Investigation of endotracheal tube complications in anaesthetised cats and dogs

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1 Abstract

Endotracheal tubes (ETT) are commonly used in the anaesthesia of cats and dogs. They perform a variety of essential functions that may facilitate safe general anaesthesia in these animals. However, their use is not without risk, and complications can arise. This work presents the findings of a retrospective and an experimental study, both investigating complications related to ETT use in cats and dogs.

1.1 Retrospective study

The retrospective study aimed to discover the prevalence of ETT constriction and rostral and caudal mispositioning in anaesthetised cats and dogs, and to identify associated risk factors.

Computed tomography (CT) images of the head/neck/thorax from orotracheally intubated cats and dogs were visually assessed for constriction or mispositioning of the ETT. If constriction was present, measurements of the cross-sectional area (CSA) of the ETT lumen at constricted and un-constricted locations were compared. Location and cause of constriction was noted and expected increase in resistance to gas flow was calculated. Patient information was collected from clinical records. Normality of continuous variables was assessed via the Shapiro-Wilk test. Chi square tests examined associations between variables. Kendall's tau-b test was performed between measured ETT size and degree of constriction.

The ETT extended rostrally beyond incisors in 52% of cases. The ETT connector was within the oral cavity in 19% of cases. The ETT extended beyond the first rib in 25.5% of cases. The prevalence of ETT constriction was 22.7%. Median reduction in CSA was 7.68% (0.14 – 64.19%). Median increase in resistance assuming laminar and turbulent flow was 16.5% (0.3 – 680%) and 21% (0.3 – 1200%), respectively. The most common cause of constriction was the presence of a radiotherapy mouth gag. Significant associations existed between presence of constriction and rostral mispositioning, and caudal mispositioning and extreme brachycephaly. Increased severity of constriction was more likely in smaller ETT.

Constriction and mispositioning of ETT occurred very commonly in the population studied. Checking the ETT within the oral cavity for constriction and mispositioning is consequently recommended. Radiotherapy mouth gags increased the risk of ETT compression. Smaller ETT were at greater risk of severe constriction. Brachycephalic dogs were at particular risk of caudal mispositioning.

1.2 Experimental study

The influence of three variables on the force required to cause constriction of the ETT lumen by application of a securing tie was evaluated. The variables assessed were ETT material (polyvinyl chloride (PVC) and silicone), ETT size (4.0, 7.0 and 11.0 mm, internal diameter) and securing tie material (knitted stretch, non-stretch woven and plastic).

Each combination of ETT material, size and tie material was tested. The tie material was secured to a fixed structure with a loop tied 30 cm away. A knot was created around the body of the ETT. A luggage scale was hooked into the loop and pulled, tightening the knot until constriction of the ETT lumen occurred. The maximum force applied was recorded. Constriction was evaluated via CT imaging. The process was repeated, with the force applied decreasing by 1 kg (~ 9.81 N) each time, or halved if the preceding force was ≤1 kg, until no constriction of the ETT was detected.

The median minimum force required for constriction of silicone and PVC ETT was 9.8 and 28.4 N, respectively. The median minimum force required for constriction of the small, medium and large ETT was 6.9, 18.6 and 37.3 N, respectively. The median minimum force required for constriction by the stretch and woven materials was 14.7 and 22.6 N, respectively. The plastic securing tie loosened spontaneously in all combinations prior to CT.

Silicone ETT were more likely to be constricted by a tie than PVC ETT. Smaller ETT were more vulnerable to constriction by the tie. Stretch fabric was most likely to cause constriction of the ETT. Plastic securing ties may fail to adequately secure the ETT.

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Alternative Format Preface

The manuscript in Chapter 5 has been published in Veterinary Anaesthesia and Analgesia.

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The manuscript in Chapter 7 is written in a manner suitable for publication. The intended journal of publication is Veterinary Anaesthesia and Analgesia.

