15	Critically low
Ye (Ye et al., 2023)	2023	11			patients with gastric cancer	RDG vs LDG	ROBINS-I		High
Yu (Yu et al., 2023)	2023	6	1	5	patients with gastric cancer	RDG vs LDG		9, 13	Critically low

LG, laparoscopic gastrectomy; LDG laparoscopic distal gastrectomy; OG, open gastrectomy; ODG, open distal gastrectomy; RG, robotic gastrectomy; RDG, robotic distal gastrectomy;

Appendix 3 - Clinical effectiveness of RAS

Table A3-1 Clinical Effectiveness of Colorectal cancer surgery

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy or other approach	open				
Operative time (min)								
(Li 2017)	N=16	NR	NR	-	MD=57.43 (36.70–78.15);	P<0.001	Laparoscopy	96.0%
(Xu 2017)	N=9	354	451	-	MD=33.73 (8.48, 58.99)	*P*=0.009	Laparoscopy	96%
(Jones 2018)	N =27	2,601	2,848	-	SMD=0.65 (0.43, 0.87)	P<0.00001	Laparoscopy	93%
(Lee 2018)	N =5	273	237	-	RISR vs LISR MD=41.89 (15.51, 68.27)	p= 0.002	Laparoscopy	73%
(Li 2019)	N =6	484	487	-	MD= 27.04 (-1.06, 55.14)	P = 0.06	NS	98%
(Ohtani 2018)	N =23	2068	2274	-	MD=44.80 (28.44, 61.15)	p<0.00001	Laparoscopy	97%
(Pezzolla 2018)	RCTs, N =5	344	337	-	MD=38.43 (31.84, 45.01)	p<0.00001	Laparoscopy	4%
(Huang 2019)	RCT, N =7	NR	NR	-	LS vs RAS MD=-23.491 (-3.876, -43.106)	P=0.019	Laparoscopy	NR
(Ma 2019)	N=12	656	7084	-	RRC vs LRC MD=43.61(39.11, 48.1)	P < 0.0001	Laparoscopy	92%
(Ng 2019)	NCT, N =6 nRCT, N 53	902 7391		-	MD=38.19 (28.78, 47.60)	P<0.001	Laparoscopy	93%
(Rausa 2019)	NR	414	1324	1067	RRH vs TLRH RR=-24.0 (-70.0, 21.0) RRH vs ORH RR=-4.1 (-52.0, 44.0)	NR	NS NS	90%
(Sun 2019)	N =6	819	855	-	MD=54.15 (13.02, 95.29)	P=0.01	Laparoscopy	98%
(Eltair 2020)	RCTs, N =9	728	735	-	MD=31.64 (12.09, 51.19)	P=0.002	Laparoscopy	97%
(Gavriilidis 2020)	N =26	4,734		-	MD= 50.35 (31.70, 70.69)	P<0.001	Laparoscopy	97%
(Wang 2020)	N =19	NR	NR	-	SMD = 0.48 (0.14, 0.82)	P = 0.0001	Laparoscopy	94%
(Ryan 2021)	NR	NR	NR	NR	Open vs LS MD=-38.2 (-58.4, -17.9)	NR	Open NS	NR

					RAS vs LS MD=26.8(-0.49, 54.4)			
(Butterworth 2021)		3163	1220	-	MD=53.0 (18.8, 87.2)	P=0.002	Laparoscopy	
(Chen 2021)		NR	NR	-	NOTES vs RAS MD = 0.11 (0.34, 0.55)	P=0.642	NS	
(Genova 2021)	N=8	735	656	-	LRC vs RRC MD= -66.71(-81.08, -52.34)	P<0.00001	Laparoscopy	76%
(Safiejko 2021)	N=34	NR	NR	NR	MD= 43.39 (25.26, 61.51)	P<0.001	Laparoscopy	98%
(Zang 2021)	N=5	273	237	-	MD=43.27 (16.48, 70.07)	P=0.002	Laparoscopy	71%
(Zhu 2021)	N=6	255	267	-	MD=65.20 (53.40, 77.01)	P<0.00001	Laparoscopy	55%
(Bianchi 2022)	N=2	38	64	-	MD=104.64 (19.42, 190.87)	P=0.02	Laparoscopy	58%
(Solaini 2022)	N=10	13438	39001	-	MD=39.08 (17.26, 60.91)	NR	Laparoscopy	97%
(Tschann 2022)		NR	NR	-	LS vs RAS MD= -42.01 (-51.06, -32.96)	P<0.001	Laparoscopy	89%
(Flynn 2023)		NR	NR	-	MD=0.82 (0.60, 1.04)	P<0.001	Laparoscopy	96%
(Huang 2023)	N=9	1384	1382	-	MD=28.91 (18.00, 39.82)	P<0.00001	Laparoscopy	95%
(Khajeh 2023)		NR	NR		LS vs RAS MD=-36.29 (-47.34, -25.25)	P<0.00001	Laparoscopy	0%
(Oweira 2023)		269	408	-	MD= 36.62 (-24.30, 96.93)	P=0.24	NS	0%
(Seow 2023)		NR	-	NR	RAS vs OS MD=78 (54.1, 100)	NR	Open	
(Yang 2023)	N=5	NR	NR	-	MD=44.28 (9.36, 79.19)	NR	Laparoscopy	93%
(Yao 2023)	N=8	1350	1333	-	MD=27.32 (12.29, 42.35)	P=0.0004	Laparoscopy	95%
(Zheng 2023)		2413	11751	-	MD=50.87 (41.66, 60.09)	P<0.00001	Laparoscopy	91%
(Zheng 2023)		757	3318	-	MD=46.62 (30.96, 62.29)	P<0.00001	Laparoscopy	91%

CI confidence interval; ISR=intersphincteric resection; LRC laparoscopic right hemicolectomy; MD mean difference; NOTES Natural orifice transluminal endoscopic surgery; NR not reported; NS not significant; OR odds ratio; ORH right hemicolectomy; RCT randomised controlled study; RRC right colectomy; RRH robotic right hemicolectomy; SMD Standardized mean difference; TLRH total laparoscopic right hemicolectomy

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I2**
		Robot	Laparoscopy	Open				
Estimated blood loss (ml)								
(Eltair 2020)	RCTs, n=4	311	324	-	MD=19.65 (− 94.27, 133.57)	P=0.74	NS	94%

(Gavriilidis 2020)	n=16	3,210		-	MD=10.48 (15.50, 36.46)	P=0.43	NS	84%
(Jones 2018)	n=18	1,393	1,609	-	SMD=-0.10 (-0.26, 0.05)	P=0.20	NS	74%
(Lee 2018)	n=5	273	237	-	MD=-19.50 (− 33.5, - 5.49)	p = 0.006	Robot	23%
(Li 2019)	n=3	116	134	-	MD=-7.47 (-95.19, 80.24)	P = .87	NS	83%
(Li 2017)	n=11	NR	NR	-	MD=12.45 (-48.66, 23.76)	P=.500	NS	75.9%
(Ng 2019)	RCT, n=2 nRCT, n=35	209 4299			MD=87.93 (- 128.62, 304.49) MD=-25.23 (- 38.88, - 11.57)	P=0.43 P <0.001	NS Robot	98% 85%
(Ohtani 2018)	n=15	1143	1355		MD=-9.29 (-32.82, 14.24)	P=0.44	NS	85%
(Rausa 2019)	NR	414	1324	1067	RRH vs TLRH RR=0.4 (- 28.0, 28.0). RRH vs ORH RR=42.0 (10.0, 72.0)	NR	NS Open	89%.
(Ryan 2021)	NR	NR	NR	NR	Open vs LS MD=106 (63.3, 150) RAS vs LS MD=-30.6 (-12.4, 65.5)	NR	Laparoscopy NS	NR
(Sheng 2018)	NR	NR	NR	NR	RAS vs Open MD=-97.55 (-260.39, 68.03) RAS vs LS MD=-21.12 (-175.07, 133.17)	NR	NS	NR
(Simillis 2019)	NR	NR	NR	NR	RAS vs Open MD=-87.09 (-100.23, -73.95) RAS vs LS MD=-29.07 (-43.87, -14.27)	NR	**Robot** **Robot**	NR
(Sun 2019)	n=3	340	381	-	MD=26.82 (-7.39, 61.03)	P=0.12	NS	0%
(Wang 2020)	n=15	NR	NR	-	SMD = -0.08 (-0.31, 0.15)	NR	NS	84.6%
(Xu 2017)	n=5	253	204		MD=−41.15(−77.51, −4.79)	P=0.03	**Robot**	84%
(Ma 2019)	n=8	234	460		RRC vs LRC MD=-16.89 (-24.80, -8.89)	P<0.0001	**Robot**	35%
(Butterworth 2021)	NR	1873	611	-	MD=-45.2 (-113.5, 23.1)	P=0.194	NS	NR
(Genova 2021)	N=2	123	141	-	LS vs RAS MD=1.75(-21.69, 25.59)	P=0.87	NS	0%
(Safiejko 2021)	N=24	NR	NR	-	MD= -0.94 (-30.11, 28.22)	P=0.95	NS	98%
(Zang 2021)	N=5	273	237	-	MD= -23.31 (-41.98, -4.64)	P=0.01	**Robot**	24%
(Zhu 2021)	N=5	194	260	-	MD= -13.43 (-20.65, -6.21)	P=0.0003	**Robot**	33%
(Solaini 2022)	N=3	118	293	-	MD= -19.77 (-39.10, -0.43)	NR	**Robot**	79%
(Tschann 2022)	NR	NR	NR	-	LS vs RAS	P=0.02	**Robot**	65%

					MD= 10.03 (1.61,18.45)			
(Huang 2023)	N=7	1098	1098	-	MD=-19.29 (-33.24, -5.35)	P=0.007	**Robot**	97%
(Yang 2023)	N=2	NR	NR	-	MD= -33.72 (-205.06, 137.63)		NS	89%
(Yao 2023)	N=7	1336	1268	-	MD= -15.72 (-23.18, -8.26)	P<0.0001	**Robot**	86%
(Zheng 2023)	NR	996	1720	-	MD= -9.48 (-20.56, 1.61)	P=0.09	NS	76%
(Zheng 2023)	NR	537	954	-	MD= -2.04 (-27.40, 23.33)	P=0.88	NS	91%
(Zheng 2023)	NR	590	3115	-	MD= -0.74 (-1.33, -0.16)	P=0.01	**Robot**	60%

CI confidence interval; LRC laparoscopic right hemicolectomy; MD mean difference; NR not reported; NS not significant; OR odds ratio; ORH right hemicolectomy; RCT randomised controlled study; RRC right colectomy; RRH robotic right hemicolectomy; SMD Standardized mean difference; TLRH total laparoscopic right hemicolectomy

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Conversion to open procedure (%)								
(Li 2017)	n=12				OR=0.35 (0.19–0.62)	P<0.001	**Robot**	0.0%
(Xu 2017)	n=8	3/467	29/443	-	RD=−0.05 (−0.09, −0.01)	P=0.02	**Robot**	63%
(Jones 2018)	n=24	56/2,379	169/ 2,582		OR= 0.40 (0.29, 0.55)	P<0.00001	**Robot**	0%
(Ohtani 2018)	n=21	27/1864	139/2015	-	OR=0.30 (0.19, 0,46)	P<0.00001	**Robot**	0%
(Pezzolla 2018)	RCTs, n=4	20/273	35/271		RR=0.58 (0.35–0.97)	P=0.04	**Robot**	0%
(Lee 2018)	n=2	2/153	8/143		RR 0.22 (0.05, 0.97)	p = 0.04	**Robot**	0%,
(Huang 2019)	RCT n=7	23/402	49 /412		LS vs RAS OR= 2.215 (1.357, 3.613)	P<0.001	**Robot**	NR
(Ma 2019)	n=9	8/336	26/464	-	RRC vs LRC OR=0.34 (0.15, 0.75)	P=0.008	**Robot**	0%
(Ng 2019)	NCT, n=5 nRCT, n=58	765 145,378	NR	=	OR=0.40 (0.30, 0.53)	P<0.001	**Robot**	65%
(Phan 2019)	n=11	6.7%	14.5%	-	OR=0.38 (0.30, 0.46)	P=0.472	**Robot**	0%
(Li 2019)	n=6	433	441	-	OR: 0.29 (0.09, 0.96)	P = .04	**Robot**	47%
(Rausa 2019)	NR	414	1324	1067	RRH vs TLRH RR=1.7 (0.53, 5.9)	NR	NS	23%
(Simillis 2019)	NR	NR	NR	NR	RAS vs LS RR=0.19 (0, 2228.24)	NR	NS	NR

(Sun 2019)	n=6	22/818	41/851	NR	OR=0.55 (0.33,0.93)	P=0.003	**Robot**	26%
(Eltair 2020)	RCTs, n=7	23/484	55/493	-	RR=0.46 (0.18,1.01)	P=0.05	NS	32%
(Gavriilidis 2020)	nRCT=7 RCT=3	29/1,725 20/320	113/1,656 30/319		OR = 0.26 (0.17, 0.38) OR =0.63 (0.35, 1.13)	P<0.001 P<0.12	**Robot** NS	0%
(Wang 2020)	n=17	NR	NR	-	OR=0.55 (0.44, 0.69)	NR	**Robot**	50.3%
(Butterworth 2021)		3654	1226	-	MD=− 0.003 (− 0.014 to 0.011)	P=0.908	NS	
(Genova 2021)	N=8	11/735	31/656	-	LS vs RAS OR=2.57 (0.85, 7.81)	P=0.1	NS	32%
(Safiejko 2021)	N=30	76/2917	236/3255	-	OR=0.35 (0.26, 0.46)	P<0.001	**Robot**	0%
(Tang 2021)	N=6	24/436	34/450	-	OR=0.61 (0.35, 1.07)	P=0.08	NS	0%
(Zang 2021)	N=2	2/153	8/143		RR=0.23 (0.05, 1.12)	P=0.07	NS	0%
(Zhu 2021)	N=9	15/488	58/598	-	OR=0.30 (0.17, 0.54)	P<0.0001	**Robot**	43%
(Bianchi 2022)	N=3	6/364	1338/9678	-	OR=0.17 (0.04, 0.82)	P=0.03	**Robot**	38%
(Solaini 2022)	N=9	908/13281	5016/38777	-	RR=0.53 (0.50, 0.57)	NR	**Robot**	0%
(Tschann 2022)	NR	94/1534	1155/11629	-	LS vs RAS OR=1.53 (1.08, 2.17)	P=0.02	**Robot**	14%
(Flynn 2023)	NR	95/4381	301/5022	-	OR=0.34 (0.27, 0.43)	P<0.001	**Robot**	0%
(Huang 2023)	N=10	53/1590	96/1583	-	MD=0.55 (0.40, 0.76)	P=0.003	**Robot**	0
(Khajeh 2023)	NR	NR	NR	-	LS vs RAS OR=3.13 (1.87, 5.21)	P<0.0001	**Robot**	0%
(Oweira 2023)	NR	0/269	19/408	-	OR=0.17 (0.04, 0.74)	P=0.02	**Robot**	0%
(Seow 2023)	NR	NR	NR	-	RR=0.23 (0.034, 0.7)	NR	**Robot**	
(Yang 2023)	N=5	NR	NR	-	RR=0.61 (0.31, 1.17)	NR	NS	0%
(Yao 2023)	N=6	20/ 1255	41/1239	-	OR=0.49 (0.29, 0.84)	P=0.009	**Robot**	0%
(Zheng 2023)	NR	71/2179	888/9397	-	OR=0.49 (0.38, 0.64)	P<0.00001	**Robot**	18%
(Zheng 2023)	NR	33/929	141/1470	-	OR=0.30 (0.10, 0.91)	P=0.03	**Robot**	67%

CI confidence interval; LRC laparoscopic right hemicolectomy; MD mean difference; NR not reported; NS not significant; OR odds ratio; ORH right hemicolectomy; RCT randomised controlled study; RRC right colectomy; RRH robotic right hemicolectomy; SMD Standardized mean difference; TLRH total laparoscopic right hemicolectomy

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Length of hospital stay(day)								
(Li 2017a)	n=16	NR	NR	-	MD= 0.69 (1.48, 0.10)	P=.089	NS	82%
(Xu 2017)	n=8	423	420	-	MD=−1.07 (−1.80, −0.33)	*P*=0.005	**Robot**	75%
(Jones 2018)	n=24	2409	2601	-	SMD=-0.15 (-0.27, -0.03)	P=0.01	**Robot**	74%
(Lee 2018)	n=5	273	237	-	MD=- 0.97 (- 2.11, 0.17)	p = 0.10	NS	0%
(Pezzolla 2018)	RCTs, n=4	250	262		MD=-0.61(-2.23, 1.02)	P=0.46	NS	66%
(Sheng 2018)	NR	NR	NR	NR	RAS vs Open MD=-2.90 (-5.85, -0.06) RAS vs LS MD=-0.34 (-2.93, 2.21)	NR	**Robot** NS	NR
(Li 2019)	n=3	330	335	-	MD=-0.51 (-1.92, 0.90)	P = .48	NS	74%
(Huang 2019)	RCT n=6	NR	NR		MD=0.677 (0.332, 1.69)	P=0.188	NS	43%
(Ng 2019)	NCT, n=5 nRCT, n=54	743 149,340			MD= - 0.77 (-1.12, - 0.41) MD= - 0.85 (- 1.69, 0.00)	P<0.001 P=0.05	**Robot**	88%
(Rausa 2019)	NR	414	1324	1067	RRH vs TLRH RR=2.9 (- 0.7, 6.5) RRH vs ORH RR=6.7 (2.9, 10.0).	NR	NS **Robot**	80%
(Rubinkiewicz 2019)	n=6	797	783	-	MD=-0.15 (-0.60, 0.90)	P=0.70	NS	29%
(Ma 2019)	n=10	533	7001	-	RRC vs LRC MD=-0.85 (-1.07, -0.63)	P=0.04	**Robot**	52%
(Simillis 2019)	NR	NR	NR	NR	RAS vs OS MD=-1.49 (-1.70, -1.27) RAS vs LS MD=-0.91 (-1.17, -0.65)	NR	**Robot** **Robot**	NR
(Sun 2019)	n=6	819	855	-	MD=-0.64 (-1.57, 0.29)	P=0.18	NS	54%
(Wang 2020)	n=20	NR	NR	NR	SMD = -0.15 (-0.30, 0.00)	NR	**Robot**	80%
(Eltair 2020)	RCTs, n=8	657	669	-	MD= -0.60 (-1.36,0.16)	P=0.12	NS	66%
(Gavriilidis 2020)	n=3	3,646		-	MD= -1.00 (-2.13, 0.13)	P=0.08	NS	63%
(Hoshino 2021)	RCT n=6 Cohort n=25 CMS n=8	3,460	4,191	-	RR= -0.87 (-1.38, -0.35)	P<0.001	**Robot**	70%

(Ryan 2021)	NR	NR	NR	NR	Open vs LS MD=2.6 (1.5, 3.8) RAS vs LS MD=0.16 (-1.5, 1.9)	NR	Laparoscopy NS	NR
(Butterworth 2021)	NR	3163	1083	-	MD=0.56 (− 0.89, 2.01)	P=0.447	NS	
(Genova 2021)	NR	181	408	-	MD=0.11(-0.73, 0.95)	P=0.79	NS	38%
(Safiejko 2021)	N=34	NR	NR	-	MD= -2.01 (-2.9, -1.11)	P<0.001	**Robot**	99%
(Zhang 2021)	N=5	273	237	-	MD=-1.52 (-2.10, -0.94)	P<0.00001	**Robot**	2%
(Zhu 2021)	N=4	188	254	-	MD= -0.23 (-0.73, 0.28)	P=0.38	NS	0%
(An 2022)	N=2	207	204	-	MD= -1.06 (-1.64, -0.47)	NR	**Robot**	8%
(Bianchi 2022)	N=2	38	64	-	MD= -1.86 (-3.99, 0.26)	P=0.09	NS	0%
(Ravindra 2022)	N=12	872	1101	-	MD= -0.10 (-0.19, -0.01)	P=0.04	**Robot**	0%
(Solaini 2022)	N=9	13378	38955	-	MD= -0.28 (-0.63, 0.06)	NR	NS	89%
(Tschann 2022)	NR	NR	NR	-	LS vs RAS MD=0.84 (0.29, 1.38)	P=0.03	**Robot**	87%
(Flynn 2023)	NR	NR	NR	-	MD=−0.22 (−0.33, −0.11)	P<0.001	**Robot**	99%
(Huang 2023)	N=8	1247	1249	-	MD=-0.96 (-1060, -0.33)	P=0.003	**Robot**	95%
(Khajeh 2023)	NR	NR	NR	-	LS vs RAS MD=-0.00 (-0.55, 0.54)	P=0.99	NS	96%
(Seow 2023)	NR	NR	NR	-	LS vs RAS MD=1.7 (-1.1, 7.4)	NR	NS	NR
(Yang 2023)	N=5	NR	NR		MD= -0.29 (-1.0, 0.51)		NS	0%
(Yao 2023)	N=7	1199	1189		MD= -0.97 (-1.11, -0.83)	P<0.00001	**Robot**	46%
(Zheng 2023)		2246	11548		MD= -0.59 (-0.94, -0.24)	P=0.0009	**Robot**	67%

CI confidence interval; LRC laparoscopic right hemicolectomy; MD mean difference; NR not reported; NS not significant; OR odds ratio; ORH right hemicolectomy; RCT randomised controlled study; RRC right colectomy; RRH robotic right hemicolectomy; SMD Standardized mean difference; TLRH total laparoscopic right hemicolectomy

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy other approach	Open				
Postoperative complications (%)								
(Li 2017)	n=16	1673	1875	-	OR=1.02 (0.82–1.25)	P=.883	NS	23.9%
(Xu 2017)	n=9	64/473	108/476	-	OR=0.58(0.41, 0.83)	P=0.003	**Robot**	0%
(Jones 2018)	n=21	512/ 2,315	607/ 2,518		OR=0.92 (0.75, 1.12)	P=0.40	NS	39%
(Lee 2018)	n=5	61/273	63/237		RR=0.81 (0.59, 1.11)	p = 0.19	NS	0%
(Sheng 2018)	NR	NR	NR	NR	RAS vs Open OR=0.62 (0.21, 1.68) RAS vs LS OR=0.79 (0.28, 2.13)	NR	NS NS	NR
(Li 2019)	n=6	483	483	-	OR=1.08 (0.82, 1.43)	P = .57	NS	17%
(Ohtani 2018)	n=21	410/2005	488/2196		OR=0.93(0.77, 1.14)	P=0.49	NS	27%
(Ma 2019)	n=11	85/402	148/559		RRC vs LRC OR=0.73 (0.52, 1.01)	P=0.05	NS	1%
(Rausa 2019)	NR	414	1324	1067	RR=1.0 (0.6, 1.5)	NR	NS	20%
(Rubinkiewicz 2019)	n=4	47/695	48/742		RR = 1.01(0.60, 1.69)	P=0.98	NS	45%
(Wang 2020)	n=19	NR	NR	-	OR=0.79 (0.65, 0.97)	NR	**Robot**	39%
(Eltair 2020)	RCTs, n=8	657	669	-	RR=0.97 (0.76, 1.24)	P=0.81	NS	23%
(Tang 2021)	n=7	135/ 507	123/516	-	OR=1.18 (0.88, 1.57)	P = 0.27	NS	0%
(Hoshino 2021)	RCT n=6 Cohort n=30 CMS n=9	855/ 3,779	1080/ 4,611	-	RR=0.92 (0.85, 1.00)	P=0.05	NS	6%
(Butterworth 2021)	NR	3880	1387	-	MD=0.054 (− 0.012, 0.0123)	P=0.100	NS	
(Chen 2021)	NR	NR	NR	-	NOTES vs RAS OR = 1.03 (0.63, 1.68)	P=0.989	NS	
(Genova 2021)	N=8	184/735	174/656	-	LS vs RAS OR=1.06 (0.8, 1.40)	P=0.68	NS	0%
(Liu 2021)	N=3	96/543	101/517	-	RR=0.91 (0.71, 1.17)	P=0.45	NS	0%
(Zhang 2021)	N=5	61/273	63/237	-	RR=0.81 (0.59, 1.11)	P=0.20	NS	0%
(Zhu 2021)	N=5	86/383	120/471	-	OR=0.83 (0.60, 1.14)	P=0.25	NS	0%
(An 2022)	N=6	32/199	70/195	-	RR=0.47 (0.30, 0.74)	NR	**Robot**	8%
(Bianchi 2022)	N=3	89/364	2427/ 9678	-	OR= 0.86(0.54, 1.38)	P=0.54	NS	19%

(Solaini 2022)	N=10	2868/1330	9706/38731	-	RR=0.86 (0.83, 0.90)	NR	**Robot**	0%
(Flynn 2023)	NR	1015/3302	1355/3848	-	OR=0.84 (0.76, 0.92)	P=0.0001	**Robot**	47%
(Huang 2023)	N=11	NR	NR	-	RR=3.31 (0.64,0.89)	P=0.009	**Robot**	26%
(Khajeh 2023)	NR	NR	NR	-	LS vs RAS OR=1.11 (0.86, 1.43)	P=0.44	NS	43%
(Yang 2023)	N=5			-	RR=1.15 (0.87, 1.53)		NS	0%
(Zheng 2023)	NR	573/2447	2296/9740	-	OR=0.88 (0.77, 0.99)	P=0.04	**Robot**	15%
(Zheng 2023)	NR	245/1027	381/1631	-	OR=1.01 (0.83, 1.24)	P=0.89	NS	0%

CI confidence interval; LRC laparoscopic right hemicolectomy; MD mean difference; NR not reported; NS not significant; OR odds ratio; ORH right hemicolectomy; RCT randomised controlled study; RRC right colectomy; RRH robotic right hemicolectomy; MD mean difference; TLRH total laparoscopic right hemicolectomy