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Author’s Declaration

I, Ffion Sian Lloyd, declare that this dissertation is the result of my own work, and that it is an original project not submitted for any other degree or professional qualification at the University of Glasgow or any other institution. Contributions of others and replication of figures are explicitly acknowledged and referenced.

Abbreviations

BOAS	Brachycephalic obstructive airway syndrome
bpm	Breaths per minute
CSA	Cross-sectional area
ETT	Endotracheal tube/s
FiO2	Fraction of inspired oxygen
HVLP	High volume low pressure cuff
I:E	Inspiratory:expiratory ratio
ID	Internal diameter
IPPV	Intermittent positive pressure ventilation
ISO	International organisation for standardisation
LMA	Laryngeal mask airway
LVHP	Low volume high pressure cuff
P_aCO_2	Partial pressure of arterial carbon dioxide
PVC	Polyvinyl chloride
P_vCO_2	Partial pressure of venous carbon dioxide
RAE	Ring, Adair and Elwin
Re	Reynold's number
UE	Unplanned extubation of the trachea
WOB	Work of breathing

Chapter 2

Introduction

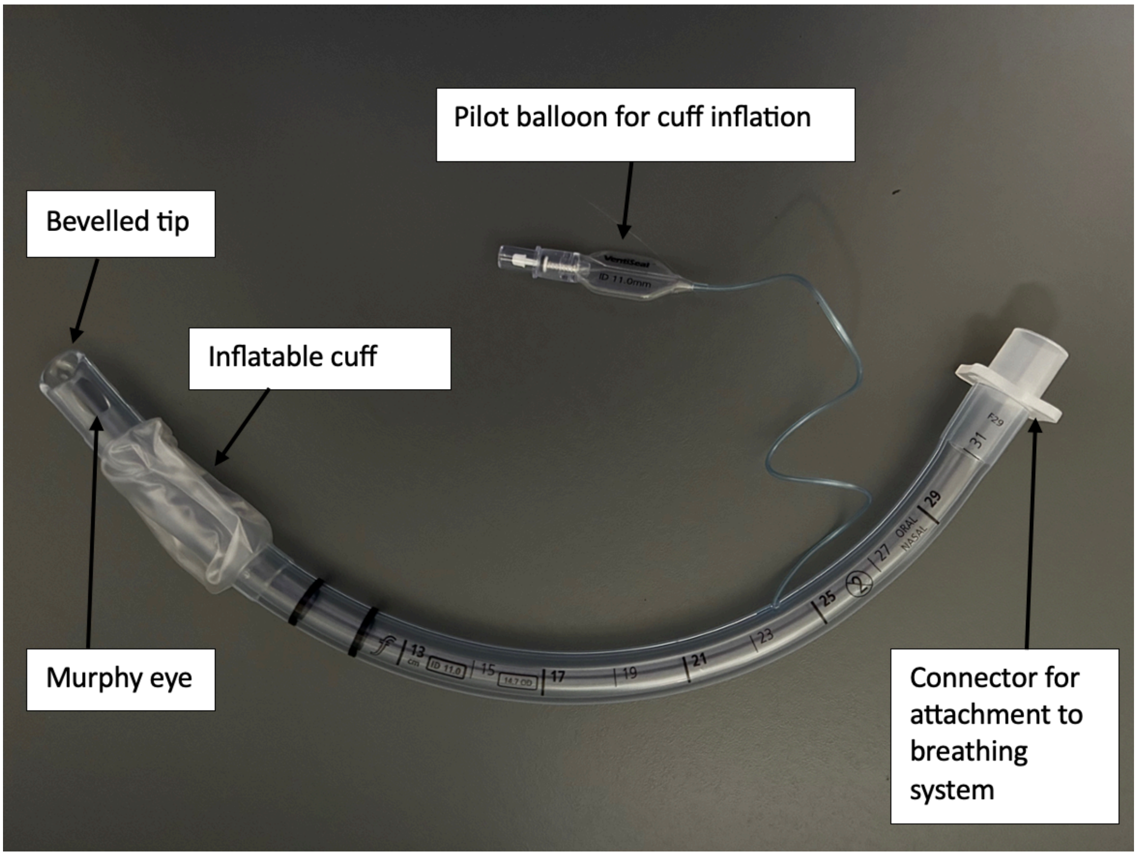
Endotracheal tubes play a vital role in the practice of general anaesthesia for cats and dogs. They are hollow tubes that are inserted into the patient's upper airway, usually sitting within the oral cavity at the rostral end, extending through the larynx to terminate in the trachea at the distal end. Endotracheal tubes are manufactured in a multitude of different designs and materials. Each type has specific properties that make it more or less suitable for various clinical situations and types of patient.

2.1 The standard oral endotracheal tube

Many ETT used in animals are models that are designed and manufactured for use in humans. Specific veterinary ETT do exist, usually in internal diameter sizes outwith those typically utilised in humans (Mosley 2015). The standard ETT is a hollow tube with a bevelled tip at its distal end and a plastic or metal connector attached to its proximal end that permits attachment to an anaesthetic breathing system (see Figure 2-1). In the author's experience, the Murphy-type ETT is the most commonly used type in cats and dogs. Murphy ETT feature a consistent luminal internal diameter (Cook 2012).

Figure 2-1

Murphy-type endotracheal tube with labelled features



2.1.1 Common design features of the Murphy endotracheal tube

Several design features of the Murphy ETT serve specific functions. A bevelled distal tip aids in the tracheal intubation process by providing a narrow edge to advance through the arytenoid cartilages. A Murphy eye is a small hole in the wall of the distal ETT opposite the bevelled edge. Its purpose is to provide an alternative route for gas flow through the tube, should the bevelled edge become occluded due to contact with the tracheal wall (Hughes 2016). Endotracheal tubes without a Murphy eye are referred to as Magill types, in reference to the creator of the original ETT, Ivan Magill (Magill 1928). The connector, located at the proximal end of the ETT, features a tapered cone that inserts into the body of the ETT and is of a standard design with a consistent outer diameter (15 mm), as prescribed by the International Organization for Standardization (ISO) (Cook 2012). Murphy ETT have a pre-formed curvature of the body, which aids in passage of the ETT through the larynx into the trachea, and also helps to reduce the risk of kinking of the tube (Cook 2012).

2.1.2 Endotracheal tube cuffs

Some Murphy ETT have an inflatable cuff positioned at their distal end; these are typically referred to as cuffed ETT. Those without a cuff are colloquially called plain ETT. Inflation of the cuff in cuffed ETT is achieved via attachment of an air-filled syringe and subsequent injection into a pilot balloon. The pilot balloon connects to the cuff via a tube embedded within the ETT wall. It provides a visual indicator of cuff inflation once the ETT has been inserted. Cuffs are constructed from a variety of materials including soft polyurethane, silicone and rubber in PVC, silicone and rubber ETT respectively (Cook 2012). Their purpose is to form a seal with the trachea, thereby providing a physical barrier for the respiratory tract against aspiration of gastric and oral material (Mosley 2015).

Most ETT cuffs are of two distinct types: high volume-low pressure (HVLP), and low volume-high pressure (LVHP) (See Figure 2-2) (Hughes 2016). The ability of each type to prevent leakage of fluid beyond the cuff has been evaluated. Fluid leakage beyond the cuff can occur with HVLP cuffs (Dave et al. 2010), through the formation of folds in the cuff material acting as tunnels for fluid (Oikkonen & Aromaa 1997; Zanella et al. 2011). Whilst LVHP cuffs may provide a superior seal with the airway (Hughes 2016), the higher pressure exerted on the tracheal mucosa can lead to injury, including tracheal erosion and stenosis (Cooper & Grillo 1969). Mucosal injury may be comparatively less likely with HVLP cuffs due to the lower pressure exerted.

Figure 2-2

Image showing examples of two fully inflated endotracheal tube (ETT) cuffs. Left: high volume-low pressure (HVLP) cuff. Right: low volume-high pressure (LVHP) cuff.