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Time to first flatus (days)								
(Li 2017a)	n=8	NR	NR	NR	MD= -0.11 (-0.26, 0.03)	P-0.13	NS	46%
(Xu 2017)	n=6	390	377		MD= −0.03 (-0.40, 0.34)	P=0.89	NS	73%
(Jones 2018)	n=13	85	86		SMD= -0.48 (-0.79, -0.18)	P=0.002	**Robot**	0%
(Lee 2018)	NR	NR	NR	NR	MD= −0.23 (-0.75, 0.29)	P=0.38	NS	0%
(Li 2019)	n=3	291			MD= −0.06 (−0.35, 0.22)	P=0.66	NS	
(Simillis 2019)	NR	NR	NR	NR	RAS vs Open MD= -1.7 (-3.34, -0.05) RAS vs LS MD= -0.61 (-2.71, 1.5)	NR	**Robot** NS	NR
(Eltair 2020)	n=4	338	344		MD= -0.30 (-0.96, 0.36)	P=0.37	NS	92%
(Genova 2021)	N=4	74	146		MD=0.47 (-0.14, 1.83)	P=0.13	NS	83%
(Ryan 2021)					MD= -0.095 (-0.68, 0.50)	NR	NS	
(Safiejko 2021)	N=13				MD= -0.34 (-0.5, -0.03)	P=0.03	**Robot**	85%
(Zang 2021)	N=2	76	68		MD= -0.21 (-0.75, 0.33)	P=0.44	NS	0%
(Zhu 2021)	N=4	178	224		MD= -0.37 (-1.09, 0.36)	P=0.32	NS	83%
(Ravindra 2022)	N=7	466	655		MD= -0.03 (-0.15, 0.09)	P=0.62	NS	9%
(Tschann 2022)					LS vs RAS	P=0.38	NS	93%

					MD= 0.15 (-0.18, 0.48)			
(Huang 2023)	N=7	996	1004		MD=-0.18 (-0.59, 0.23)	P=0.38	NS	99%
(Yang 2023)	N=2				MD=0.2 (-0.20, 0.61)		NS	0%
(Yao 2023)	N=4	935	923		MD= -0.16 (-0.25, -0.06)	P=0.001	**Robot**	0%
(Zheng 2023)		1330	1508		MD= -0.48 (-0.78, -0.19)	P=0.001	**Robot**	93%

CI confidence interval; MD mean difference; NR not reported; NS not significant; MD Mean difference;

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Time to soft diet								
(Eltair 2020)	n=3	165	167		MD= -0.50 (-0.94, -0.06)	P=0.03	**Robot**	33%
(Gavriilidis 2020)	n=11	2107			MD = -0.22 (-0.92, 0.49)	P=0.55	NS	95%
(Lee 2018)					MD= −0.09 (-0.55, 0.36)	P=0.69	NS	0%
(Ng 2019)	nRCTs=19 RCT=3	2108 265			MD= - 0.43 (- 0.68, - 0.19) MD= - 0.30 (- 0.70, 0.11)	P<0.001 P=0.15	**Robot** NS	NP
(Simillis 2019)	NR	NR	NR	NR	RAS vs Open MD= -0.68 (-2.52, 1.16) RAS vs LS MD= -0.01 (-1.90, 1.88)	NR	NS NS	NR

CI confidence interval; MD mean difference; NR not reported; NS not significant; RCT randomised controlled study; MD Mean difference;

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy or other	Open				
Ileus								
(Genova 2021)	N=5	7/160	35/385		LS vs RAS OR=1.64 (0.69, 3.89)	P=0.27	NS	2%
(Kowalewski 2021)	N=34	4525	16927		OR=0.86 (0.75, 0.98)	P=0.02	**Robot**	0%
(Ryan 2021)					RR=0.64 (0.30, 1.3)	NR	NS	

(Safiejko 2021)	N=19	787/6363	1221/8637		OR=0.94 (0.77, 1.14)	P=0.51		11%
(Tang 2021)	N=4	23/353	35/368		OR=0.66 (0.38, 1.15)	P=0.14	NS	0%
(Zhang 2021)	N=3	13/197	11/169		RR=0.90 (0.41, 1.77)	P=0.80	NS	0%
(Ravindra 2022)	N=8	14/301	20/447		RR=1.04 (0.56, 1.91)	P=0.91	NS	7%
(Solaini 2022)	N=8	915/13206	3652/38593		RR=0.97 (0.65, 1.14)	NR	NS	37%
(Tschann 2022)		70/1209	70/1209		LS vs RAS OR=1.30 (0.91, 1.87)	P=0.14	NS	18%
(Yao 2023)	N=5	24/924	27/915		OR=0.80 (0.46, 1.41)	P=0.44	NS	0%
(Zheng 2023)		92/1581	1012/10887		OR=0.80 (0.63, 1.10)	P=0.07	NS	20%
(Zheng 2023)		34/583	270/2972		OR=0.91 (0.60, 1.39)	P=0.66	NS	0%

CI confidence interval; MD mean difference; NR not reported; NS not significant; OR odds ratio;

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy or other	Open				
urinary retention/ urinary complications								
(Kowalewski 2021)	N=19	1832	2580		OR=0.66 (0.47, 0.94)	P=0.02	**Robot**	0%
(Wee 2021)	N=21	108/ 2231	152/2208		RR=0.78 (0.61, 0.99)	P=0.04	**Robot**	3%
(Zhang 2021)	N=5	7/273	20/237		RR=0.36 (0.16, 0.82)	P=0.02	**Robot**	0%
(Yao 2023)	N=6	28/1125	58/1125		OR=0.45 (0.29, 0.71)	P=0.0006	**Robot**	0%

CI confidence interval; MD mean difference; NR not reported; NS not significant; OR odds ratio;

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Re-operation (%)								
(Li 2017)	n=8	NR	NR	NR	OR=0.66 (0.41, 1.05)	P=0.80	NS	0%
(Jones 2018)	n=10	43/509	65/618		OR=0.76 (0.50, 1.16)	P=0.20	NS	0%
(Simillis 2019)	NR	NR	NR	NR	RAS vs Open OR=1.08 (0.11, 10.11)	NR	NS NS	NR

					RAS vs LS OR=1.1 (0.12–10.47)			
(Genova 2021)	N=15	20/803	13/3588		LS vs RAS OR=1.30 (0.71, 2.37)	P=0.4	NS	0%
(Liu 2021)	N=5	18/478	25/541		RR=0.85 (0.46, 1.54)	P=0.58	NS	0%
(Ryan 2021)					RR=0.32 (0.039, 1.6)	NR	NS	
(Safiejko 2021)		67/1061	80/1120		OR=0.87 (0.61, 1.25)	P=0.46	NS	0%
(Tang 2021)	N=4	2/181	5/198		OR=0.59 (0.16, 2.21)	P=0.44	NS	0%
(Zhu 2021)	N=3	233	288		OR=1.66 (0.67, 4.10)	P=0.27	NS	0%
(Huang 2023)	N=4	20/616	36/817		RR=0.56 (0.33, 0.96)	P=0.03	NS	0%
(Khajeh 2023)					LS vs RAS OR=1.69 (1.10, 2.62)	P=0.02	**Robot**	0%
(Yao 2023)	N=3	22/836	29/786		OR=0.71 (0.40, 1.25)	P=0.23	NS	0%

CI confidence interval; RR relative risk; OR odds ratio; NR not reported; NS not significant

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy or other	Open				
Readmission(%)								
(Genova 2021)	N=12	42/1072	539/7619		LS vs RAS OR=1.02 (0.55, 1.90)	P=0.95	NS	38%
(Liu 2021)	N=4	252/2730	441/5502		RR= 1.17 (0.75, 1.83)	P=0.48	NS	57%
(Safiejko 2021)	N=11	91/882	203/2066		OR=1.14 (0.82, 1.60)	P=0.44	NS	6%
(Ravindra 2022)	N=7	18/327	24/470		RR=0.89 (0.50, 1.60)	P=0.70	NS	6%
(Huang 2023)	N=4	23/816	34/817		RR=0.68 (0.41, 1.14)	P=0.15	NS	4%
(Yao 2023)	N=3	27/870	28/859		OR=0.95 (0.56, 1.63)	P=0.86	NS	0%

CI confidence interval; RR relative risk; OR odds ratio; NR not reported; NS not significant

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				

Positive circumferential resection margins (%)								
(Xu 2017)	n=6	20/426	24/368		RD= −0.02(−0.05, 0.01)	*P*=0.23	NS	34%
(Li 2017a)	n=13	NR	NR		OR=0.80 (0.55–1.17)	P=.256	NS	0%
(Lee 2018)	n=3	190	172		MD=-0.39 (-2.37, 1.59)	p = 0.70	NS	0%
(Jones 2018)	n=23	91/2344	1111/ 2537		OR= 0.91 (0.68, 1.22)	P= 0.53	NS	0%
(Pezzolla 2018)	RCTs, n=2	12/248	14/241		RR=0.82 (0.38, 1.73)	P=0.6	NS	-
(Huang 2019)	n=2	16/ 300	18/ 296		LS vs RAS RR=1.139 (0.592, 2.191)	P= 0.697	NS	0%
(Li 2019)	n=5	23/407	32/415		OR: 0.71 (0.41, 1.59)	P = .24	NS	0%
(Simillis 2019)	NR	NR	NR	NR	RAS vs Open OR=0.78 (0.40, 1.53) RAS vs LS OR=0.70 (0.34 1.45)	NR	NS	NR
(Sun 2019)	n=4	61/770	94/792	-	OR=0.86 (0.56, 1.32)	P=0.49	NS	0%
(Wang 2020)	n=14	NR	NR	-	OR=1.02 (0.76, 1.37)	NR	NS	0%
(Eltair 2020)	n=3	21/547	26/549		RR=0.82 (0.47, 1.44)	P=0.49	NS	0%
(Qiu 2020)	n=7	2593			MD= 0.98(0.63, 1.51)	P= 0.92	NS	0%
(Ryan 2021)					Open vs LS RR=0.8 (0.56, 1.14) RAS vs LS RR=0.7 (0.36, 1.39)	NR	NS	NR
(Guo 2021)	n=12	1067	-	1522	OR: 0.58 (0.29, 1.16)	P=0.13	NS	53%
(Butterworth 2021)		3736	1124		MD= 0.52 (0.14, 0.89)	P=0.007	**Robot**	
(Chen 2021)					NOTES vs RAS OR= 1.43 (0.76, 2.71)	P=0.333	NS	
(Genova 2021)	N=6	4/522	24/2760		LS vs RAS OR=0.73 (0.18, 2.93)	P=0.66	NS	0%
(Safiejko 2021)	N=7				MD=0.30 (-0.25, 0.86)	P=0.28	NS	66%
(Zang 2021)	N=4	12/167	14/131		RR=0.65 (0.31, 1.36)	P=0.25	NS	0%
(Khajeh 2023)					OR=1.56 (1.11, 2.20)	P=0.010	LS	0%
(Yang 2023)	N=2				RR= 1.18 (0.75, 1.87)		NS	33%

CI confidence interval; LRC laparoscopic right hemicolectomy; MD mean difference; NR not reported; NS not significant; OR odds ratio; ORH right hemicolectomy; RCT randomised controlled study; RD risk difference; RRC right colectomy; RRH robotic right hemicolectomy; MD Mean difference; TLRH total laparoscopic right hemicolectomy

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Distal resection margin (cm)								
(Li 2017)	n=8	NR	NR		MD=1.98 (1.25, 5.22)	P=0.229	NS	68%
(Jones 2018)	n=19	1906	2017		SMD=0.00 (-0.11, 0.11)	P=0.97	NS	56%
(Lee 2018)	n=5	273	237		MD=0.01 (-0.16, 0.18)	P=0.92	NS	0%
(Li 2019)	n=4	172	185		MD=0.60 (0.09, 1.10)	P =0.02	**Robot**	66%
(Huang 2019)	n=4	NR	NR		LS vs RAS MD=-0.581 (-1.165, 0.003)	P=0.051	NS	60 %
(Simillis 2019)	NR	NR	NR	NR	RAS vs Open MD=0.76 (0.38,1.14) RAS vs LS MD=0.68 (0.29, 1.07)	NR	**Robot**	NR
(Eltair 2020)	n=5	222	233		MD=0.80 (0.26, 1.34)	P=0.004	NS	75%
(Wang 2020)	n=14	NR	NR	-	SMD=0.13 (-0.08, 0.35)	NR	NS	80.0%
(Guo 2021)	n=6	284		361	MD: -0.49(−1.04, 0.06)	P=0.08	NS	72%
(Qiu 2020)	n=5	1899			MD=1.17 (-2.42, 4.76)	P=0.52	NS	65%
(Ryan 2021)	NR	NR	NR	NR	LS vs Open MD=0.13 (-0.76, 0.95) RAS vs Open MD=-0.32 (-2.86, 1.96)	NR	NS	NR
(Tang 2021)	n=4	170	179	-	MD=0.13 (− 0.04, 0.30)	P =0.13	NS	0%
(Butterworth 2021)		3065	688		MD= 0.52 (0.14 to 0.89)	P=0.007	**Robot**	
(Safiejko 2021)	N=20				MD= -0.22 (-0.32, -0.11)	P<0.001	Laparoscopy	87%
(Zang 2021)	N=5	273	237		MD= 0.01(-0.16, 0.18)	P=0.88	NS	0%
(Huang 2023)					MD=2.16 (0.04,0.94)	P=0.03	**Robot**	92%
(Seow 2023)					RAS vs OS MD=0.93 (0.66, 1.2)		**Robot**	

CI confidence interval; CMS case-matched study; MD mean difference; NR not reported; NS not significant; RCT randomised controlled study; MD Mean difference

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Number of harvested lymph nodes								
(Li 2017a)	n=12	NR	NR	-	MD=0.49, (0.98, 1.96)	P=.515	NS	64.2%
(Lee 2018)	n=5	273	237		MD=- 1.36 (- 2.88, - 0.15)	p = 0.08	**Robot**	30%
(Jones 2018)	n=26	2342	2600		SMD=0.04 (-0.07, 0.14)	P=0.49	NS	64%
(Pezzolla 2018)	RCTs, n=5	344	350	-	MD=-0.35 (-1.83, 1.12)	P=0.84	NS	0%
(Huang 2019)	n=6	NR	NR		LS vs RAS MD=-0.154 (-1.398, 1.090)	P=0 .808	NS	11%
(Li 2019)	n=5	243	251	-	MD: 0.08 (-0.88, 1.04)	P = .87	NS	0%
(Rausa 2019)	NR	414	1324	1067	RRH vs TLRH RR=−2.2 (-6.5, 2.1) RRH vs ORH RR=-2.8 (-7.3, 1.7)	NR	NS	80%
(Simillis 2019)	NR	NR	NR	NR	RAS vs Open MD=0.48 (-0.96, 1.91) RAS vs LS MD=0.27 (-1.3, 1.84)	NR	NS	NR
(Sun 2019)	n=6	818	851	-	MD=-0.90 (-1.82, 0.02)	P=0.05	NS	0%
(Eltair 2020)	n=8	705	709		MD=0.33(-0.84, 1.49)	P=0.58	NS	56%
(Wang 2020)	n=19	NR	NR	-	SMD=0.06 (-0.05, 0.17)	NR	NS	54%
(Qiu 2020)	n=7	2593			MD=0.03 (-2.13, 2.19)	P=0.98	NS	87%
(Tang 2021)	n=7	507	516	-	MD = 0.47 (−0.41, 1.35)	P = 0.29	NS	45%
(Guo 2021)	n=12	917	-	1409	MD=-0.31(-2.16, 1.53)	P=0.74	NS	81%,
(Ryan 2021)	NR	NR	NR	NR	Open vs LS MD=0.18 (-0.71, 1.1) RAS vs LS MD=0.08 (-1.5, 1.7)	NR	NS	NR
(Butterworth 2021)		3161	1223		MD=0.25 (− 2.63, 3.13)	P=0.866	NS	
(Genova 2021)	N=6	147	356		LS vs RAS MD=-3.80 (-7.56, -0.05)	P=0.05	Laparoscopy	0%
(Safiejko 2021)	N=34				MD= -0.05 (-1.06, 0.96)	P=0.92	NS	85%
(Zang 2021)	N=5	273	237		MD= -1.83 (-3.7, 0.04)	P=0.06	NS	30%

(Zhu 2021)	N=7	344	402		MD=1.47 (-0.00, 2.94)	P=0.05	NS	0%
(Tschann 2022)					LS vs RAS MD=-0.85 (-2.19, 0.48)	P=0.21	NS	75%
(Huang 2023)	N=9	1391	1389		MD=0.61 (-0.09, 1.31)	P=0.09	NS	79%
(Khajeh 2023)					MD=0.38 (-0.39, 1.16)	P=0.33	NS	59%
(Kim 2023)	N=4				MD=− 1.20 (− 3.94, 1.54)	P=0.39	NS	13%
(Seow 2023)					RAS vs OS MD=1.2 (-0.3, 2.9)		NS	
(Yao 2023)	N=8	1350	1333		MD=1.10 (0.34, 1.85)	P=0.004	Laparoscopy	87%
(Zheng 2023)		2153	5286		MD= 1.89 (0.72, 3.06)	P=0.002	Laparoscopy	72%
(Zheng 2023)		1116	4036		MD=1.47 (-0.32, 3.26)	P=0.11	NS	83%

CI confidence interval; LRC laparoscopic right hemicolectomy; MD mean difference; NR not reported; NS not significant; OR odds ratio; ORH right hemicolectomy; RCT randomised controlled study; RD risk difference; RRC right colectomy; RRH robotic right hemicolectomy; SMD Standardized mean difference; TLRH total laparoscopic right hemicolectomy

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Disease free survival								
(Lee 2018) (3 year)		167/197	145/169		RR 1.00 (0.92, 1.09)	P=0.97	NS	0%
(Qiu 2020) (3 year)	n=7	2593			HR=0.93 (0.79, 1.10)	P=0.40	NS	0%
(Gavriilidis 2020) (3 year)	N=6	6, 1315			HR = 0.94 (0.72, 1.23)	P=0.65	NS	7%
(Ryan 2021) (3 year)	NR	NR	NR	NR	Open vs LS HR=1.0 (0.91, 1.1) RAS vs LS HR=1.0 (0.66, 1.6)	NR	NS	NR
(Tschann 2022) (5 years)		162/190	178/213		LS vs RAS OR= 0.87 (0.50, 1.51)	P=0.62	NS	0%
(Flynn 2023) (3 year)		350/1500	371/1473		OR=0.94 (0.83, 1.08)	P=0.386	NS	23%
(Kim 2023)	NR	NR	NR	NR	HR=0.72 (0.46, 1.13)	P=0.15	NS	0%
(Seow 2023) (3 year)	NR	NR	NR	NR	RAS vs OS HR=0.97 (0.56, 1.6)		NS	

CI confidence interval; NR not reported; NS not significant; RCT randomised controlled study; RR relative risk; OR odds ratio; HR hazard ratio

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Overall survival								
(Li 2017) (3 year)	n=3	NR	NR		OR=0.71 (0.44, 1.12)	P=1.140	NS	0%, p = 0.652
(Lee 2018) (3 year)		18/273	20/237	-	RR=0.74, (0.41–1.35)	p =0.32	NS	0%, p = 0.51
(Ohtani 2018) (3 year)	n=3	611/654	552/ 587		OR= 0.92 (0.58, 1.46)	P=0.74	NS	0%, p = 0.65
(Gavriilidis 2020) (3 year)	n=6	6, 1681			HR=1.03 (0.80, 1.32)	P=0.83	NS	0%
(Qiu 2020) (3 year)	n=7	2593			HR=0.94 (0.64, 1.39)	P=0.75	NS	51%, P=0.06
(Ryan 2021) (3 year)	NR	NR	NR	NR	Open vs LS HR=0.96 (0.85, 1.1) RAS vs LS HR=1.0 (0.65, 1.7)	NR	NS	NR
(Tschann 2022) (5 year)	NR	157/190	172/213	NR	LS vs RAS OR= 0.90 (0.54, 1.52)	P=0.70	NS	0%
(Flynn 2023) (3 year)	NR	160/1890	206/1838	NR	OR=0.79 (0.65, 0.97)	P=0.03	**Robot**	60%
(Kim 2023)	NR	NR	NR	NR	HR=0.73 (0.48, 1.13)	P = 0.16	NS	0%
(Seow 2023) (3 year)	NR	NR	NR	NR	RAS vs OS HR=1.1 (0.73, 1.5)		NS	NR

CI confidence interval; NR not reported; NS not significant; RCT randomised controlled study; RR relative risk; OR odds ratio; HR hazard ratio

Table A3-2 Clinical Effectiveness of Hysterectomy

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Operative time (min)								
(Laios 2017)	n=27	2142	2522	-	MD=16.42 (−0.04, 32.88)	P=0.05	NS	97%
(Li 2017)	n=11 n=10	296 335	 344	307	RAS vs Open MD=39.71 (-6.69, 86.11) RAS vs LS MD=11.78 (7.09, 16.48)	P=0.09 P<0.00001	NS Laparoscopy	99% 92%
(Park 2017)	n=12	NR	NR	NR	RAS vs Open MD=16.76 (-11.87, 45.38) RAS vs LS MD=24.90 (-78.96, 29.16)	NR	NS NS	95% 97%
(Jin 2018)	NR	NR	NR	NR	RAS vs Open MD=24.24 (-24.44, 69.02) RAS vs LS MD= 7.29 (-40.40, 54.25)	NR	NS NS	NR
(Lawrie 2019)	n=2	73	75		MD= 41.18 (-6.17, 88.53)	P=0.09	NS	80.06%
(Shi 2019)	n=5	151 104	 90	259	RAS vs Open MD= 9.8527 (− 57.09, 76.80) RAS vs LS MD= − 0.856 (−46.37, 44.66)	P= 0.7730 P=0.9706	NS NS	93.3 70%
(Zhang 2019)	n=6 n=9	640 305	 373	610 -	RAS vs Open MD=36.07 (5.83, 66.31) RAS vs LS MD=18.30 (-14.94, 51.13)	P=0.02 P=0.28	Open NS	95% 93%
(Wang 2020)	n=18 n=21	1635 1664	 1996	2249	RAS vs Open MD=28.97 (7.60,50.35) RAS vs LS MD= 19.87 (0.60, 39.15)	P=0.08 P = 0.04	Open Laparoscopy	99% 99%
(Kampers 2022)	N=5 N=4	139 398	204 359		LS vs RAS MD= -61.48 (-67.04, -55.92)		Laparoscopy Open	

					RAS vs OS MD= 44.79 (38.16, 51.42)			
(Hunag 2023)	N=4	394	560		MD=13.01 (-41.38, 67.41)	P=0.64	NS	98%
(Lenfant 2023)		28042 21880 23255	91839 56822	 145890	RAS vs LS MD=7.97 (-11.76, 27.69) RAS vs OS MD= -0.98 (-6.74, 4.78) RAS vs NOTES MD=42.87 (22.94, 62.80)	P=0.79 P=0.74 P<0.001	NS NS NOTES	99% 0% 100%
(Marchand 2023)		1823		1829	MD=15.34 (2.21, 28.47)	P=0.02	Open	96%
(Marchand 2023)		1217	1480		LS vs RAS MD=6.01 (-4.64, 16.66)	P-0.27	NS	92%

CI confidence interval; MD mean difference; NR not reported; NS not significant; NOTES Natural orifice transluminal endoscopic surgery

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Estimated blood loss (ml)								
(Laios 2017)	n=28	2394	2721		MD=−57.74 (−77.20, −38.27)	P<0.00001	**Robot**	89%
(Li 2017)	n=7 n=10	215 335	 344	214	RAS vs Open MD=-1.83 (-2.06, -1.59) RAS vs LS MD=51.97 (49.07, 54.87)	P<0.00001 P<0.00001	**Robot** Laparoscopy	74% 98%
(Park 2017)	n=8 n=6	NR	NR	NR	RAS vs Open MD=-409.04 (-551.97, -266.11) RAS vs LS MD=-78.08 (-192.08, 35.92)	NR	**Robot** NS	94% 96%
(Jin 2018)	NR	NR	NR	NR	RAS vs Open MD =-399.52 (-600.64, -204.78) RAS vs LS MD= -122.38 (-319.98, 71.19)	NR	**Robot** NS	NR
(Lawrie 2019)	n=1	47	48		MD=7(-18.26, 32.26)	P=0.59	NS	NA
(Shi 2019)	n=6	125		274	RAS vs Open	P=0.0004	**Robot**	94%

	n=5	96	79		MD=-521 (-809.78, -233.62) RAS vs LS MD=-55.09 (139.01, 28.83)	P=0.1983	NS	55%
(Zhang 2019)	n=5 n=8	460 283	 357	640 -	RAS vs Open MD=-322.59 (-502.75, -142.43) RAS vs LS MD=-22.25 (-81.38, 36.87)	P=0.0004 P=0.46	**Robot** NS	98% 89%
(Prodromidou 2020)	n=5	125	162	-	MD=-10.84 (-20.35, -1.43)	P=0.03	**Robot**	55%
(Wang 2020)	n=17 n=19	1607 1596	 1856	2263	RAS vs Open MD=-147.02 (-185.72, -108.31) RAS vs LS MD=-53.66 (-74.86, -32.47)	P < 0.00001 P < 0.00001	**Robot** **Robot**	97% 91%
(Kampers 2022)	N=5 N=4	139 398	204	 359	LS vs RAS MD= -61.10 (-64.16, -58.04) RAS vs OS MD= -287.14 (-329.99, -181.23)	P<0.01	Laparoscopy **Robot**	
(Hunag 2023)	N=6	394	560		MD= -77.69 (-132.08, -23.30)	P=0.005	**Robot**	71%
(Lenfant 2023)		2525 1099 2474	2292 4187	 7579	RAS vs LS MD= -52.31, (-98.17, -6.45) RAS vs OS MD= -123.01 (-214.83, -176.51) RAS vs NOTES MD= -71.18 (-85.15, -57.20)	P=0.03 P=0.009 P<0.0001	**Robot** **Robot** **Robot**	95% 99% 79%
(Marchand 2023)		1754		1833	MD= -397.75 (-471.65, -324.24)	P<0.00001	**Robot**	94%
(Marchand 2023)		1112	1418		LS vs RAS MD= 35.24 (-0.40, 70.89)	P=0.05	NS	97%