Different shapes of ETT cuff are available, which can influence the degree and location of pressure exerted on the tracheal mucosa.

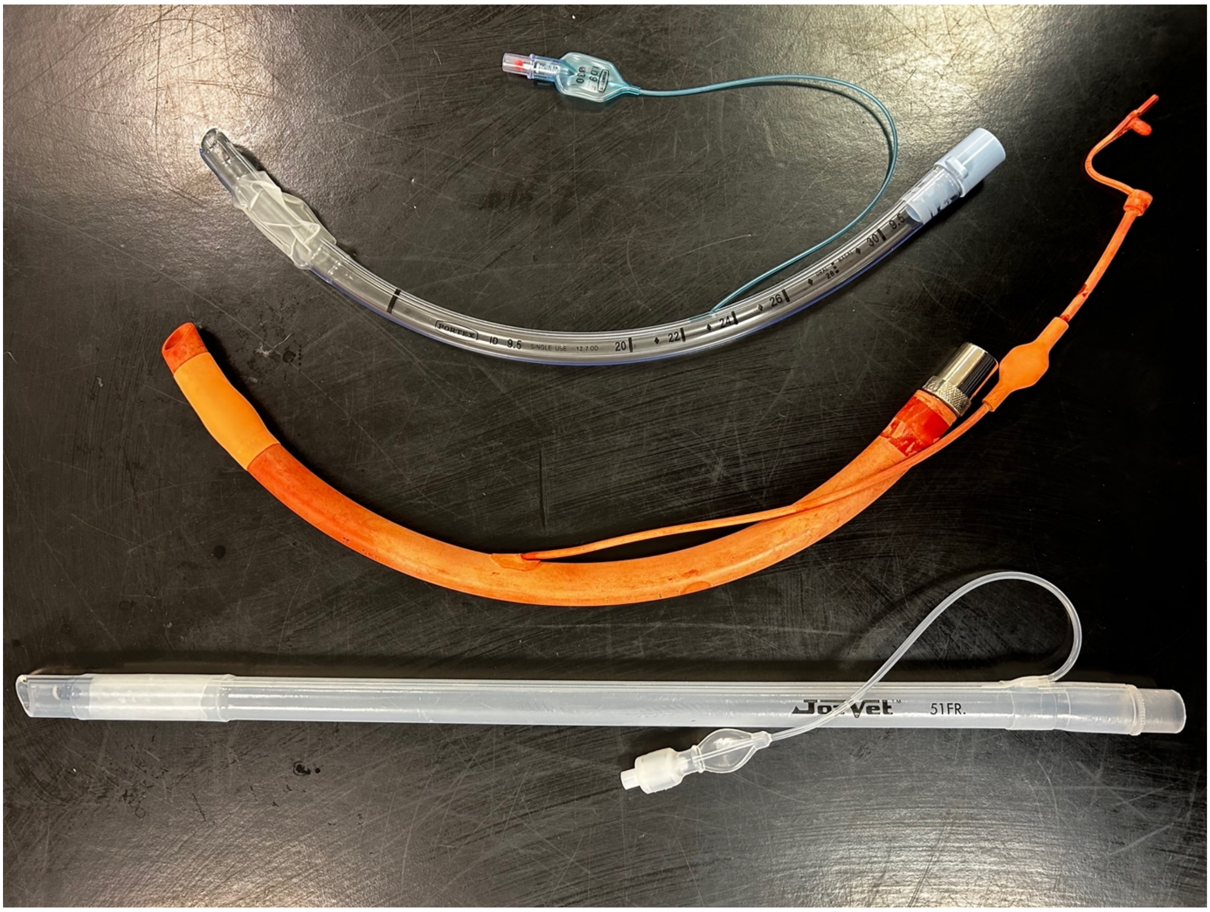
Cuff type may also influence the size (internal diameter) of ETT that can be passed into an individual patient. Anecdotally, larger ETT sizes may be possible to insert if LVHP cuffs are present, as there is less excess material surrounding the body of the ETT when the cuff is fully deflated when compared to HVLP cuffs.