CI confidence interval; MD mean difference; NR not reported; NS not significant; NOTES Natural orifice transluminal endoscopic surgery

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Conversion to laparotomy (%)								
(Laios 2017)	n=68	115/3106	274/3452		RR=0.41 (0.29, 0.59)	P<0.00001	**Robot**	30%
(Park 2017)	n=5	NR	NR	NR	RR 0.23 (0.04, 1.29).	NR	NS	0%
(Cusimano 2019)	n=29 n=14	- 91/1314	173/1826 -	-	LS to Open 6.5% (4.3-9.9) RAS vs Open 5.5% (3.3-9.1)	NR	NR	82% (LS) 79% (RAS)
(Lawrie 2019)	n=3	3/134	3/135		RR=1.17 (0.24, 5.77)	P=0.85	NS	0%
(Wang 2020)	n=14	48/1313	83/1442		RR=0.55 (0.38, 0.81)	P=0.002	**Robot**	29%
(Lenfant 2023)		889/39927 534/24345	6902/127973 222/64741		RAS vs LS RD= -0.037 (-0.064, -0.010) RAS vs NOTES OR= 1.23 (0.05, 33.38)	P=0.008 P=0.9	**Robot** NS	100% 99%

CI confidence interval; MD mean difference; NR not reported; NS not significant; RR relative risk; NOTES Natural orifice transluminal endoscopic surgery; OR odds ratio

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Length of hospital stay(days)								
(Laios 2017)	n=25	2130	2237		MD=−0.46 (−0.66, −0.26)	P<0.00001	**Robot**	85%
(Li 2017)	n=9 n=10	274 335	 344	270	RAS vs Open MD=-3.36 (-3.99, -2.73) RAS vs LS MD=-0.39 (-0.58. -0.21)	P<0.00001 P<0.00001	**Robot** **Robot**	94% 95%
(Park 2017)	n=7 n=6	NR	NR	NR	RAS vs Open MD=-4.33 (-5.96, -2.70) RAS vs LS MD=-1.39 (-2.44, -0.35)	NR	**Robot** **Robot**	96% 89%
(Jin 2018)	NR	NR	NR	NR	RAS vs Open	NR	**Robot**	NR

					MD=-3.49 (-5.79, -1.24) RAS vs LS MD=-0.25 (-2.60, 2.06)		NS	
(Lawrie 2019)	n=2	108	84		MD= -0.3 (-0.53, -0.07)	P=0.01	**Robot**	0%
(Shi 2019)		159 96	 79	274	RAS vs Open MD=−5.22 (−6.15, − 4.30) RAS vs LS MD=−1.43 (−3.53, 0.67)	P< 0.0001 P= 0.1827	**Robot** NS	40.2% 69.4%
(Zhang 2019)	n=6 n=9	482 305	 373	660 -	RAS vs Open MD=-2.71 (-3.74, -1.68) RAS vs LS MD=-0.24 (-1.33, 0.85)	P< 0.00001 P=0.67	**Robot** NS	78% 87%
(Prodromidou 2020)	n=4	119	209		MD=-0.32(-0.44, -0.19)	P<0.00001	**Robot**	0%
(Wang 2020)	n=18 n=21	1635 1594	 1846	2319	RAS vs Open MD=-2.76 (-3.08, -2.43) RAS vs LS MD=-0.35 (-0.54, -0.17)	P< 0.0001 P< 0.0001	**Robot** **Robot**	86% 82%
(Kampers 2022)	N=5 N=4	139 398	204	 359	LS vs RAS MD= 1.07 (0.66, 1.48) RAS vs Open MD=-3.77 (-5.10, -2.44)		**Robot** **Robot**	
(Lenfant 2023)		43054 31152 24217	111454 64582	 162691	RAS vs LS MD= -0.14 (-0.21, -0.08) RAS vs Open MD= -1.31 (-1.85, -0.43) RAS vs NOTES MD= -0.39 (-0.70, -0.08)	P<0.0001 P<0.0001 P=0.01	**Robot** **Robot** **Robot**	95% 100% 99%
(Marchand 2023)		2845		6274	MD= -3.99 (-4.67, -3.31)	P<0.00001	**Robot**	98%
(Marchand 2023)		1244	1640		LS vs RAS MD= 0.80 (0.38, 1.21)	P=0.0002	**Robot**	89%

CI confidence interval; MD mean difference; NR not reported; NS not significant; NOTES Natural orifice transluminal endoscopic surgery

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Postoperative complications (%)								
(Laios 2017)	n=18	4327			RR=0.85 (0.72, 1.02)	NP	NP	NP
(Li 2017)	n=10 n=10	31/284 66/335	 82/344	69/281	RAS vs Open RR=0.34 (0.21, 0.56) RAS vs LS RR=0.63 (0.32, 1.24)	P=0.0001 P=0.18	**Robot** NS	0% 57%
(Park 2017)	n=6	NR	NR	NR	RAS vs Open RR=0.78 (0.42, 1.43) RAS vs LS RR=0.78 (0.49,1.23)	NR	NS NS	0% 50%
(Jin 2018)	NR	NR	NR	NR	RAS vs Open OR= 0.21 (0.08, 0.65) RAS vs LS OR=0.39 (0.14, 1.31)	NR	**Robot** NS	NR
(Lawrie 2019)	n=5	11/58 37/291	 34/242	17/58	RAS vs Open RR= 0.67 (0.35,1.27) RAS vs LS RR= 0.82 (0.42,1.59)	P=0.2 P=0.56	NS NS	0% 51.25%
(Marra 2019)*	N=15 N=11	49/2745 20/500	58/2548 31/785		RAS vs LS for endometrial cancer OR=0.94 (0.55, 1.73) RAS vs LS for cervical cancer OR=1.09 (0.60, 1.97)	P=0.93 P=0.78	NS NS	33% 0%
(Shi 2019)		159 144	 166	274	RAS vs Open RR=0.4710 (0.25, 0.87) RAS vs LS RR=1.45 (0.6502, 3.25)	P= 0.0171 P= 0.3619	**Robot** NS	0% 6%
(Zhang 2019)	n=7 n=9	152/741 47/305	 80/373	187/892	RAS vs Open RR=0.74 (0.45, 1.22) RAS vs LS RR=0.66 (0.39, 1.12)	P=0.24 P=0.13	NS NS	65% 31%
(Hwang 2020)					OR=0.94 (0.64, 1.38)	P=0.767	NS	NR

(Wang 2020)	n=15 n=16	135/1457 115/1372	 155/1669	516/2106	RAS vs Open RR=0.41 (0.33, 0.50) RAS vs LS RR=0.96 (0.76, 1.20)	P<0.00001 P = 0.69	**Robot** NS	49% 13%
(Huang 2023)	N=6	8/491	23/807		OR=0.54 (0.25, 1.19)	P=0.13	NS	0%
(Huang 2023)	N=19				OR=1.27 (0.86, 1.89)	P=0.53	NS	
(Lenfant 2023)		5441/48824 36009/29270 3348/25350	20847/138163 10076/64943	 43640/160920	RAS vs LS OR=0.83 (0.66, 1.05) RAS vs OS OR= 0.42 (0.27, 0.66) RAS vs NOTES OR= 0.75 (0.41, 1.37)	P=0.08 P=0.0001 P=0.22	NS **Robot** NS	95% 98% 96%
(Marchand 2023)		468/2450		1157/5981	OR=0.65 (0.46, 0.91)	P=0.01	**Robot**	73%
(Marchand 2023)		243/1191	250/1633		LS vs RAS OR=0.84 (0.60, 1.17)	P=0.30	NS	50%

CI confidence interval; NR not reported; NS not significant; RR relative risk; OR odds ratio

*infectious complications

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Positive resection margin rate (%)								
(Park 2017)	n=4 n=5	NR	NR	NR	RAS vs Open RR=0.66 (0.22, 1.96) RAS vs LS RR=0.87 (0.29, 2.62)	NR	NS	0% 0%

CI confidence interval; NR not reported; NS not significant; RR relative risk; OR odds ratio

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Retrieved lymph node yield/ pelvic nodes								
(Laios 2017)	n=14	2086			MD=−0.14 (−5.73, 5.46)		NS	
(Li 2017)	n=4 n=5	99 173	 180	97	RAS vs Open MD=-6.66 (-8.19, -5.12) RAS vs LS MD=0.74 (-0.55, 2.03)	P=0.00001 P=0.26	**Robot** NS	93% 89%
(Park 2017)	n=9 n=4	721	 246		RAS vs Open MD=0.56 (-2.76, 3.88) RAS vs LS MD=2.81(-3.68, 9.30)	NS	NS NS	85% 92%
(Jin 2018)	NR	NR	NR	NR	RAS vs Open MD=-2.17 (-5.49, 1.08) RAS vs LS MD= -1.34 (-4.44, 1.89)	NR	NS NS	NR
(Lawrie 2019)	n=1	48		48	RAS vs Open MD=-8 (-14.97, -1.03)	P=0.02	**Robot**	NA
(Shi 2019)		141 78	 58	262	RAS vs Open (pelvic nodes) MD= 0.005 (−1.94, 1.95) RAS vs LS (pelvic nodes) MD=−0.57 (−3.16, 2.03)	P=0.9962 P= 0.6688	NS NS	37% 28%
(Zhang 2019)	n=6 n=9	482 305	 373	659	RAS vs Open MD=-3.43 (-7.74, 0.88) RAS vs LS MD=2.46 (-0.46, 5.38)	P=0.12 P=0.10	NS NS	89% 67%
(Wang 2020)	n=7 n=10	477 774	 961	629	RAS vs Open MD=3.30 (0.06, 6.04) RAS vs LS MD=0.73 (-3.62, 5.08)	P=0.05 P=0.74	Open NS	86% 96%
(Marchand 2023)		2465		4648	MD= -2.64 (-4.12, -1.15)	P=0.0005	**Robot**	86%
(Marchand 2023)		1077	1291		LS vs RAS MD= -1.22 (-3.28, 0.84)	P= 0.25	NS	88%

CI confidence interval; MD mean difference; NR not reported; NS not significant

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Postoperative recurrence (%)								
(Laios 2017)	n=2	453			RR= 0.66 (0.33, 1.34)	NR	NS	NR
(Shi 2019)		73 26	 32	59	RAS vs Open RR=0.85 (0.34, 2.16) RAS vs LS RR=0.24 (0.045, 1.28)	P=0.7332 P= 0.0944	NS NS	42% 25%
(Zhang 2019)	n=5 n=7	58/643 21/237	 26/324	62/677	RAS vs Open OR=0.85(0.58, 1.27) RAS vs LS OR=0.96(0.50, 1.87)	P= 0.43 P=0.91	NS NS	0% 0%
(Hwang 2023)	N=20				OR=1.19 (0.91, 1.55)	P=0.613	NS	0%
(Marchand 2023)		204/ 1884		227/1942	OR= 0.92 (0.75, 1.13)	P=0.44	NS	23%
(Marchand 2023)		56/635	87/841		OR= 1.14 (0.79, 1.64)	P=0.50	NS	0%

CI confidence interval; MD mean difference; NR not reported; NS not significant; RR relative risk; OR odds ratio

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Postoperative mortality (%)								
(Behbehani 2019)		1842	2195		LS vs RAS RR= 1.12 (0.36, 3.51)		NS	0%

CI confidence interval; RD risk difference; NR not reported; NS not significant; RG robotic gastrectomy; LG laparoscopic gastrectomy; OG open gastrectomy

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
3-year disease free survival								
(Lee 2018)		167/197	145/169		RR 1.00 (0.92, 1.09)	P=0.97	NS	0%, P=0.90
(Shi 2019)	NR	60	44		HR=1.69 (0.26, 11.12)	P=0.5850	NS	0%
(Qiu 2020)	n=7	2593			HR=0.93 (0.79, 1.10)	P=0.40	NS	0%, P=92
(Gavriilidis 2020)	N=6	6, 1315			HR = 0.94 (0.72, 1.23)	P=0.65	NS	7%
(Ryan 2021)	NR	NR	NR	NR	Open vs LS HR=1.0 (0.91, 1.1) RAS vs LS HR=1.0 (0.66, 1.6)	NR	NS NS	NR
(Marchand 2023)		1971/2282		1981/2251	OR= .094 (0.77, 1.14)	P=0.51	NS	71%
(Marchand 2023)		493/ 541	635/711		OR= 0.89 (0.59, 1.32)	P=0.55	NS	0%

CI confidence interval; HR hazard ratio; NR not reported; NS not significant.

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Overall survival								
(Shi 2019) (3 year)	NR	107 60	 44	99	RAS vs Open HR=6.44 (1.67, 24.77) RAS vs LS HR= 2.2 (0.08, 57.48)	P=0.0070 P=0.6360	**Robot** NS	0% NA
(Marchand 2023) (5 year)		1188/1316		1113/1264	OR=1.28 (0.66, 2.46)	P=0.46	NS	74%
(Marchand 2023) (5 year)		274/293	369/395		OR= 1.37 (0.51, 3.69)	P=0.53	NS	36%

CI confidence interval; HR hazard ratio; NR not reported; NS not significant.

Table A3-3 Clinical Effectiveness of Hepatopancreaticobiliary surgery

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Operative time (min)								
(Peng 2017)	n=4	132		234	RPD vs OPD MD=114.87 (-34.19, 263.92)	P=0.131	NS	97.2%
(Shin 2017)	n=6	160		294	RPD vs OPD MD=98.58 (37.82, 159.34)		Open	90.8%
(Lauretta 2017)	n=8	228	375		RP vs LP MD=26.91 (-11.83, 65.65)	P=0.17	NS	88%
(Zhao 2018)	n=9 n=4	506 270		1194 1593	RPD vs OPD MD= 88.69 (38.38, 138.99) RP vs OP MD= 36.38 (21.92, 50.8)	P=0.0005 P < 0.00001	Open Open	93% 42%
(Hu 2018)	n=17	NR	NR	NR	RH vs LH MD=44.85 (21.81, 67.9)	P<0.001	Laparoscopy	82.6%
(Guan 2019)	n=13				RH vs LH MD=65.49 (42, 88.98)	P < 0.00001	Laparoscopy	80%
(Gavriilidis 2019)	n=5 n=17				RP vs OP MD = −8.94 (−84, 66) RP vs LP MD = 16.78 (-12, 46)	P=0.82 P= 0.25	NS NS	57% 95%
(Kamarajah 2019)	n=18	700	1377		RP vs LP MD= 28.11 (2.89, 53.33)	P=0.03	Laparoscopy	94%
(Niu 2019)	n=6	NR	NR	NR	RP vs OP MD=32.93 (17.52, 79.29) RP vs LP MD=37.27 (6.34, 68.21)	NR	Open Laparoscopy	87.8% 90.6%
(Machairas 2019)	n=9	407		645	RH vs OH MD=65.91 (22.39, 109.44)	0.003	Open	90%
(Wong 2019)	n=7	328		426	RH vs OH MD=61.47 (7.03, 115.91)	P=0.03	Open	91%

(Gavriilidis 2020)	n=10 n=17	NR	NR	NR	RH vs OH MD=50.82 (6.16, 95.47) RH vs LH MD=60.41 (-7.52, 128.35)	P=0.03 P=0.08	Open NS	100% 100%
(Mavrovounis 2020)	n=18	666	1359		LP vs RP MD=-28.28 (-49.98, -6.60)	P=0.01	Laparoscopy	87%
(Kamarajah 2020)	n=25	746	1150	-	RH vs LH MD=56.84 (36.04, 77.64)	NR	Laparoscopy	90%
(Ciria 2020)	n=24	NR	NR	NR	RH vs OH MD=64.71 (36.68, 94.75) RH vs LH MD=53.89 (32.26, 75.62)	NR	Open Laparoscopy	88.2% 90.27%
(Zhang 2020)	n=24	916	1375		RH vs LH MD=36.93 (19.74, 54.12)	P< 0.001	Laparoscopy	86%
(Zhao 2020)	n=12 n=20	NR	NR	NR	RH vs OH MD= 59.42 (21.89, 96.94) RH vs LH MD= 45.64 (27.06, 64.21)	P = 0.002 P < 0.001	Open Laparoscopy	87.5% 90%
(Zhou 2020)	n=7	515		1749	RP vs OP MD=12.95 (-32.51, 58.41)	P=0.58	NS	92%
(Aiolfi 2020)	n=32	NR	NR	NR	RPD vs OPD MD=33.1 (24.02, 42.3) RPD vs LPD MD=27.8 (17.1, 38.6)	NR	Open Laparoscopy	NR
(Kamarajah 2020)	n=5				RPD vs LPD MD=-13 (-40, 14)	P=0.3	NS	80%
(Podda 2020)		1363		11750	RPD vs OPD MD= 1.06 (0.48, 1.64)	P=0.004	Open	99%
(Yan 2020)	n=7	325		515	RPD vs OPD MD= 71.74 (23.37, 120.12)	P= 0.004	Open	95%
(Zhang 2020)	n=9	468		598	RPD vs OPD MD= 80.85 (16.09,145.61)	P < 0.00001	Open	96%
(Hu 2021)	n=6	345	748		RH vs LH MD=58.79 (25.54, 92.04)	P<0.001	Laparoscopy	86.1%

(Bhattacharya 2021)	n=7	125	292		RS vs LS MD=3.63, (-16.99, 24.25)	P=0.73	NS	90%
(Wang 2021)	n=12	297	454		RH vs LH MD=28.65 (13.12, 44.17)	P=0.0003	Laparoscopy	59%
(Ziogas 2021)	n=7	225	300		LH vs RH MD=-0.08 (-0.51, 0.34)	P=0.70	NS	76%
(Dong 2021)	N=23	2086		103131	RPD vs OPD MD= 75.17 (48.05, 102.28)	P<0.00001	Open	99%
(Di Martino 2021)	N=9	467	438		LDP vs RDP SMD- -0.09 (-0.64, 0.47)	P=0.75	NS	93%
(Feng 2021)	N=2	58	70		RDP vs LDP MD= 36.43 (-6.47, 79.33)	P=0.10	NS	74%
(Rompianesi 2021)	N=9	242	276		RDP vs LDP MD= 6.13 (-39.36, 52.33)	P=0.79	NS	97%
(Zhang 2021)	N=9	468		598	RPD vs OPD MD= 80.85 (16.09, 145.61)	P=0.01	Open	96%
(Aboudou 2022)		682	1101		RH vs LH MD= 43.99 (23.45, 64.53)	P<0.00001	Laparoscopy	86%
(Hajibandeh 2022)	N=6	140	163		RH vs LH MD= 29.40 (5.91, 52.88)	P=0.01	Laparoscopy	72%
(Fu 2022)	N=17	1924		2690	RPD vs OPD MD= 64.60 (26.89, 102.21)	P=0.001	Open	97.8%
(Kabir 2022)					RPD vs LPD MD= 33.73 (-14.54, 82.00) RPD vs OPD MD=91.08 (48.61, 113.56)	P=0.459 P=0.042	NS Open	
(Lincango 2022)	N=1 N=4	52 151	118	248	RLDRH vs LADRH MD= 137.7 (107.4, 168.0) RLDRH vs OADRH MD= 133.4 (72.8, 194.1)		Laparoscopy Open	
(Ouyang 2022)	N=8	984	1125		RPD vs LPD MD= 13.74 (-9.46, 36.94)	P=0.25	NS	96%
(Rahimli 2022)	N=13	565	894		RH vs LH MD= 28.12 (3.66, 52.57)	P=0.02	Laparoscopy	90%

(Yeow 2022)					RH vs LH MD= 113.24 (53.28, 173.20) RH vs OH MD= 148.05 (97.35, 198.74)		Laparoscopy Open	
(Yin 2022)*		177	307		LS s RAS MD= -17.27 (-91.79, 57.25)	P=0.65	NS	99%
(Chaouch 2022)	N=4	65	91		RTP vs LTP MD=14.58 (-102.30, 131.46)	P=0.81	NS	98%
(Gao 2023)	N=19				RH vs LH SMD= 0.07 (-0.05, 0.18)	P=0.25	NS	68%
(Long 2023)	N=3	132	132		RH vs LH MD= 16.20 (-10.67, 43.07)	P=0.24	NS	0%
(Mao 2023)	N=11				RH vs LH MD=0.67 (-14.72, 27.65)	P=0.55	NS	77%
(Papadopoulou 2023)		640		1161	RH vs OH MD= 58.89 (19.44, 98.34)		Open	93%
(van Ramshorst 2023)					RDP vs LDP WMD= 18.21 (2.18, 34.24)		Laparoscopy	91%
(Xuea 2023)	N=8	378		701	RH vs OH MD= 70.55 (37.58, 103.53)	P<0.00001	Open	89%

CI confidence interval; MD mean difference; NR not reported; NS not significant; OR odds ratio; RH robotic hepatectomy; LH laparoscopic hepatectomy; OH open hepatectomy; RP robotic pancreatectomy; LP laparoscopic pancreatectomy; OP open pancreatectomy; RPD robotic pancreaticoduodenectomy; LPD laparoscopic pancreaticoduodenectomy; OPD open pancreaticoduodenectomy

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2 (P-value)**
		Robot	Laparoscopy	Open				
Estimated blood loss (ml)								
(Shin 2017)	n=6	160		294	RPD vs OPD MD=-205.70 (-367.58, -43.82)		**Robot**	62.1%
(Hu 2018)	n=14	NR	NR	NR	RH vs LH MD=39.56 (4.65, 74.4)	P=0.013	Laparoscopy	51.5%

(Zhao 2018)	n=8 n=2	423 33		1158 35	RPD vs OPD MD= −197.02 (−313.42, −80.61) RP vs OP MD= −481.5 (−759.45, −203.61)	P= 0.0009 P= 0.0007	**Robot** **Robot**	93% 0%
(Guan 2019)	N=11				RH vs LH MD= 69.88 (27.11, 112.65)	P= 0.001	Laparoscopy	67%
(Machairas 2019)	n=7	381		576	RH vs OH MD=-159.82 (-342.45, 22.81)	P=0.09	NS	93%
(Gavriilidis 2019)	n=4 n=18				RP vs OP MD = −426 (−558, −295) RP vs LP MD = −68.02 (−103, −33)	P < 0.001 P < 0.001	**Robot** **Robot**	55% 98%
(Kamarajah 2019)	n=14	425	513		RP vs LP MD=−51.94 (-107.83, 3.95)	P=0.07	NS	98%
(Niu 2019)	n=4 n=10	NR	NR	NR	RP vs OP MD=-185.89 (-478.10, 103.32) RP vs LP MD=-14.94 (-125.97, 96.10)	NR	NS NS	94.1%
(Wong 2019)	n=5	302		357	RH vs OH MD=-220.44 (-447.47, 6.58)	P=0.06	NS	86%
(Ciria 2020)	n=22 n=11	NR	NR	NR	RH vs OH RR=-103.67 (-296.62, 89.29) RH vs LH RR=69.02 (4.88, 133.17)		NS Laparoscopy	98.83% 86.39%
(Kamarajah 2020)	n=24	685	1049	-	RH vs LH MD=-51.74 (-67.74, -35.75)	NR	**Robot**	99%
(Gavriilidis 2020)	N=18	NR	NR	NR	RH vs OH MD= -163.36 (-260, -66) RH vs LH MD= -25.28 (-34.78, -15.78)	P < 0.001 P < 0.001	**Robot** **Robot**	100% 100%
(Mavrovounis 2020)	n=14	391	495		LP vs RP MD=34.00 (-10.28, 78.29)	P=0.13	NS	87%
(Zhang 2020)	n=21	829	1155		RH vs LH MD=3.58 (-31.38, 38.54)	P = 0.84	NS	78%

(Zhao 2020)	n=10 n=18	NR NR	NR	NR	RH vs OH MD=-126.91 (-126.91, -59.21) RH vs LH MD=45.46(7.04, 83.89)	P < 0.001 P = 0.02	**Robot** Laparoscopy	75.6% 81.%
(Coletta 2021)	n=7	223	238		RH vs LH MD=-0.72 (0.92, -0.52)	P<0.0001	**Robot**	80%
(Hu 2021)	n=4	169	123	-	RH vs LH MD= -1.96 (-44.04, 40.12)	0.927	NS	36.2%
(Wang 2021)	n=10	276	417		RH vs LH MD=-12.91 (-44.75, 18.09)	P=0.43	NS	0%
(Ziogas 2021)	n=6	217	297		LH vs RH MD=0.27 (-0.24, 0.77)	P=0.30	NS	84%
(Zhou 2020)	n=5	278		191	RP vs OP MD=-246.95 (-300.83, -193.07)	P < 0.00001	**Robot**	75%
(Aiolfi 2020)	n=29	NR	NR	NR	RPD vs OPD MD=− 158.5 (− 169.2, -147.9) RPD vs LPD MD=10.04 (− 3.21, 23.3)	NR	**Robot** NS	NR
(Kamarajah 2020)	n=2				RPD vs LPD MD=-80 (-170, 10)	P=0.1	NS	34%
(Podda 2020)					RPD vs OPD MD=− 0.94 (-1.45, -0.42)	P=0.0003	**Robot**	96%
(Yan 2020)	n=8	444		1314	RPD vs OPD MD= -374.03 (-506.84, -241.21)	P< 0.00001	**Robot**	96%
(Zhang 2020)	n=9	410		599	RPD vs OPD MD= -175.65 (− 251.85, − 99.44)	P< 0.00001	**Robot**	82%
(Dong 2021)	N=18	1549		2935	RPD vs OPD MD= -191.35 (-2282.12, -144.59)	P<0.00001	**Robot**	96%
(Di Martino 2021)	N=8	455	430		LP vs RP SMD= -0.05 (-0.19, 0.08)	P=0.44	NS	0%
(Hu 2021)	N=4				RH vs LH WMD= -1.96 (44.04, 40.12)		NS	36%
(Wang 2021)	N=10	276	417		RH vs LH MD= -12.91 (-44.75, 18.94)	P=0.43	NS	0%

(Zhang 2021)	N=9	410		599	RPD vs OPD MD= -175.65 (-251.85, -99.44)	P<0.00001	**Robot**	82%
(Aboudou 2022)					RH vs LH MD= -20.95 (-64.90, 23.34)	P=0.36	NS	84%
(Hajibandeh 2022)	N=6	140	163		RH vs LH MD= -1.96 (-31.55, 35.47)	P=0.91	NS	40%
(Fu 2022)	N=14	1,640		1,583	RPD vs OPD MD= −185.44 (−239.66, −131.21)	p < 0.001	**Robot**	92.7%
(Kabir 2022)					RPD vs LPD MD= -112.58 (-118.20, -36.95) RPD vs OPD MD= -209.87 (-279.36, -140.39)		**Robot** **Robot**	
(Lincango 2022)	N=1 N=4	52 151	118	 248	RLDRH vs LADRH MD= -155.7 (-214.6, -96.8) RLDRH vs OADRH MD= -18.2 (-149.5, 113)		**Robot** NS	
(Ouyang 2022)	N=5	171	192		RPD vs LPD MD= -120.47 (-171.09, -69.85)	P<0.00001	**Robot**	76%
(Rahimli 2022)	N=11	404	748		RH vs LH MD= -8.56 (-70.86, 53.73)	P=0.79	NS	82%
(Yeow 2022)					RH vs LH MD= 53.07 (-116.86, 223.00) RH vs OH MD= -267.04 (-437.82, -84.26)		NS **Robot**	
(Yin 2022)*		111	174		LS vs RAS MD= 2.28 (-13.51, 18.06)	P=0.78	NS	96%
(Zhang 2022)	N=3	67	154		LS vs RS MD= 1.49 (-1.47, 4.47)	P=0.33	NS	1%
(Gao 2023)	N=17				RH vs LH SMD= -0.31 (-0.48, -0.14)	P=0.0005	**Robot**	84%
(Li 2023)		342	540		RP vs LP MD= -52.029 (-82.92, -33.65)	P<0.00001	**Robot**	26%
(Mao 2023)					RH vs LH MD= -91.42, -142.18, -40.66)	P=0.0004	**Robot**	74%

(Papadopoulou 2023)		614		1092	RH vs OH MD= -182.40 (-283.02, -81.79)		**Robot**	92%
(van Ramshorst 2023)					RP vs LP WMD= -54.50 (-84.49, -24.50)		**Robot**	92%
(Xuea 2023)	N=5	281		544	RH vs OH MD= -152.2 (-266.85, -38.18)	P=0.009	**Robot**	62%

CI confidence interval; MD mean difference; NR not reported; NS not significant; RR relative risk; OR odds ratio; RH robotic hepatectomy; LH laparoscopic hepatectomy; OH open hepatectomy; RP robotic pancreatectomy; LP laparoscopic pancreatectomy; OP open pancreatectomy; RPD robotic pancreaticoduodenectomy; LPD laparoscopic pancreaticoduodenectomy; OPD open pancreaticoduodenectomy.

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Conversion to open approach (%)								
(Lauretta 2017)	n=8	19/230	109/503		RP vs LP OR=0.33 (0.12, 0.92)	P=0.03	**Robot**	48%
(Hu 2018)	n=13				RH vs LH OR=1.36 (0.78, 2.35)	P=0.183	NS	25.8%
(Guan 2019)	N=13	25/411	41/465		RLR vs LLR OR=0.75 (0.45, 1.25)	P=0.27	NS	0%
(Gavriilidis 2019)	NR	36/590	117/764		RP vs LP OR = 0.49 (0.33, 0.71)	P= 0.002	**Robot**	33%
(Kamarajah 2019)	n=18	66/823	500/2413		RP vs LP OR=0.48 (0.35, 0.67)	P<0.0001	**Robot**	10%
(Kamarajah 2020)	n=21	606	884	-	RH vs LH OR=0.86 (0.49, 1.51)	NR	NS	32%
(Gavriilidis 2020)	n=10	27/406	39/532		RH vs LH OR= 0.95 (0.57, 1.58)	P=0.85	NS	0%
(Mavrovounis 2020)	n=18	53/759	406/2061		LP vs RP OR=2.38 (1.75, 3.22)	P<0.00001	**Robot**	22%
(Aiolfi 2020)	NR	NR	NR	NR	RPD vs LPD RR=0.71(0.59, 0.83)	NR	**Robot**	15.1%
(Kamarajah 2020)	n=6				RPD vs LPD	P<0.001	**Robot**	0%

					OR= 0.45 (0.36, 0.56)			
(Zhang 2020)	n=22	59/920	123/1253		RH vs LH OR=0.63 (0.46, 0.87)	P= 0.005	**Robot**	48%
(Zhao 2020)	n=15				RH vs LH OR=0.66 (0.43, 1.02)	P= 0.059	NS	0%
(Ciria 2020)	n=19	514/550	871/947	-	RH vs LH RR=0.015(-0.014, 0.045)	NR	NS	NA
(Hu 2021)	n=6	347	762		RH vs LH OR= 0.403 (0.224, 0.725)	P= 0.002	**Robot**	0%
(Wang 2021)	n=10	15/254	29/402		RH vs LH OR=0.86 (0.46, 1.58)	0.62	NS	33%
(Coletta 2021)	n=6	8/168	14/109		RH vs LH RR=0.27(0.10, 0.78)	P=0.02	**Robot**	0%
(Ziogas 2021)	n=6	8/217	9/297		RH vs LH RD=0.03 (−0.01, 0.08)	P= 0.15	NS	42%
(Bhattacharya 2021)	n=8	6/202	21/358		RS vs LS OR=0.63 (0.24, 1.70)	P=0.36	NS	0%
(Di Martino 2021)	N=7	41/390	16/432		RDP vs LDP OR= 2.56 (1.31, 5.00)	P=0.06	**Robot**	11%
(Wang 2021)	N=10	255	398		RH vs LH MD= 0.15 (-0.47, 0.77)	P=0.64	NS	55%
(Zhang 2021)	N=10	615	757		RPD vs LPD MD= -2.95 (-5.33, -0.56)	P=0.02	**Robot**	87%
(Aboudou 2022)		635	1037		RH vs LH MD=0.10 (-0.38, 0.58)	P=0.69	NS	75%
(Bhattacharya 2022)	N=4	38	58		RS vs LS MD= =0.21 (-1.17, 0.75)	P=0.67	NS	86%
(Hajibandeh 2022)	N=6	140	163		RH vs LH MD= 0.22 (-0.45, 0.88)	P=0.52	NS	81%
(Kabir 2022)					RPD vs LPD MD= 0.96 (-0.86, 2.78) RPD vs OPD MD= -1.37 (-2.85, 0.10)		NS NS	
(Lincango 2022)	N=1	52	118		RLDRH vs LADRH		NS	

	N=4	151		248	MD= 0.3 (-0.3, 0.9) RLDRH vs OADRH MD= -0.8 (-1.4, -0.3)		**Robot**	
(Ouyang 2022)	N=9	1149	2583		RPD vs LPD MD= -1.29 (-2.64, 0.05)	P=0.06	NS	89%
(Rahimli 2022)	N=11	531	846		RH vs LH MD= -0.02 (-0.56, 0.53)	P=0.94	NS	76%
(Yeow 2022)					RH vs LH MD=0.60 (−2.11, 3.31) RH vs OH MD=−1.00 (−3.43, 1.43)		NS NS	
(Yin 2022)*		177	307		LS vs RAS MD= 0.89 (-0.13, 1.91)	P=0.09	NS	89%
(Chaouch 2022)		65	91		RP vs OP MD= 0.32 (-3.97, 4.61)	P=0.88	NS	93%
(Gao 2023)	N=18				RH vs LH SMD= -0.02 (-0.13, 0.08)	P=0.66	NS	62%
(Li 2023)		683	995		RDP vs LDP MD= -0.57 (-0.92, -0.21)	P=0.002	**Robot**	1%
(Long 2023)	N=4				RH vs LH MD= 1.66 (-0.10, 3.42)	P=0.07	NS	68%
(Mao 2023)	N=11				RH vs LH MD= -0.64 (-0.78, -0.49)	P<0.00001	**Robot**	46%
(Papadopoulou 2023)		640		1161	RH vs OH MD= -2.74 (-4.20, -1.28)		**Robot**	93%
(van Ramshorst 2023)					RDP sv LDP MD= -0.45 (-0.92, 0.01)		NS	71%
(Xuea 2023)	N=7	314		637	RH vs OH MD= -2.79 (-4.19, -1.40)	P<0.0001	**Robot**	88%

CI confidence interval; MD mean difference; NR not reported; NS not significant; RR relative risk; OR odds ratio; RH robotic hepatectomy; LH laparoscopic hepatectomy; OH

open hepatectomy; RP robotic pancreatectomy; LP laparoscopic pancreatectomy; OP open pancreatectomy; RPD robotic pancreaticoduodenectomy; LPD laparoscopic pancreaticoduodenectomy; OPD open pancreaticoduodenectomy.

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Length of hospital stay(days)								
(Shin 2017)	n=5	160		294	RPD vs OPD MD=-4.09 (-6.88, -1.31)		**Robot**	63.6%
(Peng 2017)	n=4	132		234	RPD vs OPD MD= -6.00 (-9.80, -2.21)	P<0.001	**Robot**	67.9%
(Lauretta 2017)	n=8	211	357		RP vs LP MD=-0.74 (-1.34, -0.15)	P=0.01	**Robot**	60%
(Zhao 2018)	n=8 n=4	476 270		1164 1593	RPD vs OPD MD= −2.55 (−5.21, 0.12) RP vs OP MD= −2.97 (−4.75, −1.20)	P=0.06 P=0.001	NS **Robot**	88% 67%
(Hu 2018)	n=14	NR	NR	NR	RH vs LH MD=0.16 (-0.19, 0.50)	NR	NS	5%
(Guan 2019)	n=10	401	453		RLR vs LLR OR=0.12 (-0.52, 0.77P	0.71	NS	68%
(Wong 2019)	n=7	328		426	RH vs OH MD=-2.57 (-3.31, -1.83)	P<0.00001	**Robot**	0%
(Machairas 2019)	n=9	407		645	RH vs OH MD=-2.76(-3.84, -1.68)	P<0.0001	**Robot**	61%
(Gavriilidis 2019)	n=5 n=18	NR	NR	NR	RP vs OP MD = −4.06 (-0.28, -1.14) RP vs LP MD= −0.69 (−1.16, −0.23)	P=0.002 P=0.004	**Robot** **Robot**	74% 63%
(Kamarajah 2019)	n=20	860	2456		RP vs LP MD=−1.21 (−1.88, - 0.54)	P < 0.001	**Robot**	61%
(Niu 2019)	n=6	NR	NR	NR	RP vs OP MD=-4.66 (-8.38, -0.93) RP vs LP MD=-1.33 (-2.53, -0.13)	NR	**Robot** **Robot**	82.8% 71.0%
(Zhang 2020)	n=23	1095	1782		RH vs LH MD=-0.06 (-0.47, 0.34)	P=0.76	NS	86%

(Zhao 2020)	n=10 n=9	NR	 NR	NR	RH vs OH MD=−2.51(-3.14, -1.87) RH vs LH MD=0.23 (-0.41, 0.88)	P < 0.001 P=0.48	**Robot** NS	0% 52.2%
(Kamarajah 2020)	n=23	872	1552	-	RH vs LH MD=-0.27 (-0.83, 0.28)	NR	NS	80%
(Ciria 2020)	n=17	NR	NR	NR	RH vs OH MD=-3.53 (-4.35, -2.72) RH vs LH MD=-0.35 (-0.08, 0.19)	NR	**Robot** NS	87% 87%
(Gavriilidis 2020)	n=10 n=16	NR	NR	NR	RH vs OH MD= -3.10 (-4.34, -1.86) RH vs LH MD= -0.16 (-0.73, 0.41)	P<0.001 P=0.59	**Robot** NS	95% 93%
(Zhou 2020)	n=7	515		1749	RP vs OP MD= -2.42(-2.99, -1.85)	P<0.00001	**Robot**	76%
(Aiolfi 2020)	n=35	NR	NR	NR	RPD vs OPD MD=− 2.23 (− 3.6, − 0.99) RPD vs LPD MD=0.3 (− 1.2, 1.93)	NR	**Robot** NS	NR
(Kamarajah 2020)	n=6	NR	NR	NR	RPD vs LPD MD=0.81 (0.50, 1.13)	P<0.0001	**Robot**	77%
(Podda 2020)		1555		11947	RPD vs OPD MD= − 0.23 (-0.64, 0.17)	P=0.25	NS	98%
(Yan 2020)	n=11	738		1561	RPD vs OPD MD= − 5.19 (− 8.42, − 1.97)	P=0.002	**Robot**	96%
(Zhang 2020)	n=10	615		757	RPD vs OPD MD=− 2.95 (− 5.33, − 0.56)	P<0.0001	**Robot**	87%
(Coletta 2021)	n=7	223	238		RH vs LH MD=-0.46 (-0.67, -0.26)	P<0.0001	**Robot**	93%
(Hu 2021)	n=4	215	155	-	RH vs LH MD=0.076 (-0.935, 0.783)	P=0.863	NS	23.2%
(Wang 2021)	n=10	255	398		RH vs LH MD=0.15 (-0.47, 0.77)	P=0.64	NS	55%

(Ziogas 2021)	n=6	217	297		LH vs RH MD=0.13 (-0.58, 0.84)	P=0.72	NS	92%
(Bhattacharya 2021)	n=4	38	58		RS vs LS MD=-0.21 (-1.17, 0.75)	P=0.67	NS	86%
(Dong 2021)	N=20	1893		9903	RPD vs OPD MD= -1.00 (-1.88, -0.12)	P=0.03	**Robot**	97%
(Di Martino 2021)	N=11	561	625		LDP vs RDP SMD= -0.00 (-0.12, 0.12)	P=0.98	NS	0%
(Hu 2021)					RH vs LH WMD= -0.08 (-0.94, 0.78)		NS	23%
(Rompianesi 2021)	N=8				RDP vs LDP MD= -1.52 (-2.84, -0.20)	P=0.02	**Robot**	72%
(Wang 2021)	N=10	255	398		RH vs LH MD= 0.15 (-0.47, 0.77)	P=0.64	NS	55%
(Zhang 2021)	N=10	615	757		RPD vs OPD MD= -2.95 (-5.33, -0.56)	P=0.02	**Robot**	87%
(Aboudou 2022)		635	1037		RH vs LH MD=0.10 (-0.38, 0.58)	P=0.69	NS	75%
(Bhattacharya 2022)	N=4	38	58		RS vs LS MD= =0.21 (-1.17, 0.75)	P=0.67	NS	86%
(Hajibandeh 2022)	N=6	140	163		RH vs LH MD= 0.22 (-0.45, 0.88)	P=0.52	NS	81%
(Fu 2022)	N=20	2,496		3,220	RPD vs OPD MD=−1.90 (−2.47, −1.33)	P<0.001	**Robot**	68.5%
(Kabir 2022)					RPD vs LPD MD= 0.96 (-0.86, 2.78) RPD vs OPD MD= -1.37 (-2.85, 0.10)		NS NS	
(Lincango 2022)	N=1 N=4	52 151	118	 248	RLDRH vs LADRH MD= 0.3 (-0.3, 0.9) RLDRH vs OADRH MD= -0.8 (-1.4, -0.3)		NS **Robot**	
(Ouyang 2022)	N=9	1149	2583		RPD vs LPD MD= -1.29 (-2.64, 0.05)	P=0.06	NS	89%

(Rahimli 2022)	N=11	531	846		RH vs LH MD= -0.02 (-0.56, 0.53)	P=0.94	NS	76%
(Yeow 2022)					RH vs LH MD=0.60 (−2.11, 3.31) RH vs OH MD=−1.00 (−3.43, 1.43)		NS NS	
(Yin 2022)*		177	307		LS vs RAS MD= 0.89 (-0.13, 1.91)	P=0.09	NS	89%
(Chaouch 2022)		65	91		RP vs OP MD= 0.32 (-3.97, 4.61)	P=0.88	NS	93%
(Gao 2023)	N=18				RH vs LH SMD= -0.02 (-0.13, 0.08)	P=0.66	NS	62%
(Li 2023)		683	995		RDP vs LDP MD= -0.57 (-0.92, -0.21)	P=0.002	**Robot**	1%
(Long 2023)	N=4				RH vs LH MD= 1.66 (-0.10, 3.42)	P=0.07	NS	68%
(Mao 2023)	N=11				RH vs LH MD= -0.64 (-0.78, -0.49)	P<0.00001	**Robot**	46%
(Papadopoulou 2023)		640		1161	RH vs OH MD= -2.74 (-4.20, -1.28)		**Robot**	93%
(van Ramshorst 2023)					RDP sv LDP MD= -0.45 (-0.92, 0.01)		NS	71%
(Xuea 2023)	N=7	314		637	RH vs OH MD= -2.79 (-4.19, -1.40)	P<0.0001	**Robot**	88%

CI confidence interval; MD mean difference; NR not reported; NS not significant; RR relative risk; OR odds ratio; RH robotic hepatectomy; LH laparoscopic hepatectomy; OH open hepatectomy; RP robotic pancreatectomy; LP laparoscopic pancreatectomy; OP open pancreatectomy; RPD robotic pancreaticoduodenectomy; LPD laparoscopic pancreaticoduodenectomy; OPD open pancreaticoduodenectomy.

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				

Overall complication (%)								
(Peng 2017)	n=9	245		435	RPD vs OPD RR=0.65 (0.47, 0.91)	P= 0.01	**Robot**	0%
(Hu 2018)	n=16	NR	NR	-	RH vs LH OR=0.90 (0.64, 1.28)	NR	NS	0%
(Guan 2019)	N=13	83/433	118/505		RLR vs LLR OR= 0.80 (0.56, 1.14)	P=0.21	NS	16%
(Machairas 2019)	n=9	14/443		41/748	RH vs OH RR= 0.58 (0.32, 1.05)	P=0.07	NS	0%
(Zhao 2018)	n=8 n=3	141/270 89/254		223/413 844/1580	RPD vs OPD OR= 0.67 0(.47, 0.95) RP vs OP OR= 0.68 (0.51, 0.91)	P=0.02 P=0.009	**Robot** **Robot**	37% 0%
(Wong 2019)	n=7	47/328		99/426	RH vs OH RR=0.63 (0.46, 0.86)	P=0.004	**Robot**	0%
(Gavriilidis 2019)	n=17	22/102 62/530	 104/729	176/734	RP vs OP OR = 1.30 (0.76, 2.22) RP vs LP OR = 1.04 (0.73, 1.47)	P=0.35 P=0.85	NS NS	48% 20%
(Kamarajah 2019)	n=14	177/447	309/629		RP vs LP OR= 0.87 (0.66, 1.14)	P=0.31	NS	0%
(Niu 2019)	n=5 n=12	NR	NR	NR	RP vs OP OR=0.55 (0.32, 0.96) RP vs LP OR=1.08 (0.74, 1.57)	NR	**Robot** NS	8.9% 0%
(Aiolfi 2020)	NR	NR	NR	NR	RPD vs OPD OR=0.79 (0.72, 0.91) RPD vs LPD OR= 1.03 (0.94, 1.13)	NR	**Robot** NS	NR
(Kamarajah 2020)	n=4	NR	NR	NR	RPD vs LPD OR= 1.04 (0.73, 1.48)	P=0.8	NS	64%
(Yan 2020)	n=10	299/529		369/746	RPD vs OPD OR= 0.85 (0.66, 1.11)	P=0.23	NS	20%
(Zhang 2020)	n=10	155/409		182/458	RPD vs OPD	P=0.01	**Robot**	33%

					RR=0.78 (0.64, 0.95)			
(Mavrovounis 2020)	n=12	46/400	84/563		LP vs RP MD=0.92 (0.62, 1.38)	P=0.70	NS	27%
(Ciria 2020)		NR	NR	NR	RH vs OH RR= 0.093 (0.036, 0.15) RH vs LH RR=0.02 (−0.01, 0.04).	NR NR	**Robot** NS	46.49% 0%
(Kamarajah 2020)	n=25	746	1160		RH vs LH OR=0.93 (0.70, 1.24)	NR	NS	0%
(Zhang 2020)	n=25	177/994	257/1454		RH vs LH OR=1.02 (0.81, 1.28)	P = 0.90	NS	9%
(Zhao 2020)	n=12 n=21	NR	 NR	NR	RH vs OH OR=1.27 (0.93, 1.72) RH vs LH OR= 0.87 (0.67, 1.13)	P = 0.129 P = 0.297	NS NS	0% 0%
(Coletta 2021)	n=8	10/244	20/241		RH vs LH RR=0.61 (0.28, 1.32)	P=0.21	NS	0%
(Hu 2021)	n=6	345	349	-	RH vs LH OR=1.161 (0.676, 1.996)	P=0.588	NS	30.2%
(Wang 2021)	n=12	38/297	68/454		RH vs LH OR=0.98 (0.63, 1.53)	P=0.92	NS	2%
(Ziogas 2021)	n=6	40/217	84/297		LH vs RH OR= 1.42 (0.90, 2.23)	P=0.13	NS	0%
(Gavriilidis 2020)	NR	NR	NR	NR	OH vs RH OR= 0.69 (0.38, 1.24) RH vs LH OR= 0.83 (0.52, 1.33)	P=0.22 P=0.44	NS NS	0% 0%
(Bhattacharya 2021)	n=7	13/192	18/338		RS vs LS OR=0.91 (0.40, 2.06)	P=0.82	NS	0%
(Di Martino 2021)	N=6	29/276	39/341		LDP vs RDP OR= 0.99 (0.57, 1.70)	P=0.96	NS	0%
(Hu 2021)	N=6				RH vs LS OR=1.16 (0.68, 2.00)		NS	30%
(Rompianesi)	N=6	29/197	35/209		RDP vs LDP	P=0.27	NS	0%

					RD= -0.04 (-0.11, 0.33)			
(Wang 2021)	N=12	28/297	68/454		RH vs LH OR= 0.98 (0.63, 1.53)	P=0.92	NS	2%
(Zhang 2021)	N=11	155/409		182/458	RPD vs OPD RR= 0.78 (0.64, 0.95)	P=0.01	**Robot**	33%
(Aboudou 2022)	N=11	63/437	129/769		RH vs LH OR=0.94 (0.66, 1.35)	P=0.75	NS	0%
(Bhattacharya 2022)	N=7	13/192	18/338		RS vs LS OR=0.91 (0.40, 2.06)	P=0.82	NS	0%
(Kabir 2022)					RPD vs LPD OR= 1.23 (0.81, 1.85) RPD vs OPD OR=1.02 (0.72, 1.46)		NS NS	
(Fu 2022)	N=13	1,192		1,856	RPD vs OPD OR=0.66 (0.44 to 0.97)	P<0.001	**Robot**	76.2%
(Lincango 2022)	N=1 N=3	2/52 3/100	2/118	 3/186	RLDRH vs LADRH RR=2.27 (0.33, 15.67) RLDRH vs OADRH MD=2.10 (0.44, 9.96)		NS NS	
(Murtha-Lemekhova 2022)	N=4	201 167	160	 289	RH vs LH OR= 0.61 (0.18, 2.06) RH vs OH OR=0.76 (0.49, 1.18)	P=0.28 P=0.12	NS NS	11% 0%
(Ouyang 2022)	N=8	469/984	533/1125		RPD vs LPD OR=1.03 (0.87, 1.23)	P=0.71	NS	20%
(Rahimli 2022)	N=13	534	841		RH vs LH OR= 0.78 (0.56, 1.09)	P=0.15	NS	21%
(Yeow 2022)					RH vs LH OR=0.69 (0.26, 1.87) RH vs OH OR=0.48 (0.19, 1.20)		NS NS	
(Yin 2022)*		46/307	16/177		LS vs RAS OR=1.53 (0.59, 3.94)		NS	
(Chaouch 2022)		1/65	5/91		RP vs OP	P=0.36	NS	0%

					OR=0.42 (0.07, 2.67)			
(Gao 2023)	N=212				RH vs LH OR= 0.99 (0.86, 1.14)	P=0.91	NS	41%
(Long 2023)		55/226	49/226		RH vs LH RR= 1.12 (0.80, 1.57)	P=0.50	NS	1%
(Mao 2023)	N=11	161/752	201/774		RH vs LH OR=0.83 (0.62, 1.06)	P=0.4	NS	0%
(Papadopoulou 2023)					RH vs OH (Clavien-Dindo I–II) RR= 0.67 (0.54, 0.85) RH vs OH (Clavien-Dindo III–IV) RR= 0.67 (0.44, 1.01)		**Robot** NS	0% 0%
(Xuea 2023)	N=8	57/378		143/701	RH vs OH OR= 0.67 (0.47, 0.95)	P=0.02	**Robot**	3%

CI confidence interval; MD mean difference; NR not reported; NS not significant; RR relative risk; OR odds ratio; RH robotic hepatectomy; LH laparoscopic hepatectomy; OH
open hepatectomy; RP robotic pancreatectomy; LP laparoscopic pancreatectomy; OP open pancreatectomy; RPD robotic pancreaticoduodenectomy; LPD laparoscopic pancreaticoduodenectomy; OPD open pancreaticoduodenectomy.