2.1.3 Endotracheal tube materials

Polyvinyl chloride (PVC), silicone and rubber are the most common materials used in the construction of ETT (Cook 2012). (See Figure 2-3)

Figure 2-3

Image showing ETT constructed from (top to bottom) polyvinyl chloride (PVC), red rubber and silicone



In the author's experience, the use of rubber ETT is declining in veterinary species, due to several undesirable characteristics. Rubber was historically the most common material for ETT manufacturing, prior to the development of alternative materials (Watson 1980). Rubber ETT were reused in the human field and the ability to re-sterilise rubber was considered a benefit. However, time, repeated sterilisation and use degrades the material, predisposing to the formation of ruptures and kinks in ETT (Cook 2012). Rubber is allergenic and has been implicated in the development of tracheal granulomas (Quevedo 1960). Its opacity prevents thorough inspection of the ETT lumen, which may lead to failures in detecting lumen obstructions and debris. Warming of rubber ETT, such as would be expected due to the body temperature of a patient, causes hardening of the material (Watson 1980).

Polyvinyl chloride ETT are common in both human and veterinary anaesthesia. Their development coincided with a general move towards single-use ETT in humans, which is now accepted practice (Riaz 2019). The material is transparent, making detection of obstructions and debris within the ETT lumen straightforward. Additionally, PVC is less irritant to the tracheal mucosa than rubber (Guess 1970). The flexibility of PVC is less than that of rubber, potentially leading to an increased risk of mucosal damage through trauma during intubation, but a gentle technique should mitigate this.

Silicone (polymethylsiloxane) ETT are also available. This material is generally softer and more flexible than PVC, which may increase the technical difficulty of tracheal intubation. However, the material properties of silicone ETT may make mucosal trauma less likely. Flexometallic stylets can be used to aid the tracheal intubation process with these ETT.

2.2 Function of endotracheal tubes

Endotracheal tubes perform several important functions, associated with the logistics of anaesthesia administration, the maintenance of patient safety and protection of personnel.

2.2.1 Provision of a conduit for gases and vapours

Endotracheal tubes provide a conduit for oxygen, anaesthetic vapours and gases from the anaesthetic machine to the patient's lungs (Grimm et al. 2015). Oxygen, medical air, nitrous oxide and inhalant anaesthetic vapours (such as isoflurane and sevoflurane) can all be delivered to the patient via an ETT. Alternatives to ETT, including face masks and laryngeal mask airways (LMA), can also provide a link between the anaesthetic machine and the lungs, but ETT provide the most direct route (Hughes 2016). This is advantageous for the accurate delivery of gases and vapours.

2.2.2 Provision of a means for lung inflation

Through providing the structural link between anaesthetic machine and patient, ETT permit the provision of mechanical or manual intermittent positive pressure ventilation (IPPV). IPPV is performed via the anaesthetic breathing system, either manually via the anaesthetist, or mechanically with a ventilator. This is an intervention that may be necessary in patients exhibiting hypoventilation and/or hypoxaemia (Hopper 2015).

General anaesthesia can cause hypoventilation (Egger 2016). Anaesthetic and sedative drugs typically cause depression of the respiratory system, decreasing the patient's tidal volume, respiratory rate or both. Hypoventilation causes hypercapnia, characterised by an elevated arterial and venous partial pressure of carbon dioxide (P_aCO_2 and P_vCO_2, respectively). Severe hypercapnia causes narcosis (Price 1960) and is reported clinically in the dog (Phillips & Mathis 2020).