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Pancreatic fistula (%)								
(Peng 2017)	n=7	212		341	RPD vs OPD RR= 0.77 (0.49, 1.22)	P=0.27	NS	2%
(Shin 2017)	n=4	24/130		57/263	RPD vs OPD OR=0.75 (0.44, 1.29)		NS	49.5%
(Zhao 2018)	n=9 n=3	93/506 47/253		150/1194 237/1471	RPD vs OPD OR= 1.20 (0.88, 1.63) RP vs OP OR= 1.13 (0.79, 1.62)	P=0.25 P=0.49	NS NS	37% 0%
(Gavriilidis 2019)	n=5 n=17	12/102 98/592	 161/807	85/734	RP vs OP OR = 0.57 (0.28, 1.14) RP vs LP	P=0.11 P=0.18	NS NS	0% 0%

					OR = 0.81 (0.60, 1.10)			
(Kamarajah 2019)	n=16	164/663	313/1334		RP vs LP OR= 0.95 (0.75, 1.20)	P=0.65	NS	0%
(Niu 2019)	n=5 n=11	NR	NR	NR	RP vs OP OR=0.60 (0.29, 1.24) RP vs LP OR=0.99 (0.67, 1.47)	NR	NS NS	0% 0%
(Zhou 2020)	n=7	137/515		288/1749	RP vs OP OR=1.19 (0.90, 1.57)	P=0.22	NS	2%
(Kamarajah 2020)	n=5				RP vs LP OR= 1.02 (0.81, 1.29)	P=0.9	NS	0%
(Yan 2020)	n=8	468		550	RPD vs OPD OR= 1.12 (0.64, 1.96)	P=0.69	NS	57%
(Dong 2021)	N=20	265/1909		1589/9921	RPD vs OPD OR=0.89 (0.65, 1.22)	P=0.48	NS	64%
(Di Martino 2021)	N=8	90/436	77/461		OR=1.20 (0.84, 1.71)	P=0.32	NS	0%
(Rompianesi 2021)	N=7	31/209	36/238		RDP vs LDP RD= 0.00 (-0.06, 0.07)	P=0.9	NS	0%
(Zhang 2021)		75/969		151/1078	RPD vs OPD RD=0.54 (0.41, 0.70)	P<0.00001	**Robot**	0%
(Kabir 2022)					RPD vs LPD OR= 0.73 (0.37, 1.44) RPD vs OPD OR=0.63 (0.36, 1.09)		NS NS	
(Fu 2022)	N=13	1938	2104		RPD vs OPD OR= 0.67 (0.55, 0.82)	P<0.0001	**Robot**	26.9%
(Ouyang 2022)	N=8	172/984	199/1125		RPD vs LPD OR= 0.99 (0.79, 1.24)	P=0.94	NS	0%
(Li 2023)		318/1828	410/2280		RPD vs LPD OR=0.91 (0.77, 1.08)	P=0.26	NS	0%
(van Ramshorst 2023)					RPD vs LPD OR=0.98 (0.85, 1.14)		NS	0%
(Wang 2023)	N=5 N=24				LPD vs RPD OR= 1.60 (0.79, 3.55)	P>0.05 P<0.05	NS **Robot**	0% 25%

					RPD vs OPD OR=0.63 (0.51, 0.77)			

CI confidence interval; MD mean difference; NR not reported; NS not significant; RR relative risk; OR odds ratio; RH robotic hepatectomy; LH laparoscopic hepatectomy; OH open hepatectomy; RP robotic pancreatectomy; LP laparoscopic pancreatectomy; OP open pancreatectomy; RPD robotic pancreaticoduodenectomy; LPD laparoscopic pancreaticoduodenectomy; OPD open pancreaticoduodenectomy.

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Time to oral diet (days)								
(Hu 2018)	n=4				RH vs LH MD=1.2 (0.24, 2.17)	NR	NS	82.1%
(Gavriilidis 2020)					RH vs OH MD= -0.39 (-1.5, 0.70) RH vs LH MD= -0.48 (-1.4, 0.34)		NS NS	

CI confidence interval; MD mean difference; NR not reported; NS not significant; RR relative risk; OR odds ratio; RH robotic hepatectomy; LH laparoscopic hepatectomy; OH open hepatectomy.

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
R0 or R1 resection (%)								
(Shin 2017)	n=4	116/134		206/267	RPD vs OPD OR=1.53 (0.82, 2.85)		NS	0%
(Hu 2018)	n=4	NR	NR	NR	RH vs OH OR=2.2 (0.78, 6.23)	NR	NS	0%
(Guan 2019)*		27/345	33/396		RLR vs LLR OR= 1.03 (0.41, 2.55)	P=0.95	NS	42%
(Kamarajah 2019)	n=10	299/316	794/895		RP vs LP OR=1.01 (0.59, 1.73)	P=0.97	NS	0%
(Machairas 2019)	n=7	265/304		551/605	RH vs OH RR=1.00 (0.97, 1.02)	P=0.71	NS	0%

(Aiolfi 2020)	n=27	NR	NR	NR	RPD vs OPD RR= 1.13 (0.82, 1.66) RPD vs LPD RR=1.12 (0.86, 1.30)	NR	NS NS	NR
(Kamarajah 2020)	n=17	582	891		RH vs OH OR=1.24 (0.85, 1.79)	NR	NS	0%
(Zhang 2020)	n=10	407/433	597/625		RH vs OH OR=0.67 (0.37, 1.19)	P=0.17	NS	0%
(Zhang 2020)	n=13	502/589		413/513	RPD vs OPD OR=1.05 (1.00, 1.11)	P=0.05	**Robot**	1%
(Wang 2021)	n=7	167/174	181/190		RH vs OH OR=1.36 (0.48, 3.83)	P=0.56	NS	0%
(Hu 2021)	n=3	237	573	-	RH vs OH OR=0.858 (0.553, 1.332)	0.496	NS	0%
(Feng 2021)	N=6	126/148	250/401	1953	RDP vs LDP OR= 2.96 (1.78, 4.93)	P<0.0001	Laparoscopy	36%
(Hu 2021)	N=3				RH vs LH OR=0.86 (0.55, 1.33)		NS	0%
(Wang 2021)	N=7	167/174	181/190		RH vs LH OR= 1.36 (0.48, 3.83)	P=0.56	NS	0%
(Zhang 2021)		502/589		413/513	RPD vs OPD RR= 1.05 (1.00, 1.11)	P=0.05	NS	1%
(Hajibandeh 2022)*	N=5	0/124	0/138		RH vs LH RD= 0.00 (-0.03, 0.03)	P=1.00	NS	0%
(Fu 2022)	N=10	955		1026	RPD vs OPD MD=1.02 (0.79 to 1.30)	P=0.889	NS	0%
(Kabir 2022)					RPD vs LPD OR= 1.03 (0.68, 1.55) RPD vs OPD OR=1.03 (0.68, 1.55)		NS NS	
(Chaouch 2022)*		4/65		10/91	RP vs OP OR=0.76 (0.21, 2.72)	P=0.68	NS	NA
(Li 2023)		201/230	259/309		RDP vs LDP OR= 1.62 (0.76, 3.42)	P=0.21	NS	37%

(Mao 2023)					RH vs LH OR=1.45 (0.91, 2.31)	P=0.12	NS	0%
(Papadopoulou 2023)		405		714	RH vs OH RR= 1.00 (0.96, 1.04)		NS	58%

CI confidence interval; MD mean difference; NR not reported; NS not significant; RR relative risk; OR odds ratio; RH robotic hepatectomy; LH laparoscopic hepatectomy; OH open hepatectomy; RP robotic pancreatectomy; LP laparoscopic pancreatectomy; OP open pancreatectomy; RPD robotic pancreaticoduodenectomy; LPD laparoscopic pancreaticoduodenectomy; OPD open pancreaticoduodenectomy

*R1 resection (%)

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Positive resection margins (%)								
(Peng 2017)	n=8	233		365	RPD vs OPD OR= 0.40 (0.20, 0.77)	P <0.01	**Robot**	0%
(Zhao 2018)	n=7 n=2	12/199 0/21		40/171 32/271	RPD vs OPD OR= 0.29 (0.15, 0.56) RP vs OP OR= 0.42 (0.05, 3.63)	P=0.003 P=0.43	**Robot** NS	0% 0%
(Gavriilidis 2019)*	n=2 n=5				RP vs OP OR = 0.36 (0.08, 1.56) RP vs LP OR = 0.38 (0.11, 1.36)	P=0.17 P=0.14	NS NS	24% 0%
(Zhou 2020)	n=4	0/41		34/320	RP vs OP OR=0.70 (0.08, 5.95)	P=0.74	NS	0%
(Podda 2020)	n=8	66/439		113/591	RPD vs OPD OR=0.84 (0.60, 1.18)	P=0.34	NS	0%
(Mavrovounis 2020)	n=10	25/289	155/865		LP vs RP RD=0.02(-0.02, 0.07)	P=0.35	NS	48%
(Yan 2020)	n=9	283		773	RPD vs OPD OR= 1.31 (0.91, 1.87)	P=0.14	NS	46%

CI confidence interval; NR not reported; NS not significant; RR relative risk; OR odds ratio; RD Risk Difference

*R1 resection (%)

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Number of harvested lymph nodes								
(Shin 2017)	n=4	138		245	RPD vs OPD MD=-0.61 (-3.58, 2.30)		NS	71.2%
(Peng 2017)	n=3	94		172	RPD vs OPD MD=2.05 (-0.95, 5.05)	P=0.18	NS	58%
(Zhao 2018)	n=7 n=2	335 53		772 650	RPD vs OPD MD= 1.82 (−0.85, 4.48) RP vs OP MD= −2.87 (−5.04, −0.71)	P=0.18 P= 0.009	NS **Robot**	81% 0%
(Gavriilidis 2019)	n=3 n=9	NR	NR	NR	RP vs OP MD= −0.46 (−4.75, 3.84) RP vs LP MD = 2.63 (−1.0, 6.26)	P=0.60 P=0.16	NS NS	83% 99%
(Kamarajah 2019)	n=7	279	1195		RP vs LP MD = 0.95 (−0.45, 2.35)	P=0.18	NS	0%
(Mavrovounis 2020)	n=10	316	1241		LP vs RP MD=-2.09 (-4.17, -0.01)	P=0.05	Laparoscopy	86%
(Zhou 2020)	n=3	69		330	RP vs OP MD=1.18 (-0.47, 2.82)	P=0.16	NS	20%
(Aiolfi 2020)	NR	NR	NR	NR	RPD vs OPD MD=2.18 (− 1.23, 5.61) RPD vs LPD MD=− 0.51 (− 4.45, 3.42)	NR	NS NS	NR
(Kamarajah 2020)	n=2	NR	NR	NR	RPD vs LPD MD= 1.01 (0.84, 1.17)	P <0.001	Laparoscopy	0%
(Podda 2020)					RPD vs OPD MD= 0.20 (− 0.12, 0.52)		NS	85%
(Yan 2020)	n=7	399		1106	RPD vs OPD MD= 0.89 (− 1.80, 3.58)	P=0.52	NS	74%
(Zhang 2020)	n=6	222		217	RPD vs OPD MD=0.48 (-2.05, 3.02)	P=0.71	NS	72%

(Dong 2021)	N=15	908		1953	RPD vs OPD MD= 2.88 (1.12, 4.65)	P=0.0001	**Robot**	83%
(Feng 2021)	N=5	87	179		RDP vs LDP MD= -0.61 (-6.47, 5.24)	P=0.84	NS	99%
(Zhang 2021)	N=6	222		217	RPD vs OPD MD= 0.48 (-2.05, 3.02)	P=0.71	NS	72%
(Fu 2022)	N=13	1337		1699	RPD vs OPD MD= 1.13 (−0.27, 2.54)	P=0.115	NS	82.8%
(Kabir 2022)					RPD vs LPD MD= -0.98, (-3.75, 1.80) RPD vs OPD MD= 0.17 (-2.02, 2.36)		NS NS	
(Ouyang 2022)*	N=3	216	1520		RPD vs LPD MD= 3.34 (0.81, 5.88)	P=0.010	Laparoscopy	89%
(Chaouch 2022)		65		91	RP vs OP MD= 11.27 (-13.93, 36.47)	P=0.38	NS	100%
(Li 2023)	N=4	52	126		RDP vs LDP OR= 0.9 (-1.15, 2.96)	P=0.39	NS	0%

CI confidence interval; MD mean difference; NR not reported; NS not significant; RR relative risk; OR odds ratio; RH robotic hepatectomy; LH laparoscopic hepatectomy; OH open hepatectomy; RP robotic pancreatectomy; LP laparoscopic pancreatectomy; OP open pancreatectomy; RPD robotic pancreaticoduodenectomy; LPD laparoscopic pancreaticoduodenectomy; OPD open pancreaticoduodenectomy

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Postoperative Readmissions (%)								
(Zhao 2018)	n=7	21/265		27/347	RPD vs OPD OR=0.78 (0.41, 1.46)	P=0.43	NS	0%
(Gavriilidis 2019)	n=6	25/201	36/324		RP vs LP OR = 1.76 (0.99, 3.24)	P=0.05	NS	0%
(Kamarajah 2019)	n=8	60/496	182/1582		RP vs LP OR=1.31 (0.94, 1.83)	P=0.11	NS	0%

(Mavrovounis 2020)	n=6	26/276	86/868		LP vs RP OR=0.73 (0.44, 1.20)	P=0.21	NS	0%
(Aiolfi 2020)	NR	NR	NR	NR	RPD vs OPD OR=0.73 (0.64, 0.86) RPD vs LPD OR=1.05 (0.78, 1.72)	NR	**Robot** NS	NR
(Kamarajah 2020)	n=6	NR	NR	NR	RPD vs LPD OR= 1.32 (1.06, 1.64)	NR	Laparoscopy	0%
(Yan 2020)	n=7	601		1294	RPD vs OPD OR= 1.25 (0.97, 1.62)	P=0.08	NS	0%
(Zhang 2020)	n=9	36/842		59/843	RPD vs OPD OR=0.61 (0.41, 0.91)	P=0.02	**Robot**	0%
(Gavriilidis 2020)	NR	20/286	100/661		RH vs LH OR= 0.38 (0.16, 0.89)	P=0.03	**Robot**	39%
(Kamarajah 2020)	N=4				RH vs LH OR=0.43 (0.24, 0.78)	P=0.005	**Robot**	9%
(Gao 2023)	N=13				RH vs LH OR= 1.12 (0.83, 1.51)	P=0.77	NS	0%
(Mao 2023)					RH vs LH OR= 0.63 (0.28, 1.44)	P=0.27	NS	52%

CI confidence interval; MD mean difference; NR not reported; NS not significant; RR relative risk; OR odds ratio; RH robotic hepatectomy; LH laparoscopic hepatectomy; OH open hepatectomy; RP robotic pancreatectomy; LP laparoscopic pancreatectomy; OP open pancreatectomy; RPD robotic pancreaticoduodenectomy; LPD laparoscopic pancreaticoduodenectomy; OPD open pancreaticoduodenectomy.

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy or other	Open				
Reoperation (%)								
(Dong 2021)	N=16	100/1521		577/8723	RPD vs OPD OR= 0.80 (0.62, 1.02)	P=0.07	NS	0%
(Kamarajah 2020)	N=6				RH vs LH OR=0.88 (0.26, 2.98)	P=0.8	NS	0%
(Zhang 2021)	N=9	36/842		59/843	RPD vs OPD RR= 0.61 (0.41, 0.91)	P=0.02	**Robot**	0%

(Aboudou 2022)	N=3	6/156	108210		RH vs LH OR=0.69 (0.25, 1.90)	P=0.47	NS	0%
(Murtha-Lemekhova 2022)		2/84	1/101		RH vs LH OR=1.96 (0.00, 11559)	P=0.58	NS	0%
(Ouyang 2022)	N=7	58/ 960	79/1088		RPD vs LPD OR= 0.83 (0.59, 1.18)	P=0.31	NS	0%
(Chaouch 2022)	N=4	3/65	9/91		RTP vs LTP OR= 0.56 (0.15, 2.07)	P=0.38	NS	0%
(Gao 2023)	N=14				RH vs LH OR=0.67 (0.38, 1.18)	P=0.20	NS	0%
(Mao 2023)					RH vs LH OR= 0.76 (0.31, 1.88)	P=0.45	NS	0%

CI confidence interval; MD mean difference; NR not reported; NS not significant; RR relative risk; OR odds ratio; RH robotic hepatectomy; LH laparoscopic hepatectomy; OH open hepatectomy; RP robotic pancreatectomy; LP laparoscopic pancreatectomy; OP open pancreatectomy; RPD robotic pancreaticoduodenectomy; LPD laparoscopic pancreaticoduodenectomy; OPD open pancreaticoduodenectomy.

Table A3-4 Clinical Effectiveness of Gastrectomy

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Operative time (min)								
(Caruso 2017)	n=6	689		5434	RG vs OG MD=72.20 (48.82, 105.13)	P < 0.001	Open	85%
(Chen 2017)	n=19	1830	4123		LG vs RG MD=−49.05 (-58.18, −39.91)	P < 0.00001	Laparoscopy	88%
(Wang 2017)	n=11	949	2425		MD=42.0 (28.11, 55.89)	P < 0.0001	Laparoscopy	88%
(Wang 2017)	n=3	165	397		MD= 21.49 (12.48, 30.50)	P < 0.00001	Laparoscopy	57%
(Magouliotis 2017)	N=5				MD=−20.66 (-23.45, -17.88)	P<0.00001	Laparoscopy	92%
(Yang 2017)	n=6	NR	NR	NR	RG vs OG MD= 63.72 (33.83, 93.61)	P < 0.0001	Open	94%
(Ai 2019)	n=24	2741	5672		MD=44.11 (24.20, 64.01)	P<0.0001	Laparoscopy	99%
(Bobo 2019)	n=16	NR	NR	NR	MD=57.98 (42.96, 73.00)	P < 0.00001	Laparoscopy	94%
(Guerrini 2020)	n=38	5020	12191		MD= 44.73, (36.01, 53.45)	P < 0.00001	Laparoscopy	97%
(Ma 2020)	n=18	2481	3925		LG vs RG MD= −32.96 (−42.08, −23.84)	P < 0.001	Laparoscopy	94%
(Aiolfi 2021)	n=17	NR	NR	NR	RG vs OG MD= 19.6 (-1.74, 40.9) RG vs LG MD= -46.3 (-68.4, -24.1)	NR	NS **Robot**	59.2%
(Feng 2021)	N=17	4993	5461		MD= 39.97 (31.15, 48.79)	P<0.000001	Laparoscopy	96%
(Zhang 2021)	N=12	1339	1837		MD= 39.78 (15.97, 43.59)	P<0.000001	Laparoscopy	98%
(Zhang 2021)	N=16	1193	2100		MD= 31.41 (15.67, 47.17)	P<0.0001	Laparoscopy	98%
(Baral 2022)		5900	13199		MD= 35.72 (28.59, 42.86)	P<0.000001	Laparoscopy	97%
(Chen 2022)	N=9				RG vs OG MD=83.21 (19.88, 146.55)		Open	99%
(Gong 2022)		2148	3238		MD= 43.88 (35.17, 52.60)	P<0.000001	Laparoscopy	96%
(Jin 2022)					MD= 40.19 (32.07, 48.31)		Laparoscopy	96%
(Sun 2022)		1046	1047		MD= 24.38 (20.66, 28.11)	P<0.000001	Laparoscopy	0%
(Davey 2023)					RG vs OG		Open	

					MD=99.3 (55.1, 145)			
(Lacovazzo 2023)		1422	1397		MD= 43.45 (17.55, 69.36)		Laparoscopy	98%
(Yu 2023)	n=6	422	296		MD= 28.20 (2.76, 53.65)	P=0.03	Laparoscopy	91%
(Multani 2023)					MD= -66.22 (-154, 21.65)	P=0.1854	NS	

CI confidence interval; MD mean difference; NR not reported; NS not significant; RG robotic gastrectomy; LG laparoscopic gastrectomy; OG open gastrectomy

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Estimated blood loss (ml)								
(Caruso 2017)	n=6	689		5434	MD= -166.83 (-205.18, -65.80)	P < 0.001	**Robot**	82%
(Chen 2017)	n=18	1762	4055		LG vs RG MD=24.38 (12.32, 36.43)	P < 0.0001	**Robot**	93%
(Wang 2017)	n=11	949	2425		MD= -23.68 (-42.25, -5.10)	P=0.01	**Robot**	91%
(Wang 2017)	n=3	165	397		MD= −16.60 (−61.31, 28.11)	P=0.47	NS	94%
(Yang 2017)	n=5	NR	NR	NR	RG vs OG MD= -129.84 (-178.31, -81.16)	P < 0.0001	**Robot**	81%
(Ai 2019)	n=23	2662	5563		MD=-17.78 (-25.62, -9.94)	P<0.00001	**Robot**	89%
(Bobo 2019)	n=16	NR	NR	NR	MD=− 23.71 (−40.10, − 7.32)	P = 0.005	**Robot**	89%
(Guerrini 2020)	n=34	4799	11780		MD= -18.24 (-25.21, -11.26)	P < 0.0001	**Robot**	88%
(Ma 2020)	n=17	2422	4196		LG vs RG MD= 28.66 (18.59, 38.73)	P < 0.0001	**Robot**	81%
(Aiolfi 2021)	n=16	NR	NR	NR	RG vs OG MD=-14.4 (-38.4, -9.4) RG vs LG MD=33.4 (-7.92, 58.9)	NR	**Robot** NS	75.8%
(Feng 2021)	N=16	4925	5393		MD=-15.87 (-23.35, -8.39)	P<0.000001	**Robot**	76%
(Zhang 2021)	N=11	1152	1493		MD= -31.91 (-44.03, -19.83)	P<0.000001	**Robot**	93%
(Zhang 2021)	N=15	1106	1812		MD= -29.56 (-43.01, -16.11)	P<0.0001	**Robot**	96%
(Ali 2022)	N=27	3921	8539		MD= −17.97 (−25.61, −10.32)	P <0.001	**Robot**	89%
(Baral 2022)		5905	13451		MD= -21.93 (-28.94, -14.91)	P<0.000001	**Robot**	93%
(Chen 2022)	N=7				RG vs OG MD= -114.63 (-182.37, -46.88)		**Robot**	89%

(Gong 2022)		2051	2940		MD= -24.84 (-41.28, -8.43)	P=0.003	**Robot**	97%
(Jin 2022)					MD= -20.09 (-26.86, -13.32)		**Robot**	83%
(Sun 2022)		1331	1332		MD= -36.8 (-37.72, -20.97)	P<0.00001	**Robot**	42%
(Davey 2023)					RG vs OG MD= –87.2 (–173., –2.75)		**Robot**	
(Lacovazzo 2023)		893	912		MD= 54.53 (-24.19, 133.26)		NS	99%
(Yu 2023)	N=6	422	296		MD= 0.28 (-29.66, 30.22)	P=0.99	NS	84%
(Multani 2023)					LG vs RG MD= 31 (5.43, 56.57)	P=0.0293	**Robot**	NS

CI confidence interval; MD mean difference; NR not reported; NS not significant; RG robotic gastrectomy; LG laparoscopic gastrectomy; OG open gastrectomy

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Conversion to open approach (%)								
(Chen 2017)	n=4	6	16		LG vs RG RR=0.88 (0.36, 2.17)	P=0.78	NS	0%
(Ai 2019)	n=6	9/996	18/1880		OR=1.34 (0.59, 3.01)	P=0.49	NS	0%
(Liao 2019)	n=4	4/578	7/1349		RR=0.00 (-0.01, 0.01)	P=0.67	NS	0%
(Bobo 2019)	n=4	7/365	14/866		OR=1.58 (0.60, 4.14)	P = 0.35	NS	0%
(Guerrini 2020)	n=28	20/3777	67/9584		OR=0.76 (0.45, 1.28)	P = 0.30	NS	1%
(Aiolfi 2021)	n=15	NR	NR	NR	OR= 0.55 (0.18, 1.63)	NR	NS	64.7%
(Feng 2021)	N=4	2301	2567		OR= 0.66 (0.40, 1.07)	P=0.09	NS	0%
(Ali 2022)	N=21	18/2899	55/6415		OR = (0.71 0.38,1.33)	P=0.29	NS	12%
(Jin 2022)	N=7				OR= 0.86 (0.44, 1.66)		NS	0%
(Lacovazzo 2023)		1396	1402		OR= 0.56 (0.34, 0.91)		**Robot**	20%

CI confidence interval; NR not reported; NS not significant; RR relative risk; OR odds ratio; RG robotic gastrectomy; LG laparoscopic gastrectomy; OG open gastrectomy

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Length of hospital stays (days)								
(Caruso 2017)	n=6	689		5434	RG vs OG MD=-1.97 (-2.47, -1.18)	P < 0.001	**Robot**	55%
(Chen 2017)	n=19	1830	4123		LG vs RG MD=0.35 (-0.25, 0.95)	P=0.25	NS	82%
(Wang 2017)	n=11	949	2425		MD= -0.65 (-1.53, 0.23)	P=0.15	NS	84%
(Wang 2017)	n=3	165	397		MD= 0.19 (-0.91, 1.30)	P=0.74	NS	0%
(Yang 2017)	n=6	NR	NR	NR	RG vs OG MD= 4.37 (-0.75, 9.49)	P=0.09	NS	99%
(Ai 2019)	n=22	2601	5487		MD= -0.36 (-0.88, 0.16)	P=0.18	NS	87%
(Bobo 2019)	n=14	NR	NR	NR	MD= −0.49 (−0.99, 0.02)	P = 0.06	NS	45%
(Guerrini 2020)	n=39	5060	12231		MD= -0.32 (-0.71, 0.07)	P=0.11	NS	86%
(Liao 2019)	n=8	994	2180		MD= -0.24 (-0.60, 0.11)	P=0.18	NS	0%
(Ma 2020)	n=19	2677	4598		MD=0.23 (-0.53, 0.98)	P=0.56	NS	93%
(Aiolfi 2021)	n=15	NR	NR	NR	RG vs OG MD=-0.29 (-3.21, 2.42) RG vs LG MD=0.66 (-2.03, 3.62)	NP	NS NS	2.7%
(Feng 2021)	N=18	5765	6562		MD=-0.31 (-0.47, -0.15)	P=0.000001	**Robot**	25%
(Zhang 2021)	N=12	1339	1837		MD= -0.21 (-0.88, 0.47)	P=0.55	NS	94%
(Zhang 2021)	N=15	1037	1989		MD= -0.65 (-1.23, -0.07)	P=0.03	**Robot**	87%
(Gong 2022)		1952	2790		MD= -0.65 (-1.27, -0.08)	P=0.03	**Robot**	92%
(Baral 2022)		6136	13912		MD= -0.54 (-0.83, -0.24)	P=0.00003	**Robot**	80%
(Chen 2022)	N=9				RG vs OG MD= -2.21 (-4.32, -0.09)		**Robot**	97%
(Jin 2022)					MD= -0.37 (-0.75, 0.01)	P=0.06	NS	84%
(Sun 2022)		1381	1382		MD= -0.21 (-0.44, 0.01)	P=0.07	NS	0%
(Lacovazzo 2023)		1379	844		MD= 0.68 (-0.74, 2.09)		NS	89%
(Yu 2023)		355	205		MD= -0.81 (-1.25, -0.38)	P=0.00002	**Robot**	0%
(Multani 2023)					LS vs RG MD= -1.89 (-5.77, 1.99)	P=0.3382	NS	NR

CI confidence interval; MD mean difference; NR not reported; NS not significant; RG robotic gastrectomy; LG laparoscopic gastrectomy; OG open gastrectomy

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Postoperative complication (%)								
(Wang 2017)	n=12	133/1134	279/2610		OR=1.12 (0.89, 1.41)	P=0.33	NS	0%
(Wang 2017)	n=3	31/165	62/397		OR= 1.37 (0.81, 2.30)	P=0.24	NS	0%
(Yang 2017)	n=7	77/606		648/5364	RG vs OG OR=0.92 (0.57, 1.50)	P=0.75	NS	38%
(Caruso 2017)	n=6	88/689		649/5354	OR=0.95 (0.60, 1.34)	P = 0.65	NS	12%
(Chen 2017)	n=19	1830	4123		LG vs RG RR=0.96 (0.82, 1.13)	P = 0.65	NS	0%
(Bobo 2019)	n=15	190/1487	338/2939		OR=1.05 (0.86, 1.28)	P=0.65	NS	2%
(Liao 2019)	n=8	145/994	309/2180		OR=0.90 (0.72, 1.12)	P=0.34	NS	16%
(Ma 2020)	n=19	286/ 2677	492/4598		OR=1.07 (0.91, 1.25)	P=0.43	NS	0%
(Guerrini 2020)	n=31	643/5043	1535/11268		OR= 0.91 (0.79, 1.04)	P=0.16	NS	24%
(Aiolfi 2021)	n=17				RG vs OG OR=0.69 (0.41, 1.22) RG vs LG OR=0.91 (0.52, 1.67)	NP	NS NS	16%
(Feng 2021)	N=17	4823	5292		OR=0.81 (0.72, 0.91)	P=0.00003	**Robot**	29%
(Zhang 2021)	N=9	144/1149	237/1479		RR= 0.75 (0.62, 0.91)	P=0.003	**Robot**	7%
(Zhang 2021)	N=14	115/ 1122	277/2012		OR= 0.92 (0.72, 1.19)	P=0.54	NS	0%
(Ali 2022)	N=32	529/4484	1086/9101		OR = 0.87 (0.77,0.98)	P=0.02	**Robot**	33%
(Baral 2022)		737/6136	1875/13937		OR=0.88 (0.78, 1.00)	P=0.04	**Robot**	22%
(Chen 2022)	N=11				RG vs OG OR= 0.57 (0.35, 0.93)		**Robot**	65%
(Gong 2022)	N=7	8/1233	8/1741		OR= 1.60 (0.60, 4.29)	P=0.35	NS	0%
(Jin 2022)					OR= 0.81 (0.71, 0.93)	P=0.02	**Robot**	35%
(Sun 2022)		199/1381	228/1382		OR=0.84 (0.68, 1.04)	P=0.11	NS	18%
(Lacovazzo 2023)		3807	3779		OR= 0.79 (0.58, 1.07)	P=0.55	NS	0%

(Ye 2023)	N=4	41/216		119/453	RG vs OG MD= 0.78 (0.52, 1.18)	P=0.24	NS	31%
(Yu 2023)	N=4	16/157	65/669		MD= 0.88 (0.47, 1.63)	P=0.68	NS	0%

CI confidence interval; NR not reported; NS not significant; RR relative risk; OR odds ratio; RG robotic gastrectomy; LG laparoscopic gastrectomy; OG open gastrectomy

*lymphatic complications

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Time to first flatus (days)								
(Chen 2017)	n=9	713	1231		LG vs RG MD=0.09 (-0.10, 0.27)	P= 0.36	NS	74%
(Ai 2019)	n=13	1557	2570		MD=-0.2 (-0.53, 0.14)	P=0.25	NS	98%
(Bobo 2019)	n=7	NR	NR	NR	MD= - 0.20 (-0.42, - 0.02)	P = 0.07	NS	53%
(Guerrini 2020)	n=20	2344	4566		MD= -0.19 (-0.45, 0.07)	P<0.16	NS	98%
(Ma 2020)	n=13	1888	2847		LG vs RG MD=0.16 (0.06, 0.27)	P=0.003	**Robot**	65%
(Aiolfi 2021)	NR	NR	NR	NR	RG vs OG MD=-0.52 (-1.11, -0.30) RG vs LG MD=0.32 (-0.56, 1.19)	NP	**Robot** NS	2.7%
(Feng 2021)	N=12	4270	4538		MD= -0.14 (-0.22, -0.07)	P=0.00003	**Robot**	65%
(Zhang 2021)	N=8	1073	1365		MD= -0.13 (-0.22, -0.44)	P=0.005	**Robot**	71%
(Baral 2022)		3084	5322		MD= -0.20 (-0.42, 0.02)	P=0.08	NS	97%
(Gong 2022)	N=5	599	519		MD= -0.23 (-0.59, 0.13)	P=0.22	NS	78%
(Jin 2022)					MD= -0.11 (-0.21, -0.00)	P=0.044	**Robot**	65%
(Sun 2022)		1099	1100		MD= -0.08 (-0.13, -0.02)	P=0.006	**Robot**	44%
(Lacovazzo 2023)		954	964		MD= -0.32 (-0.55, -0.09)		**Robot**	84%
(Yu 2023)		56	73		MD= -0.76 (-0.60, -0.32)	P<0.00001	**Robot**	49%

CI confidence interval; MD mean difference; NR not reported; NS not significant; RG robotic gastrectomy; LG laparoscopic gastrectomy; OG open gastrectomy

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Time to oral intake (days)								
(Chen 2017)	n=9	1096	2055		LG vs RG MD=0.23 (0.13, 0.34)	P<0.0001	**Robot**	0%
(Guerrini 2020)	n=22	2828	5123		MD= -0.20 (-0.30, -0.10)	P<0.0001	**Robot**	58%
(Aiolfi 2021)		NR	NR	NR	RG vs OG MD=-0.39 (-3.95, 3.14) RG vs LG MD=0.03 (-3.81, 3.88)	NP	NS NS	7.1%
(Feng 2021)	N=15	4604	5673		MD= -0.12 (-0.18, -0.06)	P=0.00001	**Robot**	20%
(Zhang 2021)	N=7	747	760		MD= -0.0 (-0.28, -0.12)	P<0.00001	**Robot**	7%
(Zhang 2021)	N=11	748	758		MD= -0.31 (0.43, -0.18)	P<0.00001	**Robot**	51%
(Baral 2022)		3855	7160		MD= -0.20 (-0.29, -0.10)	P<0.00001	**Robot**	53%
(Gong 2022)		1312	1618		MD= -0.08 (-0.17, 0.01)	P=0.07	NS	0%
(Sun 2022)		623	623		MD= -0.04 (-0.31, 0.23)	P=0.78	NS	0%
(Yu 2023)		56	73		MD= -0.46 (-0.74, -0.19)	P=0.0010	**Robot**	0%
(Feng 2021)	N=15	4604	5673		MD= -0.12 (-0.18, -0.06)	P=0.00001	**Robot**	20%
(Zhang 2021)	N=7	747	760		MD= -0.0 (-0.28, -0.12)	P<0.00001	**Robot**	7%
(Zhang 2021)	N=11	748	758		MD= -0.31 (0.43, -0.18)	P<0.00001	**Robot**	51%

CI confidence interval; MD mean difference; NR not reported; NS not significant; RG robotic gastrectomy; LG laparoscopic gastrectomy; OG open gastrectomy

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Postoperative mortality (%)								
(Chen 2017)	n=7	838	2131		RG vs LG RR =0.67 (0.26, 1.74)	P=0.41	NS	0%
(Bobo 2019)	n=8	5/808	9/2087		RG vs LG OR= 1.35 (0.49, 3.76)	NR	NS	0%
(Liao 2019)	n=4	4/578	3/1349		RG vs LG RD= 0.01 (0.00, 0.01)	P = 0.19	NS	0%

(Ma 2020)	n=5	7/768	7/1356		LG vs RG OR = 0.67 (0.24, 1.90)	P= 0.450	NS	0%
(Aiolfi 2021)		NR	NR	NR	RG vs OG RR=0.93 (0.43, 2.01) RG vs LG RR=0.58 (0.22, 1.55)	NR	NS	NR

CI confidence interval; RD risk difference; NR not reported; NS not significant; RG robotic gastrectomy; LG laparoscopic gastrectomy; OG open gastrectomy

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I²**
		Robot	Laparoscopy	Open				
Reoperation rate (%)								
(Chen 2017)	n=7	789	1796		LG vs RG RR=0.69 (0.29, 1.62)	P=0.39	NS	11%
(Bobo 2019)	n=5	16/754	16/1400		OR= 1.72 (0.89, 3.35)	P = 0.11	NS	45%
(Guerrini 2020)		25/1939	55/4467		OR= 1.01 (0.60, 1.68)	P=0.98	NS	0%
(Aiolfi 2021)	n=10	NR	NR	NR	RG vs OG OR= 0.87 (0.41, 1.88) RG vs LG OR=0.82 (0.33, 2.05)	NP	NS NS	0%
(Feng 2021)	N=5	1197	1464		OR= 0.63 (0.33, 1.20)	P=16	NS	0%
(Baral 2022)		30/2192	60/4693		OR= 1.05 (0.68, 1.62)	P=0.83	NS	0%
(Jin 2022)					OR= 0.86 (0.44, 1.66)	P=0.65	NS	0%
(Feng 2021)	N=5	1197	1464		OR= 0.63 (0.33, 1.20)	P=16	NS	0%

CI confidence interval; NR not reported; NS not significant; RR relative risk; OR odds ratio; RG robotic gastrectomy; LG laparoscopic gastrectomy; OG open gastrectomy

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I²**
		Robot	Laparoscopy	Open				
Recurrence rate (%)								
(Pan 2017)	n=4	23/273	99/941		OR=0.88 (0.54, 1.44)	P=0.62	NS	0%

(Chen 2017)	n=3	500	187		RR=1.09 (0.57, 2.05)	P=0.80	NS	0%
(Liao 2019)	n=7	109/863	255/1917		OR=0.92 (0.71, 1.19)	P=0.53	NS	0%
(Ma 2020)	n=5	129/1038	102/757		LG vs RG OR=0.90 (0.67, 1.21)	P=0.50	NS	0%
(Guerrini 2020)	n=10	131/1322	263.1942		OR=0.86 (0.67, 1.11)	P=0.25	NS	0%
(Wu 2021)	N=9	121/1100	281/2170		OR= 0.88 (0.69, 1.12)	P=0.31	NS	0%
(Zhang 2021)	N=3	23/231	31/222		OR=0.69 (0.39, 1.23)	P=0.21	NS	0%
(Wu 2021)	N=9	121/1100	281/2170		OR= 0.88 (0.69, 1.12)	P=0.31	NS	0%
(Zhang 2021)	N=3	23/231	31/222		OR=0.69 (0.39, 1.23)	P=0.21	NS	0%

CI confidence interval; NR not reported; NS not significant; RR relative risk; OR odds ratio; RG robotic gastrectomy; LG laparoscopic gastrectomy; OG open gastrectomy

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Number of harvested lymph nodes								
(Caruso 2017)	n=6	689		5434	MD=-1.12 (-2.31, 0.58)	P = 0.10	NS	25%
(Chen 2017)	n=17	1585	3220		LG vs RG MD= -1.44 (-3.26, 0.37)	P=0.12	NS	86%
(Wang 2017)	n=10	849	2143		MD=0.91 (-1.16, 2.99)	P=0.39	NS	70%
(Wang 2017)	n=2	85	115		MD= −0.23 (−3.80, 3.35)	P=0.90	NS	0%
(Yang 2017)	n=7	NR	NR	NR	RG vs OG MD= -1.36 (-3.69, 0.97)	P=0.25	NS	67%
(Ai 2019)	n=21	2413	4592		MD=1.92 (0.34, 3.50)	P=0.02	Laparoscopy	86%
(Bobo 2019)	n=14				MD= 1.81 (0.00, 3.62)	P = 0.05	Laparoscopy	74%
(Guerrini 2020)	n=36	4731	10900		MD= 1.84 (0.84, 2.84)	P= 0.0003	Laparoscopy	79%
(Ma 2020)	n=19	2677	4598		LG vs RG MD= -0.96 (-2.12, 0.20)	P=0.10	NS	83%
(Aiolfi 2021)	n=17				RG vs OG MD=1.04 (-4.62, 6.64) RG vs LG MD=3.16 (-2.49, 9.16)	NP	NS NS	6.5%
(Feng 2021) *	N=16	5004	5837		MD= 1.75 (0.90, 2.60)		Laparoscopy	70%

(Zhang 2021) *	N=11	1206	1570		MD= 1.65 (-0.14, 3.44)	P=0.07	NS	91%
(Zhang 2021) *	N=15	1170	1914		MD= 3.52 (2.07, 4.99)	P<0.00001	Laparoscopy	82%
(Ali 2022)	N=28	3813	7691		MD= 2.62 (2.14,3.11)	P<0.0001	Laparoscopy	77%
(Gong 2022)*		2061	2950		MD= 2.41 (0.77, 4.05)	P<0.004	**Robot**	86%
(Baral 2022) *		5930	13082		MD= 2.81 (1.99, 3.63)	P<0.0001	Laparoscopy	87%
(Chen 2022)	N=3				RG vs OG MD= -1.15 (-5.43, 3.14)		NS	90$
(Jin 2022) *					MD= 2.03 (0.95, 3.10)	P<0.001	Laparoscopy	
(Sun 2022)		1240	1240		MD= 3.46 (2.94, 3.98)	P<0.00001	**Robot**	24%
(Davey 2023)					RG vs OG MD= –1.95 (–5.77, 1.25)		NS	

CI confidence interval; MD mean difference; NR not reported; NS not significant; RG robotic gastrectomy; LG laparoscopic gastrectomy; OG open gastrectomy
*the number of resected lymph nodes

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
Proximal resection margin (cm)								
(Chen 2017)	n=9	1024	2006		MD=-0.14 (-0.36, 0.07)	P=0.18	NS	26%
(Wang 2017)	n=5	723	1733		MD= 0.10 (-0.08, 0.28)	P=0.26	NS	4%
(Yang 2017)	n=3	NR	NR	NR	RG vs OG MD= 0.10 (-0.43, 0.64)	P=0.70	NS	72%
(Bobo 2019)	n=6				MD=0.034 (− 0.012, 0.081)	P = 0.15	NS	0%
(Guerrini 2020)	n=13	1940	4978		MD= 0.01 (-0.14, 0.17)	P=0.87	NS	23%
(Ma 2020)	n=7	761	1252		LG vs RG MD= -0.10 (-0.29, 0.09)	P=0.30	NS	28%
(Feng 2021)	N=6	1117	1319		MD= -0.02 (-0.20, 0.17)	P=0.85	NS	0%
(Zhang 2021)	N=5	3434	655		MD= -0.24 (-0.68, 0.19)	P=0.27	NS	66%
(Ali 2022)	N=12	1519	3315		MD =0.07 (-0.07, 0.22)	P=0.30	NS	80%
(Gong 2022)	N=6	1117	1614		MD= 0.22 (-0.04, 0.48)	P=0.10	NS	37%
(Jin 2022)					MD= -0.005 (-1.72, 0.161)	P=0.949	NS	0%

CI confidence interval; MD mean difference; NR not reported; NS not significant; RG robotic gastrectomy; LG laparoscopic gastrectomy; OG open gastrectomy

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
Distal resection margin (cm)								
(Wang 2017)	n=5	723	1733		MD= 0.18 (-0.67, 1.03)	P=0.88	NS	88%
(Yang 2017)	n=3	NR	NR	NR	RG vs OG MD=0.52 (-0.76, 1.79)	P-0.43	NS	91%
(Chen 2017)	n=8	NR	NR	NR	MD=0.09 (-0.46, 0.65)	P=0.74	NS	81%
(Bobo 2019)	n=5	NR	NR	NR	MD=0.073 (−0.047, 0.193)	P = 0.23	NS	64%
(Guerrini 2020)	n=12	1889	4920		MD=0.27 (-0.15, 0.69)	P=0.21	NS	79%
(Ma 2020)	n=5	710	1194		LG vs RG MD= 0.15 (-0.21, 0.53)	P=0.41	NS	59%
(Feng 2021)	N=6	1117	1319		MD= 0.07 (-0.13, 0.27)	P=0.51	NS	12%
(Zhang 2021)	N=5	3434	655		MD= 0.21 (0.02, 0.04)	P=0.03	Laparoscopy	0%
(Ali 2022)	N=11	1468	3257		MD =0.13 (-0.05, 0.32)	P=0.15	NS	80%
(Gong 2022)	N=6	1176	1614		MD= -0.08 (-0.42, 0.25)	P=0.63	NS	66%
(Jin 2022)					MD= -0.57 (-0.97, -0.20)	P=0.03	**Robot**	52%

CI confidence interval; MD mean difference; NR not reported; NS not significant; RG robotic gastrectomy; LG laparoscopic gastrectomy; OG open gastrectomy

Outcome	Studies included, n	Participant, N			Pooled effect (95%CI)	P-value	Favours	I^2
		Robot	Laparoscopy	Open				
5-year overall survival rate								
(Pan 2017)	n=3	NR	NR	NR	HR=1.32 (0.94, 1.87)	P=0.11	NS	0%
(Ai 2019)	n=3	393/495	549/645		OR=0.54 (0.22, 1.33)	P=0.18	NS	79%
(Bobo 2019)	n=3	NR	NR	NR	HR=1.15 (0.51, 2.59)	P=0.73	NS	0%
(Liao 2019)	n=8	NR	NR	NR	HR= 0.98 (0.80, 1.20)	P=0.81	NS	0%
(Ma 2020)	n=6	890	1498		LG vs RG HR=0.95 (0.76, 1.18)	P=0.64	NS	0%
(Feng 2021)	N=7	3475	4106		OR=0.96 (0.86, 1.07)	P=0.50	NS	0%
(Wu 2021)	N=11				HR= 0.97 (0.80, 1.19)	P=0.80	NS	0%
(Baral 2022) (3 year)	N=12	1665/1926	3854/4857		OR= 1.19 (0.70, 2.20)	P=0.52	NS	88%

(Jin 2022) (3 year)					OR= 0.10 (0.78, 1.35)	P=0.83	NS	1.2%

CI confidence interval; NR not reported; NS not significant; HR hazard ratio; OR odds ratio; RG robotic gastrectomy; LG laparoscopic gastrectomy; OG open gastrectomy

Outcome	**Studies included, n**	**Participant, N**			**Pooled effect (95%CI)**	**P-value**	**Favours**	**I^2**
		Robot	Laparoscopy	Open				
5-year disease-free survival rate								
(Pan 2017)	n=2	NR	NR	NR	HR 1.57 (0.82, 3.00)	P=0.17	NS	0%
(Ai 2019)	n=2	328/362	341/369		OR=0.79 (0.47, 1.33)	P=0.38	NS	0%
(Bobo 2019)	n=2	NR	NR	NR	HR=2.24 (0.79, 6.35)	P=0.13	NS	0%
(Liao 2019)*	n=8	NR	NR	NR	HR=0.92 (0.72, 1.19)	P=0.53	NS	0%
(Ma 2020)*	n=3	586	586		LG vs RG HR=0.91 (0.69, 1.21)	P=0.53	NS	0%
(Feng 2021) *	N=5	2732	2732		OR= 0.98 (0.80, 1.21)	P=0.85	NS	0%
(Wu 2021)	N=6				HR= 0.94 (0.72, 1.23)	P=0.65	NS	0%

CI confidence interval; NR not reported; NS not significant; HR hazard ratio; OR odds ratio; RG robotic gastrectomy; LG laparoscopic gastrectomy; OG open gastrectomy

*Relapse-free survival (RFS)

Appendix 4 - Database search terms for the scoping review

Database search record		
Database:	**Saved search strategy name**	**Search strategy (inc. limits and filters)**
PubMed	RAS PubMed (1685)	(Robotic AND (open or laparoscopic surgery)) AND (cost OR economic) AND (English[lang] AND (‘‘2015/01/01 ‘‘[PDat]:’’2023/12/30’’[PDat]))
Ovid Embase	RAS surgery Embase (1840)	1. (Robotic and (open or laparoscopic surgery)).mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword heading word, floating subheading word, candidate term word] 2. (cost or economic).mp. [mp=title, abstract, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword heading word, floating subheading word, candidate term word] 3. 1 and 2 4. limit 3 to english language limit 4 to yr="2015 - 2023"

Appendix 5 - Characteristics of the included studies from the scoping review

Study/ Country	Specialty/ Procedure	Comparator	Outcomes	Cost component	Model type/ Sensitivity analysis	Perspective/ Time horizon	Conclusion	RAS specific items			
								learning curve	organisational impact	incremental innovation	dynamic pricing
CUA (n=23, 46%)											
HQO (HQO, 2017) 2017 Canada	Urology, prostatectomy	Open	QALYS	Hospital costs, medication costs, capital costs	Decision tree and Markov model/ Yes	Healthcare Payer perspective/ 1 year; 10-year for SA	RAS not cost-effective	NR	Fully considered. Scenario analysis for donated robotic surgical system.	NR	NR
Mäkelä-Kaikkonen (Mäkelä-Kaikkonen et al., 2019) 2019 Finland	Colorectal, ventral mesh rectopexy	LS	QALYS	Hospital costs, medication costs, capital costs	Not model based/ Yes	Healthcare provider in hospital/ 2 years and 5 years	RAS only cost-effective in long-term.	NR	NR	NR	NR
Vicente (Vicente et al., 2020) 2020 Spain	HPB, distal pancreatectomy	LS	QALYS	Hospital costs, medication costs	Micro-simulation/ Yes	Healthcare provider in hospital/ NR	RAS cost-effective	Partial considered. All consecutive cases were conducted by the same group of six surgeons, all with considerable experience in both LS and RAS.	Partial considered. Excluded Robotic surgical system due to purchase in advance.	Partial considered. RAS was performed using a da Vinci Robotic Surgical System model Si and Xi.	NR
Caruso (Caruso et al., 2020) 2020 Spain	Upper GI, gastrectomy	Open	QALYS	Hospital costs	Micro-simulation/ Yes	Healthcare provider in hospital/ NR	RAS cost-effective	NR	NR	Partial considered. RAS were performed using the da Vinci	NR

										Robotic Surgical System model Si for the first procedures and, from 2014, the last da Vinci Xi generation was used.	
Simianu (Simianu et al., 2020) 2020 US	Colorectal, colectomy	LS, Open	QALYS	Hospital costs, medication costs, capital costs; sick leave, caregiver	Decision tree/ Yes	Both healthcare and societal/ 1 year	Both RAS and LS cost-effective, but LS is the most	Partial considered. In high volume setting.	Partial considered. Capital costs were allocated across patient cases per annum.	NR	NR
Lundin (Lundin et al., 2020) 2020 Sweden	Gynaecology, hysterectomy	Open	QALYS	Hospital costs, medication costs, capital costs; sick leave	Not model based/ No	Both healthcare and societal/ NR	RAS not cost-effective	NR	NR	NR	NR
Quijano (Quijano et al., 2020) 2020 Spain	Colorectal, rectal resection	LS	QALYS	Hospital costs, medication costs	Micro-simulation/ Yes	Healthcare provider in hospital/ NR	RAS cost-effective	NR	Partial considered. Excluded Robotic surgical system due to purchase in advance.	NR	NR
Kukreja (Kukreja et al., 2020) 2020 US	Urology, cystectomy	Open	QALYS	Hospital costs	Decision tree/ Yes	Healthcare Payer perspective/ 90 days	RAS cost-effective	Partial considered. In high volume setting. All surgeons had significant experience and were past their learning curve	NR	NR	NR

								(> 50 robotic pelvic cases).			
Parackal (Parackal et al., 2020) 2020 Canada	Urology, prostatectomy	Open	QALYS	Hospital costs, medication costs, capital costs, outpatient costs	Markov model/ Yes	Healthcare Payer perspective / 10 years	RAS cost-effective	NR	Fully considered. To reflect this uncertainty, a sensitivity analysis was conducted by using volume of 350 (low-utilization) and 500 (high-utilization) cases per year. Capital costs were allocated across patient cases per annum.	NR	NR
Simianu (Simianu et al., 2021) 2021 US	Colorectal, proctectomy	LAP, Open	QALYS	Hospital costs, medication costs, capital costs; sick leave, caregiver	Decision tree/ Yes	Both healthcare and societal/ 1 year	Both RAS and LS cost-effective, but LS is the most	NR	Partial considered. Capital costs were allocated across patient cases per annum.	NR	NR
de Oliveira (de Oliveira et al., 2021) 2021 Brazil	Urology, prostatectomy	Open	QALYS	Hospital costs, outpatient costs	Micro-simulation/ No	Healthcare Payer perspective/ 5 years	RAS is cost-effective in long-term	NR	NR	NR	NR
Ferri (Ferri et al., 2021) 2021 Spain	Colorectal, colectomy	LS	QALYS	Hospital costs, medication costs	Micro-simulation/ Yes	Healthcare Payer perspective	RAS cost-effective	Partial considered. Setting given all surgeons with LS experience. 5 of the surgeons had	Partial considered. Excluded Robotic surgical system acquisition and	Partial considered. RAS was performed using a da Vinci Robotic Surgical	NR

								experience with a robotic system and had completed a training program 3 years prior to the initiation of this study.	maintenance cost.	System model Si and Xi.	
Faria (Faria et al., 2022) 2022 Brazil	Urology, Prostatectomy	LS, Open	QALYS	Hospital costs, medication costs	Markov model/ Yes	Healthcare Payer perspective/ 20 years	RAS cost-effective	NR	Partial considered. Donation setting.	NR	NR
Caruso (Caruso et al., 2022) 2022 Spain	HPB, pancreatic enucleation	Open	QALYS	Hospital costs, medication costs	Micro-simulation/ Yes	Healthcare provider in hospital/ NR	RAS cost-effective	NR	Partial considered. Robotic surgical system acquisition or maintenance cost were recorded under the patient's unique medical record number.	NR	NR
Machleid (Machleid et al., 2022) 2022 UK	Urology, cystectomy	Open	QALYS	Hospital costs, medication costs	Decision tree/ Yes	Healthcare Payer perspective/ 90 days	RAS not cost-effective	NR	NR	NR	NR
Lindenberg (Lindenberg et al., 2022) 2022 Netherlands	Urology, proctectomy	LS	QALYS	Hospital costs, medication costs, capital costs; sick leave, caregiver	Micro-simulation/ Yes	Societal perspective/ 7 years	RAS is cost-effective in long-term	NR	NR	NR	NR
Labban (Labban et al., 2022) 2022	Urology, proctectomy	LS, Open	QALYS	Hospital costs, medication costs,	Markov model/ Yes	Both healthcare and societal/ 10 years	RAS cost-effective	Fully considered.	Fully considered.	Fully considered.	Fully considered.