Hypercapnia leads to respiratory acidosis (Johnson & Morais 2012). Abnormally high P_aCO_2 and P_vCO_2 decrease blood pH, through the increased liberation of hydrogen ions via dissociation of carbonic acid (see reaction equation below).

$$CO_2 + H_2O \Leftrightarrow H_2CO_3 \Leftrightarrow H^+ + HCO_3-$$

Respiratory acidosis is associated with several detrimental physiological sequelae, including peripheral vasodilation, decreased cardiac contractility and stimulation of the sympathetic nervous system, causing endogenous release of catecholamines (Price 1960). This can lead to cardiac arrhythmias. Severe derangements in blood pH are expected with pronounced respiratory acidosis, which can lead to enzymatic dysfunction through denaturation. Impaired enzymatic function affects essential cellular processes, predisposing to multiple organ failure (DiBartola 2012).

Manual or mechanical IPPV is also a treatment for hypoxaemia (Hopper 2015). Hypoxaemia is defined as an inadequate blood oxygen content. It quickly leads to morbidity if oxygen delivery to cells becomes insufficient, as aerobic metabolism is impaired (Hopper 2015). Hypoxaemia may be caused by an inadequate fraction of inspired oxygen (FiO_2), hypoventilation, impairment of oxygen diffusion at the alveolar-capillary barrier, excessive dead space or shunting of deoxygenated blood into the systemic circulation (Chambers et al. 2015). Manual or mechanical ventilation via an ETT can resolve or improve hypoxaemia by delivering oxygen, facilitating normoventilation and recruiting collapsed alveoli (Hopper 2015).

2.2.3 Prevention of atmospheric pollution by anaesthetic gases & vapours

Contamination of the working environment with anaesthetic vapours and gases may represent a safety hazard for personnel working with anaesthetised patients. Occupational exposure to volatile anaesthetic agents such as isoflurane and nitrous oxide has been linked to several health concerns, including effects on cognition and psychomotor ability as well as reproductive health (Burm 2000). Anecdotal reports of headaches and nausea following accidental exposure to volatile anaesthetics are common amongst clinical personnel. Evidence from observational studies performed in the

1970s suggests occupational exposure to anaesthetic vapours and gases increases the risk of spontaneous abortion, preterm labour, congenital foetal abnormalities and infertility in female anaesthetists (Knill-Jones et al. 1972; Knill-Jones et al. 1975).

Modern advances in the practice of anaesthesia are likely to significantly reduce occupational exposure (Ireland 2014): the ETT plays a pivotal role in reducing this risk. Ensuring a secure physical connection to the anaesthetic breathing system allows scavenging of exhaled waste anaesthetic gases, preventing their escape into or facilitating their removal away from the clinical environment. Well-fitting ETT with inflated cuffs prevent leakage of anaesthetic gases and vapours from the lungs to the environment (El-Orbany & Salem 2013), thereby reducing the environmental exposure of personnel. Insufficiently inflated ETT cuffs have been shown to lead directly to increased atmospheric concentrations of sevoflurane and nitrous oxide (Li et al. 2002). Official guidelines exist in the United Kingdom to limit environmental concentration of waste anaesthetic gases and vapours and mandate monitoring of short-term and long-term worker exposure (HSE 2020).

2.2.4 Maintenance of upper airway patency

Upper airway obstruction is a recognised risk for animals following the administration of sedative and anaesthetic drugs (Brodbelt et al. 2015). This is due in part to the muscle relaxation and change in head carriage caused by these drugs. Complete upper airway obstruction is a life-threatening emergency as it quickly leads to hypercapnia, hypoxaemia and pulmonary oedema (Dicpinigaitis & Mehta 1995). Placement of an ETT effectively stents the upper airway whilst in situ, maintaining airway patency in anaesthetised patients.

In the author's experience, individual animals at particular risk of upper airway obstruction benefit especially from ETT placement during anaesthesia. Such individuals include those with oral, pharyngeal, laryngeal or tracheal pathology that reduces the normal space for air flow. Examples include neoplastic masses, strictures and abscessation in these areas. Animals with upper respiratory tract dysfunction, such as laryngeal paralysis, also benefit from ETT.