UK				capital costs, productivity loss, caregiver				Examined the effect of different surgical volumes as a proxy for surgeons' learning curves.	Accounted for the capital cost of acquiring the robotic system and its use different specialties. Capital costs were allocated across patient cases per annum.	Scenario analysis of the latest prices to account various generations of da Vinci systems.	Scenario analysis was conducted using the latest prices for the various generations of da Vinci systems.
Singh (Singh et al., 2023) 2023 US	HPB, cholecystectomy	LS	QALYS	Hospital costs, medication costs	Micro-simulation/ Yes	Healthcare Payer perspective/ 1 year	RAS not cost-effective	NR	Partial considered. Excluded Robotic surgical system capital cost.	NR	NR
Lu (Lu et al., 2023) 2023 China	Upper GI, gastrectomy	LS, Open	QALYS	Hospital costs, medication costs, capital costs	Micro-simulation/ Yes	Healthcare Payer perspective/ 1 year	RAS not cost-effective	NR	NR	NR	NR
Panse (Panse et al., 2023) 2023 US	General, hernia repair	LS	QALYS	Hospital costs, medication costs, capital costs	Decision tree/ Yes	Healthcare Payer perspective/ 5 years	RAS not cost-effective	Partial considered. Low-volume setting. But sensitivity analyses to represent the RAS learning curve as best as possible.	Fully considered. Scenario analysis for with/ without accounting for capital and maintenance costs. Sensitivity analysis to compare annual volume of RAS and identify the percentage of RAS among all	NR	NR

									general surgery cases.		
McCarthy (McCarthy et al., 2023) 2023 UK	Gynaecology, hysterectomy	LS	QALYS	Hospital costs, medication costs, capital costs	Micro-simulation/ Yes	Healthcare Payer perspective/ 12 weeks	RAS cost-effective	NR	Fully considered. Assumption on surgical procedures per day across a year. Sensitivity analysis on assuming different rates of daily usage.	NR	NR
Huang (Huang et al., 2023a) 2023 China	Paediatric	LS	QALYS	Hospital costs, medication costs, capital costs	Micro-simulation/ Yes	Healthcare Payer perspective/ 2 years	RAS cost-effective	NR	NR	NR	NR
Dixon (Dixon et al., 2023) 2023 UK	Urology, cystectomy	Open	QALYS	Hospital costs, medication costs, capital costs	Micro-simulation/ Yes	Healthcare Payer perspective/ 90 days	RAS not cost-effective	NR	Partial considered. Capital costs were allocated across patient cases per annum.	NR	NR
CCA (n=16, 32%)											
Vasudevan (Vasudevan et al., 2016) 2016 US	Colorectal	LS	Monetary outcome	Hospital costs	Not model based/ No	Healthcare provider in hospital/ NR	RAS is less costly than LS	Partial considered. high-volume setting	NR	NR	NR
Probst (Probst et al., 2016) 2016 Germany	Urology, adrenalectomy	Open	Monetary outcome	Hospital costs	Not model based/ No	Healthcare Payer perspective/ NR	RAS cost-effective	Partial considered. high-volume setting;	NR	NR	NR

								surgeons had significant experience at least 100 cases. looked at the mean operating time			
Hughes (Hughes et al., 2016) 2016 UK	Urology, nephrectomy	LS, Open	Monetary outcome	Hospital costs, outpatient costs	Not model based/ No	Healthcare Payer perspective/ 1 year	RAS is less costly than LS and Open	NR	NR	NR	NR
Magge (Magge et al., 2018) 2018 US	HPB, distal pancreatectom y	LS, Open	Monetary outcome	Hospital costs, medication costs, capital costs	Not model based/ No	Healthcare provider in hospital/ NR	Open more costly than RAS and LS	Partial considered. high-volume setting.	NR	NR	NR
Rodriguez (Rodriguez et al., 2018) 2018 France	HPB, distal pancreatectom y	LS, Open	Monetary outcome	Hospital costs, medication costs	Not model based/ No	Healthcare provider in hospital/ NR	Open more costly than RAS and LS; RAS similar to LS	NR	NR	NR	NR
Souche (Souche et al., 2018) 2018 France	HPB, distal pancreatectom y	LS	Monetary outcome	Hospital costs, medication costs, capital costs	Not model based/ No	Healthcare Payer perspective/ NR	RAS not cost-effective	Fully considered. operative time and docking time analysis to identify learning curve.	Partial considered. Excluded Robotic surgical system due to purchase in advance ; shared with the Departments of Urology and gynecologic surgery.	NR	NR

Khoraki (Khoraki et al., 2020) 2020 US	General	LS	Monetary outcome	Hospital costs, medication costs, capital costs	Not model based/ No	Healthcare provider in hospital/ NR	RAS more costly than LS	Fully considered. used linear regression to examine operative time and to determine if a learning effect could change the incidence of complications along the study period.	NR	NR	NR
Merola (Merola et al., 2020) 2020 Italy	Colorectal, colectomy	LS	Monetary outcome	Hospital costs, medication costs, capital costs	Not model based/ No	Healthcare Payer perspective/ NR	RAS more costly than LS	Partial considered. Setting in all surgeons had significant experience and completed the learning curve.	NR	Partial considered. the first 25 cases were done by a different DaVinci generation.	NR
Okhawere (Okhawere et al., 2021) 2021 US	Urology, prostatectomy	Open	Monetary outcome	Hospital costs, medication costs, capital costs; sick leave	Not model based/ No	Societal perspective/ 1 year	RAS potentially offer benefit than LS	NR	NR	NR	NR
Ploussard (Ploussard et al., 2022) 2022 France	Urology, prostatectomy	LS, Open	Monetary outcome	Hospital costs	Not model based/ No	Healthcare Payer perspective/ NR	RAS reduced complication s and LOS than LS and Open	NR	Partial considered. Excluded Robotic surgical system due to purchase in advance.	NR	NR
Miller (Miller et al., 2022) 2022	HPB, hepatectomy:	LS	Monetary outcome	Hospital costs	Not model based/ No	Healthcare provider in hospital/	RAS more costly than LS	Partial considered.	NR	NR	NR

US						perioperative		high-volume setting.			
Aziz (Aziz et al., 2022) 2022 US	HPB, hepatectomy	LS, Open	Monetary outcome	Hospital costs	Not model based/ No	Healthcare provider in hospital/ NR	RAS cost-effective	NR	NR	NR	NR
Delgado-Miguel (Delgado-Miguel and Camps, 2023) 2023 US	Paediatric, redo antireflux surgery	LS	Monetary outcome	Hospital costs	Not model based/ No	Healthcare provider in hospital/ NR	RAS potentially offer benefit than LS	NR	NR	NR	NR
Steffens (Steffens et al., 2023) 2023 Australia	Multi	LS, Open	Monetary outcome	Hospital costs	Not model based/ No	Healthcare Payer perspective/ NR	RAS more costly than LS and Open but better outcomes	NR	NR	NR	NR
Okhawere (Okhawere et al., 2023) 2023 US	Urology, nephrectomy	LS	Monetary outcome	Hospital costs, sick leave	Not model based/ Yes	Societal perspective/ 1 year	RAS is less costly than LS and Open	NR	NR	NR	NR
Knitter (Knitter et al., 2023) 2023 Germany	HPB, hepatectomy	LS, Open	Monetary outcome	Hospital costs, medication costs, capital costs	Not model based/ No	Healthcare provider in hospital/ NR	RAS potentially offer benefit	NR	NR	NR	NR
CEA (n=9, 18%)											
Buse (Buse et al., 2016) 2016 US	Urology, nephrectomy	LAP, Open	Clinical outcomes and QALYS	Hospital costs, medication costs	Decision tree/ Yes	Healthcare provider in hospital/ perioperative period	RAS potentially cost-effective; LS dominated Open	Partial considered. high-volume setting.	NR	NR	NR
Basto (Basto et al., 2016) 2016	Urology, prostatectomy	LAP, Open	Clinical outcomes and QALYS	Hospital costs, capital costs	Micro-simulation/ Yes	Healthcare Payer perspective/	RAS cost-effective	Fully considered.	Fully considered.	Fully considered.	Fully considered.

Australia						NR		Analysed the effect of surgical volume to outcomes.	Performed a hospital volume analysis.	Performed one- and two-way sensitivity analyses for the four-arm da Vinci SHD, Si and Si dual surgical systems.	Applied the different capital cost for the da Vinci SHD, Si and Si dual console models.
Buse (Buse et al., 2018) 2018 US	Urology, nephrectomy	Open	Clinical outcomes and QALYS	Hospital costs, medication costs	Decision tree/ Yes	Healthcare provider in hospital/ perioperative	RAS cost-effective	Fully considered. sensitivity analysis for low- and intermediate-volume settings on cost per avoided complication.	NR	NR	NR
Bansal (Bansal et al., 2018) 2018 UK	Urology, cystectomy	Open	Clinical outcomes and QALYS	Hospital costs, capital costs	Not model based/ Yes	Healthcare Payer perspective/ NR	RAS not cost-effective	Partial considered. Incorporated outcome data during the learning curve	Fully considered. Scenarios for two capital cost models (purchase and maintenance) Capital costs were allocated across patient cases per annum.	NR	NR
Michels (Michels et al., 2019) 2019 Netherlands	Urology, cystectomy	Open	Clinical outcomes and QALYS	Hospital costs, medication costs, capital costs	Decision tree/ Yes	Healthcare provider in hospital/ NR	RAS not cost-effective	Partial considered. high-volume setting.	NR	NR	NR

De Pastena (De Pastena et al., 2021) 2021 Italy	HPB, pancreatectomy	LS	Clinical outcomes and QALYS	Hospital costs, medication costs	Micro-simulation/ No	Healthcare provider in hospital/ NR	RAS cost-effective	NR	Partial considered. Excluded Robotic surgical system due to purchase in advance ; shared with the Urology.	NR	NR
Michels (Michels et al., 2022) 2022 Netherlands	Urology, cystectomy	Open	Clinical outcomes and QALYS	Hospital costs, medication costs, capital costs; productivity losses, caregiver, travel expenses	Micro-simulation/ No	Both healthcare and societal/ 1 year	RAS not cost-effective	NR	Partial considered. Capital costs were allocated across patient cases per annum.	NR	NR
Baghli (Baghli et al., 2023) 2023 France	Urology, nephrectomy	Open	Clinical outcomes and QALYS	Hospital costs	Micro-simulation/ Yes	Healthcare Payer perspective/ NR	RAS cost-effective	Partial considered. Assumption on all surgeons had passed their learning curve period for both surgical approaches.	NR	NR	NR
Ugliono (Ugliono et al., 2023) 2023 Italy	Upper GI, revisional Roux-en-Y gastric bypass	LS, Open	Clinical outcomes and QALYS	Hospital costs, medication costs	Decision tree/ Yes	Healthcare provider in hospital/ 1 year	Both RAS and LS cost-effective, but LS is the most	Partial considered. high-volume setting with extensive experience both approaches.	NR	NR	NR
CMA (n=2, 4%)											

Tedesco (Tedesco et al., 2016) 2016 Italy	Multi	LS, Open	Monetary outcome	Hospital costs, medication costs, capital costs	Not model based/ Yes	Healthcare Payer perspective/ NR	RAS more costly than LS and open	NR	Partial considered. Excluded Robotic surgical system due to purchase in advance and shared with other specialties.	NR	NR
Martínez-Maestre (Martínez-Maestre et al., 2019) 2019 Spain	Gynae, hysterectomy	LS	Monetary outcome	Hospital costs, medication costs, capital costs; productivity losses, caregiver, travel expenses	Not model based/ Yes	Both healthcare and societal/ 5 years	RAS more costly than LS	NR	NR	NR	NR

HPB, Hepato-Pancreato-Biliary, LS, laparoscopic surgery; RAS, robotic-assisted surgery; QALY, quality-adjusted life year; NR, not report.

Appendix 6 - Discussions with key stakeholder

Open discussion topics were developed to identify possible barriers and enablers to implementation, especially organisational factors that affect implementation.

All the interviewees agreed that discussions would be reported. The following are topic area questions were used to guide the discussion:

- What is the current state of the adoption of RAS in Scotland?
- What were/are the challenges when trying to do HTA/ assess the costs and benefits of RAS?
- What role (if any) do you think HTA has in informing decisions concerning existing capacity for RAS?

General themes were identified as crucial for decision problem, and they have implications for economic evaluation in terms of assessing the use of RAS.

Main themes

Based on the conversation with key stakeholders, participants raised several key issues influencing the current provision and implementation of RAS in NHS Scotland. The five main issues were difficulties with evidence base, platform utilisation and its capacity, economic issues, surgeon and workforce factors and public expectation. The interviewees' related statements are organised and discussed in more detail below and summarised in **Figure A5-1.** The order does not indicate importance.

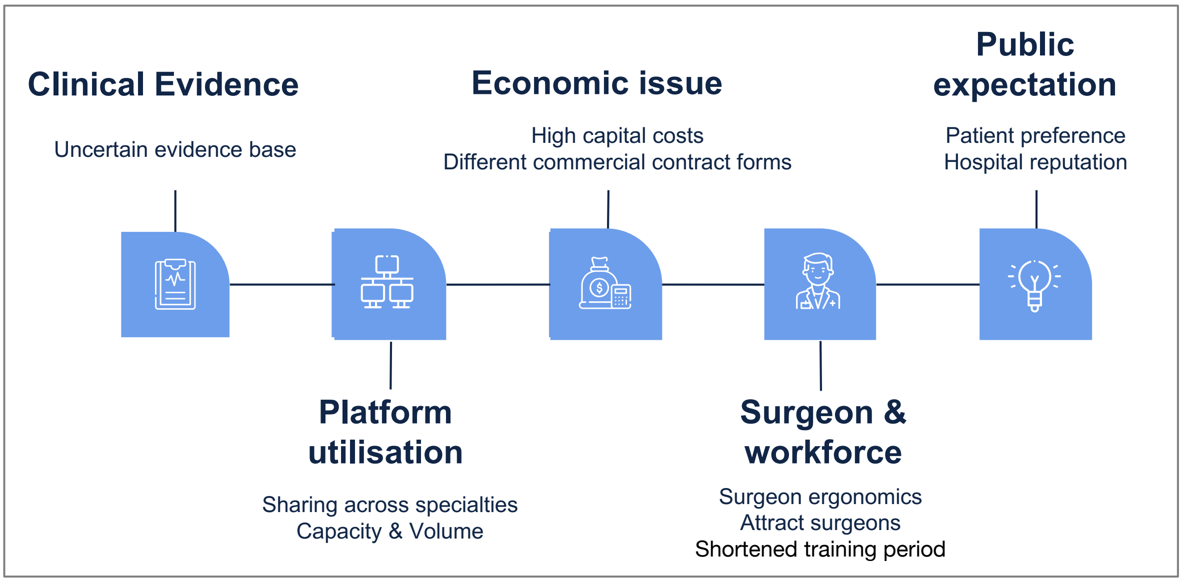

Figure A5-1 Influential factors in decision-makings for adoption of RAS

i. Difficulty in interpreting the clinical evidence base

The available evidence regarding RAS's clinical effectiveness compare to laparoscopic or open approaches in terms of clinical outcomes is inconclusive. Although randomised controlled trials have been conducted, these studies have mainly shown insignificant difference in surgical outcomes. The interviewed surgeons indicated that even they are very much proponents of evidence-based medicine find it difficult to follow the evidence. This deficiency in evidence poses a unique conundrum, even for those who strongly advocate for evidence-based medical practices, such as surgeons, as they grapple with the intricacies of RAS assessment.

All the interviewees including surgeons and industry representatives recognised design flaws in clinical trials associated with RAS. The timing of randomised controlled trials (RCTs) is challenging within the theme of clinical evidence. The limited window of equipoise presents a challenge. Pre-equipoise, where there is insufficient RAS penetration in a specific medical field, recruiting an adequate number of participants with the requisite statistical power becomes problematic. Conversely, post-equipoise, when RAS becomes widely adopted, conducting RCTs becomes less feasible due to the pervasiveness of the technology. Since RAS is a surgery involving a device, patients can be reluctant to enter RCTs if they are concerned about being randomised to an invasive surgical procedure and/or may not get the device/intervention they want.

All interviewees highlight the need for adaptable approaches to RAS evidence assessment. They indicated that real-world evidence (RWE) can provide greater sample sizes and more generalisability, offering insights into the average impact across a broader population. One surgeon indicated that he believes the real-world clinical performance will be better than the previous trial. Based on the documents I have, I recognised there are heated discussions at Scottish Health Technologies Group (SHTG) around the role of RWE from observational data versus clinical trials. Industry representatives agreed that RWE is deemed more suitable for collecting evidence regarding benefits such as training, operational aspects, and organisational factors compared to RCTs. For example, benefits to surgeons, reduced training time, and reduced complications outside the trial period. These characteristics of RAS are not captured in RCTs.

According to these conversations, it highlights the value of a comprehensive and adaptable approach to evidence collection in the evaluation of RAS. Moreover, technology that improves over time can result in better real-world clinical performance, influencing economic evaluations.

ii. Surgeon and workforce issue

One of the surgeons pointed out the debate, with regard to the learning curve in clinical trials compared highly experienced laparoscopic surgeons with less experienced RAS surgeons. One of the industry representatives said that learning time for RAS still longer but varies by procedure. Not drastic a difference overall, and it improves with surgeon training. They indicated that the ease of performing RAS varies among different specialties and procedures, the learning curve can vary by procedure. One of the surgeons from Colorectal specialty indicated that learning of laparoscopic is deeper than RAS. One industry representative indicated that surgical approaches need learning and adapting time, competency is an important consideration when assessing the learning curve and it does not necessarily equate to a fixed number of procedures.

According to these conversations, it underscores the need for a sustained learning curve, as competency is not solely defined by procedure quantity. While a surgeon may successfully navigate the learning curve and acquire proficiency, it is important to note that the outcomes of each procedure can still vary significantly. Surgical procedures entail a level of variability due to the uniqueness of each case. These differences are not solely attributed to the surgeon's skill level. Competency is context-specific, and experience is somewhat transferable between certain robotic procedures within the same platform. However, transferring competency from one platform to another is unlikely. Further, competency is not restricted to the surgeon and should be considered for the entire surgical team.

On the other hand, one surgeon indicated RAS has ergonomic advantages and the ease it offers in comparison to laparoscopic surgery. Industry representatives shared that RAS enable greater access to minimally invasive surgery because surgeons can overcome many of the physical or technical challenges of trying to perform laparoscopic surgery on patients with varying BMIs or procedures with complex or difficult anatomical features. One of the representatives presented an example of operating on an obese patient with gynaecological surgery as the height of the operating table can sometimes be a problem. He demonstrated the surgical table for robotic surgery can move together with the robotic arms and has a lower risk for work-related injuries compared to open and laparoscopic surgery. The representatives emphasised RAS brings ergonomic benefits particularly for female surgeons in gynaecological surgery. Additionally, the NHSS documents showed that the NHSS National Planning Board particularly focus on ‘difficult to get to’ cancer types such as those deep in the pelvis due to advantage of ergonomics. One of the surgeons shared that operating RAS is easier. He said he felt laparoscopic surgery is difficult technically as well as physically demanding.

The NHSS document showed that NHSS National Planning Board believes the provision of a training model for RAS will attract surgeon to train in, come to, and stay in Scotland, then can ensure the sustainability of a multidisciplinary workforce, especially there is a global workforce shortage across all specialties.

iii. Public expectation

One of the industry representatives indicated that decades ago many RCTs were unfavourable towards RAS. However, some hospitals 'ignored' unfavourable RCTs in the adoption of RAS. Instead, the impetus to adopt RAS came from patient power and clinician promoters. He shared that having available surgical robots becomes a positive institutional branding on attracting and retaining staff due to the ergonomic advantages of RAS.

One surgeon said that the key importance of other factors in adoption decision such as ability to attract and retain staff, which may be a particular issue for the North Scotland. He referenced NHSS document indicating that the robotic platform promotes equity among surgeons, enabling a wider range of surgeons, regardless of physical size or gender, to perform minimally invasive surgery on diverse patient populations.

Based on these conversations, it seems like this inclusivity is crucial amid impending surgeon shortages and the demand for skilled professionals capable of performing a variety of operations.

All interviewees said that decisions to buy surgical robots are political. Because NHSS concerned about the equality of access that only a few hospitals have surgical robot available through donations. NHSS document showed that patients in Scotland have less access to RAS by comparison to the rest of the UK, Europe and internationally. NHSS National Planning Board sees RAS as a leading way to access minimally invasive surgery.

The industry representatives indicated that patients are primarily motivated by RAS which offers improved outcomes, particularly shorter hospital stays, faster recoveries, and quicker returns to daily activities and work. Additionally, one of the surgeons indicated that patient and public demand is driven by improved outcomes, particularly length of stay. Industry representative shared that a patient's care experience can significantly influence a choice of treatment, and they presented their data on urology. It showed that 90% of urological surgeries in the US were done by RAS.

One industry representative shared a history of the use of RAS in practice. He said that RAS is initially designed for thoracic surgery, surgical robots faced limited adoption. A German surgeon identified their potential in prostatectomy due to the ease of operation compared to laparoscopic surgery. Due to the advantages and applicability of RAS, it become evident in areas where laparoscopy presents challenges.

One surgeon indicated that in some procedures, open approach is still mainstream. In the case of in NHS Greater Glasgow and Clyde and taking colorectal as an example, it is a mixed-use scenario that the comparison includes laparoscopic surgery and open surgery. He thinks RAS is the key mechanism to achieve conversion from open to minimally invasive surgery.

The industry representative shared their poll results from a conference of colorectal cancer surgeons 5 years ago, 50% of the audience were RAS ‘sceptics’ but 100% believed they would all be using them in the future. Current surgeons (particularly experienced laparoscopic surgeons) believe that RAS cannot offer much in terms of improving their accuracy or conversion and complication rates, but that it may benefit future generations. Therefore, the attitude of surgeons toward RAS adoption and expansion is sceptical, especially between different surgeon generations. He said that it is not just younger surgeons who are keen on RAS and old surgeons who are not. It is a mixed bag.

iv. Economic issues

The implementation of RAS in Scotland began with a business case from hospitals. RAS platforms require large up-front purchases, as well as maintenance per annum. In the Scottish approach, the cost-effectiveness was not considered when the national investment decision was made. With the government covering the equipment's capital costs, the Health Board only needed to consider ongoing expenses, including maintenance and consumables. Thus, the financial framework for utilising and maintaining RAS at the Health Board level is focused on running costs rather than implementation costs. However, one surgeon gave an example of

North Scotland, particularly in regions with political sensitivity surrounding service maintenance.

He also indicated that the consumable of RAS is a major cost category besides the capital cost. Industry representatives shared their data that consumables use differences across specialties. They indicated that the proficiency of surgeon can lead to reduction use of consumables. The costs of the consumables use can be improved by training. The industry representative also reported that their company offers two types of contracts including capital up-front purchase and leasing. Some of the clients adopt pay-per-use rather than straight-out purchases.

Additionally, the representatives from the industry indicated that the surgical volume is a key in terms of value for money. Price per procedure can make quite a difference when surgical volume is high. He shared that the value proposition of RAS is strongest in high-volume surgeries such as urology, colorectal, and gynaecology.

Representatives from the industry shared that traditional cost-effectiveness analyses are challenging for RAS because the system is used for many different procedures which will have different clinical outcomes and cost components.

Based on this discussion, it is apparent that decision-makers' interest and focus is the best way to use RAS with a particular focus on achieving appropriate surgical volumes to ensure optimum utilisation. This is because the capital cost allocation to the system can vary and have an impact on potential cost-effectiveness of RAS. It is also crucial that an assessment of the technology apportions those costs and outcomes across all specialties/procedures.

v. Platform utilisation issue

Surgical robots are a platform technology that can be used across specialties. They are a surgical tool like any other. Representatives from the industry said that often it is political if robots aren't shared across specialties, for example, if a particular charity has funded it is seen as the property of that department.

One of the interviewed surgeons raised his concern about demand and capacity. He indicated that there is a risk if too many units are purchased such as North of Scotland is a case in point, they will be under-utilised or expanded too quickly to indications where gains are marginal due to surgical volumes. For example, to upper GI and complex hernias where clinical evidence is still uncertain. The surgeon also shared that in his hospital, Glasgow Royal Infirmary, the surgical platform is shared with colorectal having 3 days and gynaecology 2 days.

The surgeon indicated that the operative time of RAS is significantly longer than other surgical approaches, and it is mainly due to the platform docking time. He said, the staff also need to adapt to theatre changes.

The industry representative shared that some hospitals might have issues with a lack of sustained use of RAS or struggling with scheduling access. They indicated that they offer a programme called 'Genesis', consulting services for hospitals to optimise platform and scheduling to make the system more efficient (Intuitive, 2015).

Appendix 7 - Summary of the stakeholder interviews

Interview date: 08/07/2021

Interviewee: Two Representatives from Global Market Access Intuitive.

Summary note:

New Market Entrants:

- Da Vinci’s patents are expiring, leading to new competitors such as Johnson & Johnson and Medtronic entering the robotic surgery market.

Political Approach in Scotland:

- Representatives noted that Scotland has a fully coordinated political approach for acquiring robots.

Debates Around Evidence Use:

- Representatives highlighted intense discussions within the Scottish Health Technologies Group (SHTG) regarding the use of real-world evidence (RWE) and observational data versus clinical trials.
- Intuitive supports the use of all forms of evidence, including RWE, to assess robotic surgery.

Design Flaws in RAS Trials:

- Representatives pointed out design issues in clinical trials of robotic-assisted surgery (RAS), especially in learning curve comparisons, where experienced laparoscopic surgeons are often compared to less experienced RAS surgeons.
- A common outcome measure is the conversion rate, which refers to how often minimally invasive procedures convert to open surgery.
- Limitations of Randomised Controlled Trials (RCTs):
  - RCTs often fail to capture the full value of RAS, including benefits to surgeons (e.g., reduced learning curve, fewer complications outside the trial period, and long-term outcomes).
  - Timing of RCTs is challenging due to limited windows of equipoise, where penetration rates of RAS within an indication are at 30-50%.

Once penetration is too high (e.g., 99% of prostatectomies are now RAS), equipoise is lost, making RCTs less feasible.

  - Patients' strong preferences can further complicate randomisation in trials.

HTA Discussions:

- Representatives' HTA poster presented at HTAi revealed that HTA is broadly defined, with less than half involving cost-effectiveness analysis (CEA).
- Major cost savings with RAS come from reducing variation in procedures.

Clinician Perspectives on RCTs and RAS Adoption:

- Representatives indicated that clinicians often ignore negative RCTs, with the expansion of RAS driven by patient demand and clinician advocates. Despite negative trials in the past, the adoption of RAS continued, although it may have slowed.
- Representatives shared that at a colorectal (CRC) surgeons' conference in Ireland, 50% of the audience were sceptics about RAS three years ago, but all believed they would eventually adopt it.
- Experienced laparoscopic surgeons tend to believe that RAS offers little improvement in terms of reducing complications or increasing accuracy/conversion rates. However, they acknowledge it may benefit future generations of surgeons, as RAS makes training easier.

Cost-Effectiveness of RAS:

- Representatives quoted the Health Quality Ontario's HTA showed a high incremental cost-effectiveness ratio (ICER) for RAS, with high costs and low benefits over a one-year horizon. However, long-term benefits were not captured.

Value Proposition of RAS:

- Workforce Benefits of RAS: The Royal College of Surgeons are currently investigating how RAS could benefit the workforce by shortening the path to surgical competence (from 10 to 2 years) through simulator training. Globally, there is a shortage of surgeons.

- Ergonomics: RAS offers benefits, especially for female surgeons in gynaecology, by allowing adjustments to the operating table. RAS also improves the feasibility of operating on obese patients, such as in cases of endometrial cancer.
- RAS's strongest value proposition is in high-volume surgeries, including urology, colorectal, lung, and gynaecology.
- Robots can be used across indications – they are a surgical tool like any other. Often it is political if robots aren't shared across indications – e.g. if a particular charity has funded it is seen as the property of that department.

Optimising Robot Use:

- Robots can be utilised round-the-clock to maximise their value.
- Intuitive offers several purchasing options, including leasing. Machines in the UK are typically purchased through a national framework, with separate components for the vision system, patient part, surgeon console, and training console.
- Scotland has purchased training consoles along with surgeon consoles.

Risk-Sharing and Outcomes-Based Schemes:

- Intuitive is open to outcomes-based purchasing agreements, although challenges exist in defining appropriate outcomes. They are interested in risk-sharing models, particularly around time-to-competence outcomes, though Royal College of Surgeons (RCS) data on this may not be available for some time.

Interview date: 02/11/2021

Interviewee: Surgeon from Glasgow Royal Infirmary

Summary note:

- The surgeon also chaired the Clinical Reference Group established 2-3 years ago as part of the National Planning Framework to manage the equitable implementation of RAS (Robotic Assisted Surgery) across Scotland.
- National Planning got involved as individual boards and hospitals were looking at developing RAS themselves and there was concern over equity of access and to make sure economies of scale were realised in procurement. There was a general feeling that 'RAS was coming' so the planning was focused on the best way to use it with a particular focus on achieving appropriate surgical volumes to ensure utilisation was optimum.
- Review current use of existing RAS and consider evidence use and explore current/future development.
- The surgeon indicated evidence base poor as equipoise very difficult to establish for phase III trials. Even surgeons who are very much proponents of evidence-based medicine find it difficult to follow the evidence.
- The surgeon believes volume and utilisation is key. Due to surgical volumes, there is a risk if too many units are purchased (North of Scotland is a case in point), they will be under-utilised or expanded too quickly to indications where gains are marginal. (The surgeon gave example of upper GI and complex hernias).
- Key importance of other factors in decision such as ability to attract and retain staff, which may be a particular issue for the North. Also political sensitivities around maintaining services in the North.
- The surgeon shared that the RAS Reference Group is positive on clinical efficacy and patient outcomes.
- The surgeon indicated that RAS seen as key mechanism to achieve conversion from open to laparoscopic approach. Huge range of MIS achieved in National Bowel Cancer Audit Report (2018-19) – ranging from low 20%/ /30% to approaching 100%.

- The surgeon believes the cost-effectiveness of RAS is influenced by volumes and surgical team experience.
- The surgeon shows his positive attitude that HTA can help the adoption process especially on cost related information.

RAS Adoption in Scotland:

- Given world-wide RAS adoption, the adoption in Scotland is quite slow so there was a real focus on needing to keep pace with international developments.
- The surgeon shared about the objectives and interests of the Scottish national planning board.
- Equity of access was a significant driver for the National Planning Board’s decisions.
- The Scottish national planning board identify new areas where RAS should expand. Particular focus was in ‘difficult to get to’ cancer types.
- A finance framework was created for the expansion and maintenance of RAS systems, with capacity and volume being key considerations.
- The cost-effectiveness was taken out when decision was made. The guidance for rectal cancer surgery from the SHTG was made based on available studies. It was an evidence review rather than a cost-effectiveness analysis.
- The financial budget was plan for the procurement. The government funded the capital costs of the RAS equipment, so Health Boards are only responsible for ongoing revenue costs like maintenance and consumables.

Factors Influencing Adoption:

- The surgeon indicated that political and ethical concerns around equity of access are key considerations.
- Patient and public demand, driven by improved outcomes such as shorter hospital stays.
- Surgeon demand, as RAS is easier to perform with better outcomes compared to laparoscopic surgery, which is technically and physically challenging.
- Volume of need.
- Ethical concerns around equity of access.

Local Experience with RAS

- In the surgeon personal experience from their local unit patient outcomes are much better using RAS. They have done about 60 procedures now and their data show shorter lengths of stay (LOS) and less complications.
- There have also been some unexpected cost savings such as a reduction from approx. 50% post operative contrast CT imaging scans to only 2 in the 60 operations undertaken to date.

Interview date: 16/12/2021

Interviewee: Two Surgeons from Glasgow Royal Infirmary

Summary note:

Comparison of Surgical Methods:

- Surgeons indicated that as technology advances, clinical performance in real-world settings may surpass results seen in the ROLARR Randomized Clinical Trial.
- Surgeons shared that in the real-world scenario is a mixed-used setting that the analyses have to compare both laparoscopic and open surgery.
- Discussion on segmenting clinical effectiveness evidence from Tzujung's overview review, as the interviewed surgeon noted improvements in outcomes over time.

RAS Implementation at Glasgow Royal Infirmary:

- RAS introduced in May 2020, initially for left-sided/diverticular disease due to the difficulty of operating in the pelvis.
- Plans to extend RAS to the right side eventually.
- The robot is shared with colorectal (3 days/week) and gynaecology (2 days/week).
- The team is still in the early learning phase, which may impact clinical outcomes.
- RAS training programs for the team will contribute to additional costs.

Costs Considerations:

- Surgeons reviewed major cost categories:
    - Hardware: £2 million, but NHS Scotland received a bulk discount to £1.6 million. Further details available from Kenny Rees in procurement.
    - Maintenance: £165,000 per year.
    - Consumables: Major cost category. Estimated at £2,500 per colorectal case and £1,500 per gynaecology case.
- Total costs will depend on improved outcomes (e.g., shorter length of stay and fewer complications) and the volume/utilization, similar to urologic surgeries.

- One surgeon is gathering data on instrumentation used in open, laparoscopic, and RAS.
- Consumable costs for laparoscopic surgeries are estimated at £1,600 per operation.

Health Economics Focus:

- Surgeons believe that health economics will focus on reducing complications and ward stays as key outcomes.

Interview date: 11/10/2023

Interviewee: Representative from Global Market Access Intuitive.

Global Adoption and Procedure Selection

- RAS is widely used globally, with targeted specialties such as urology, colorectal, lung, and gynaecology benefiting most from the technology.
- Representative indicated that RAS was originally designed for thoracic surgery but gained popularity in prostatectomy due to the complexity of laparoscopic surgery in that area. Now, in the US, 90% of prostatectomies are robotic.

Value propositions

- Ergonomic Benefits: RAS offers ergonomic advantages for surgeons, including reduced musculoskeletal strain, making it a preferred option for some.
- Workforce Efficiency**:** RAS is seen as advantageous for training future surgeons, potentially shortening the learning curve compared to laparoscopic surgery.
- Surgeon Training: The learning time for RAS varies by procedure, but surgeon training improves efficiency over time. Training costs and fees for RAS vary, with mixed opinions among surgeons about its benefits.
- Representative indicated that younger surgeons are generally more enthusiastic about adopting RAS, while older surgeons may prefer traditional methods.

Competitive Position & Pricing

- **Patent Expiration:** Intuitive holds over 400 patents for various parts of the RAS system. As patents expire, it is uncertain how this will impact pricing. Unlike pharmaceutical patents, the pricing is likely to remain similar across companies.

Contracts with Healthcare Providers

- **Contract Setup:** Contracts vary depending on the hospital, government, and region. Options include purchasing, leasing, or pay-per-use models.

- **Capital Costs & Maintenance:** The robotic platform costs between £1 million to £1.5 million (or equivalent), with annual maintenance contracts as part of the service. Leasing options are also available, with different interest rates and discounts, especially for national purchases.
- **Contract Length:** Typically 7-10 years due to depreciation, but details on updates (e.g., new equipment versions) and service charges are confidential.

Cost and Investment Considerations

- **Cost Per Procedure:** The more the system is used, the lower the cost per procedure. Intuitive has a "Genesis" program that provides consulting services to hospitals to optimise usage and efficiency, which is offered free within the EU.
- Representative indicated that for modelling cost-effectiveness, different service contracts or investment options (lease vs. buy) should be considered as they impact the overall price per procedure.

National and Local Policy Influence:

- In Scotland and other regions, national decisions can influence Initiative's market strategy. For example, RAS platforms are shared between departments in some hospitals to increase usage efficiency.
- in some regions, RAS can be performed approximately 400-475 procedures per hospital.

Real-World Data (RWD) in Evaluation

- **RWD in Surgical Innovation**: Intuitive supports the use of real-world data (RWD) to evaluate surgical innovations, including RAS, and is responsive to the growing embrace of RWD in healthcare evaluations.

Appendix 8 - Clinical outcomes, utilities and costs inputs

Table A8-1 Prostatectomy outcome inputs into model for base case and sensitivity analyses

Clinical outcomes	Base	Min	Max	Distribution	Source
MIS conversion to open	0.02	0.00	0.05	Beta	(Sharma and Meeks, 2014)
RAS postoperative complication	0.04	0.02	0.08	Beta	(Yaxley et al., 2016)
RAS intraoperative complication	0.02	0.00	0.05	Beta	(Yaxley et al., 2016)
LS postoperative complication	0.05	0.03	0.07	Beta	(Kim et al., 2025)
LS intraoperative complication	0.04	0.03	0.05	Beta	(Kim et al., 2025)
Open postoperative complication	0.09	0.05	0.14	Beta	(Yaxley et al., 2016)
Open intraoperative complication	0.08	0.04	0.13	Beta	(Yaxley et al., 2016)

Note: Probabilities were modelled using beta distributions based on observed event counts, with α = events and β = non-events. The 95% range was defined using the 2.5th and 97.5th percentiles.

Table A8-2 Colorectal resection outcome inputs into model for base case and sensitivity analyses

Clinical outcomes	Base	Min	Max	Distribution	Source
RAS conversion to open	0.14	0.09	0.21	Beta	(Khajeh et al., 2023)
LS conversion to open	0.34	0.28	0.40	Beta	(Marsden and Parvaiz, 2010)
RAS postoperative complication	0.23	0.11	0.38	Beta	(Sheng, 2018)
RAS intraoperative complication	0.06	0.00	0.25	Beta	(Sheng, 2018)
LS postoperative complication	0.28	0.15	0.42	Beta	(Sheng, 2018)
LS intraoperative complication	0.08	0.00	0.26	Beta	(Sheng, 2018)
Open postoperative complication	0.33	0.28	0.38	Beta	(Guillou et al., 2005)
Open intraoperative complication	0.10	0.07	0.14	Beta	(Guillou et al., 2005)

Note: Probabilities were modelled using beta distributions based on observed event counts, with α = events and β = non-events. The 95% range was defined using the 2.5th and 97.5th percentiles.

Table A8-3 Hysterectomy outcome inputs into model for base case and sensitivity analyses

Clinical outcomes	Base	Min	Max	Distribution	Source
RAS conversion to open	0.02	0.02	0.02	Beta	(Ran et al., 2014)
LS conversion to open	0.04	0.03	0.06	Beta	(Garry et al., 2004)
RAS postoperative complication	0.18	0.16	0.20	Beta	(Natarajan et al., 2024)
RAS intraoperative complication	0.05	0.05	0.05	Beta	(Natarajan et al., 2024)
LS postoperative complication	0.19	0.17	0.20	Beta	(Natarajan et al., 2024)
LS intraoperative complication	0.12	0.11	0.12	Beta	(Natarajan et al., 2024)
Open postoperative complication	0.32	0.25	0.40	Beta	(Palomba et al., 2009)
Open intraoperative complication	0.12	0.07	0.17	Beta	(Palomba et al., 2009)

Note: Probabilities were modelled using beta distributions based on observed event counts, with α = events and β = non-events. The 95% range was defined using the 2.5th and 97.5th percentiles.

Table A8-4 Pancreaticoduodenectomy outcome inputs into model for base case and sensitivity

Clinical outcomes	Base	Min	Max	Distribution	Source
RAS conversion to open	0.07	0.05	0.08	Beta	(Emmen et al., 2024)
LS conversion to open	0.18	0.15	0.21	Beta	(Emmen et al., 2024)
RAS postoperative complication	0.19	0.39	0.45	Beta	(Aiolfi et al., 2021a)
RAS intraoperative complication	0.01	0.08	0.01	Beta	(Tang et al., 2025)
LS postoperative complication	0.41	0.38	0.44	Beta	(Aiolfi et al., 2021a)
LS intraoperative complication	0.10	0.08	0.11	Beta	(Aiolfi et al., 2021a)
Open postoperative complication	0.36	0.33	0.40	Beta	(de Graaf et al., 2024)
Open intraoperative complication	0.12	0.11	0.13	Beta	(Tang et al., 2025)

Note: Probabilities were modelled using beta distributions based on observed event counts, with α = events and β = non-events. The 95% range was defined using the 2.5th and 97.5th percentiles.

Table A8-5 Utility values in model for base case and sensitivity analyses

Utility items	Base	Min	Max	Distribution	Source
Prostatectomy					
RAS utility*	0.88	0.88	0.88	Beta	(Holze et al., 2022)
LS utility*	0.88	0.87	0.88	Beta	(Holze et al., 2022)
Open utility	0.83	0.82	0.83	Beta	(Rush et al., 2015)
Colorectal resection					
RAS utility*	0.88	0.81	0.94	Beta	(Lococo et al., 2022)
LS utility*	0.87	0.79	0.94	Beta	(Lococo et al., 2022)
Open utility *	0.84	0.77	0.91	Beta	(Lococo et al., 2022)
Hysterectomy					
RAS utility	0.83	0.81	0.85	Beta	(McCarthy et al., 2023)
LS utility	0.80	0.76	0.84	Beta	(McCarthy et al., 2023)
Open utility	0.78	0.76	0.80	Beta	(Frumovitz et al., 2020)
Pancreaticoduodenectomy					
RAS utility	0.87	0.82	0.91	Beta	(De Pastena et al., 2021)
LS utility	0.75	0.67	0.82	Beta	(De Pastena et al., 2021)
Open utility	0.79	0.73	0.85	Beta	(Korrel et al., 2021)

Note: Min and Max represent the 2.5th and 97.5th percentiles of the beta distribution fitted to the mean and SE.
* converted by EORTC QLQ-C30

Table A8-6 Cost values in model for base case and sensitivity analyses

Cost of health resources	Base	Min	Max	Distribution	Source
Prostatectomy					
RAS cost of operative time	£ 4,641	£ 4,458	£ 4,827	gamma	Estimated with (Yaxley et al., 2016)
RAS cost of LOS	£ 724	£ 543	£ 931	gamma	Estimated with (Yaxley et al., 2016)
LS cost of operative time	£ 6,325	£ 6,049	£ 6,606	gamma	Estimated with (Kim et al., 2025)
LS cost of LOS	£ 915	£ 565	£ 1,349	gamma	Estimated with (Kim et al., 2025)
Open cost of operative time	£ 5,383	£ 5,248	£ 5,519	gamma	Estimated with (Yaxley et al., 2016)
Open cost of LOS	£ 1,527	£1,418	£ 1,640	gamma	Estimated with (Yaxley et al., 2016)
Colorectal resection					
RAS cost of operative time	£ 4252	£ 3,623	£ 4,919	gamma	(Sheng, 2018)
RAS cost of LOS	£ 5,371	£ 4064	£ 6,857	gamma	(Khajeh et al., 2023)
LS cost of operative time	£ 3,958	£ 3,707	£ 4,217	gamma	(Sheng, 2018)
LS cost of LOS	£ 5,520	£ 4,847	£ 6,236	gamma	(Khajeh et al., 2023)
Open cost of operative time	£ 2,715	£ 2,506	£ 2,933	gamma	(Sheng, 2018)
Open cost of LOS	£ 6,725	£ 6,371	£ 7,088	gamma	(Guillou et al., 2005)
Hysterectomy					
RAS cost of operative time	£ 6,480	£ 5,178	£ 7,927	gamma	(Natarajan et al., 2024)
RAS cost of LOS	£ 467	£ 1	£ 2,628	gamma	(Natarajan et al., 2024)
LS cost of operative time	£ 6,250	£ 4,968	£ 7,676	gamma	(Natarajan et al., 2024)
LS cost of LOS	£ 1,635	£ 805	£ 2,754	gamma	(Natarajan et al., 2024)
Open cost of operative time	£ 5,814	£ 4,560	£ 7,218	gamma	(Janda et al., 2017)
Open cost of LOS	£ 2,174	£ 1,014	£ 3,769	gamma	(Garry et al., 2004)
Pancreaticoduodenectomy					
RAS cost of operative time	£ 10,138	£ 9,927	£ 10,351	gamma	(Aiolfi et al., 2021a)
RAS cost of LOS	£ 7,559	£ 7,008	£ 8,129	gamma	(Aiolfi et al., 2021a)
LS cost of operative time	£ 9,546	£ 9,279	£ 9,817	gamma	(Aiolfi et al., 2021a)
LS cost of LOS	£ 5,905	£ 5,575	£ 6,245	gamma	(Aiolfi et al., 2021a)
Open cost of operative time	£ 8,147	£ 7,933	£ 8,363	gamma	(Aiolfi et al., 2021a)
Open cost of LOS	£ 8,600	£ 7,691	£ 9,559	gamma	(Aiolfi et al., 2021a)

Note: Min and Max represent the 2.5th and 97.5th percentiles of the gamma distribution fitted to the mean and SE.

Appendix 9 - CHEERS 2022 Checklist

Topic	No.	Item	Location where item is reported
Title			
	1	Identify the study as an economic evaluation and specify the interventions being compared.	P1 and P108
Abstract			
	2	Provide a structured summary that highlights context, key methods, results, and alternative analyses.	P2-6
Introduction			
Background and objectives	3	Give the context for the study, the study question, and its practical relevance for decision making in policy or practice.	P17-22 and P108-112
Methods			
Health economic analysis plan	4	Indicate whether a health economic analysis plan was developed and where available.	P112
Study population	5	Describe characteristics of the study population (such as age range, demographics, socioeconomic, or clinical characteristics).	P118-119
Setting and location	6	Provide relevant contextual information that may influence findings.	P117
Comparators	7	Describe the interventions or strategies being compared and why chosen.	P118
Perspective	8	State the perspective(s) adopted by the study and why chosen.	P123
Time horizon	9	State the time horizon for the study and why appropriate.	P122
Discount rate	10	Report the discount rate(s) and reason chosen.	N/A
Selection of outcomes	11	Describe what outcomes were used as the measure(s) of benefit(s) and harm(s).	P120
Measurement of outcomes	12	Describe how outcomes used to capture benefit(s) and harm(s) were measured.	P127-128
Valuation of outcomes	13	Describe the population and methods used to measure and value outcomes.	P127-128
Measurement and valuation of resources and costs	14	Describe how costs were valued.	P129-130
Currency, price date, and conversion	15	Report the dates of the estimated resource quantities and unit costs, plus the currency and year of conversion.	P129-130
Rationale and description of model	16	If modelling is used, describe in detail and why used. Report if the model is publicly available and where it can be accessed.	P113-117

Topic	No.	Item	Location where item is reported
Analytics and assumptions	17	Describe any methods for analysing or statistically transforming data, any extrapolation methods, and approaches for validating any model used.	P132-134
Characterising heterogeneity	18	Describe any methods used for estimating how the results of the study vary for subgroups.	N/A
Characterising distributional effects	19	Describe how impacts are distributed across different individuals or adjustments made to reflect priority populations.	P132-134
Characterising uncertainty	20	Describe methods to characterise any sources of uncertainty in the analysis.	P132-134
Approach to engagement with patients and others affected by the study	21	Describe any approaches to engage patients or service recipients, the general public, communities, or stakeholders (such as clinicians or payers) in the design of the study.	P113
Results			
Study parameters	22	Report all analytic inputs (such as values, ranges, references) including uncertainty or distributional assumptions.	P314-320
Summary of main results	23	Report the mean values for the main categories of costs and outcomes of interest and summarise them in the most appropriate overall measure.	P314-320
Effect of uncertainty	24	Describe how uncertainty about analytic judgments, inputs, or projections affect findings. Report the effect of choice of discount rate and time horizon, if applicable.	P137-142
Effect of engagement with patients and others affected by the study	25	Report on any difference patient/service recipient, general public, community, or stakeholder involvement made to the approach or findings of the study	P296-313
Discussion			
Study findings, limitations, generalisability, and current knowledge	26	Report key findings, limitations, ethical or equity considerations not captured, and how these could affect patients, policy, or practice.	P148-154 and P163-164
Other relevant information			
Source of funding	27	Describe how the study was funded and any role of the funder in the identification, design, conduct, and reporting of the analysis	P13
Conflicts of interest	28	Report authors conflicts of interest according to journal or International Committee of Medical Journal Editors requirements.	P13

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