Brachycephalic obstructive airway syndrome (BOAS) is characterised by a range of anatomical abnormalities that reduce the space for passage of gas through the upper airway. These abnormalities include aberrant nasal turbinates, reduced size of nares, macroglossia, everted laryngeal saccules, an overly long soft palate and tracheal hypoplasia (Meola 2013). Placement of an ETT is considered essential for the anaesthesia of dogs and cats with brachycephalic conformation (Downing & Gibson 2018).

2.2.5 Protection of respiratory system from aspiration

Anaesthesia depresses or abolishes the swallowing reflex (Dugdale et al. 2020b), rendering the lower airway vulnerable to aspiration of material. Passage of foreign material into the lungs, such as blood, saliva, gastric contents and flush fluid, can lead to morbidity. The negative effects of aspiration depend somewhat on the nature of the material being aspirated. Injury to the tracheal mucosa can result from aspiration of acidic gastric contents (Wynne et al. 1981). Aspiration of any type of fluid can cause bronchoconstriction and oxygen diffusion impairment in the alveoli. Aspiration pneumonia, characterised by pulmonary inflammation with or without infection (Son et al. 2017), can result from aspiration of unsterile material (Kogan et al. 2008).

Presence of an ETT can prevent the passage of material through the trachea and into the lungs. Through inflation of the cuff in cuffed ETT, a seal is formed with the trachea, protecting the respiratory tract from aspiration (Mosley 2015). Plain ETT can act as a physical barrier reducing the passage of material, but do not form a seal with the trachea. In the author’s opinion, the effectiveness of the barrier provided by plain ETT depends on their size relative to the tracheal size; they should be as large as possible. Placement of a plain ETT large enough to prevent aspiration may be practically difficult to achieve.

Regurgitation is a known risk of general anaesthesia (Lamata et al. 2012). It is defined as the passive discharge of gastric or oesophageal fluid from the mouth or nose, and results from a decrease in lower oesophageal sphincter tone, permitting egress of gastric fluid into the oesophagus (Fernandez Alasia et al. 2021). Aspiration pneumonia is a possible sequel of regurgitation with significant associated morbidity and mortality (Egger 2016). Endotracheal tubes therefore play a significant role in the prevention of aspiration pneumonia (Bone et al. 1974).

2.3 History of endotracheal tube development

The historical development of endotracheal intubation and the ETT is complex and nonlinear, composed of several discoveries, abandonments and rediscoveries (Szmuk et al. 2008). The first oral endotracheal intubation for anaesthesia in a human patient was documented in 1880 by Scottish surgeon Sir William MacEwen (Macewen 1880).

Animals contributed significantly to the development of ETT, through participation in a collection of notable early experiments. Andreas Vesalius performed tracheal intubation through a tracheostomy to provide manual ventilation in a pig in 1542, using a tube fashioned from reed (Vesalius 1542). In 1667, Robert Hooke demonstrated ventilatory resuscitation in a dog by performing a tracheostomy and using bellows to inflate the lungs (Hooke 1667). Arthur Guedel and Ralph Waters anaesthetised a pet dog (appropriately named 'Airway'), using an ETT to permit suspension of the dog in a tank of water in 1928 (Guedel & Waters 1928). The role of endotracheal intubation for veterinary anaesthesia was cemented between 1940-1950, coupled to the discovery of cyclopropane and trichlorethylene as inhalational anaesthetics (Jones 2002).

Initially, ETT were developed as a means of performing ventilatory resuscitation. The first documentation of ventilatory resuscitation in a human, using a wire pipe wrapped in leather inserted into the trachea, appeared in 1754 by Benjamin Pugh (White 1960). In 1788, ventilatory resuscitation of drowning victims was successfully orchestrated via a curved metal tracheal tube by Charles Kite (Kite 1788).

Prevention of aspiration pneumonia was the next focus in ETT development, heralded by the increasing practice of upper respiratory tract surgery and its associated risk of aspiration (White 1960). The use of ETT with collars constructed from absorptive material, creating a physical barrier within the trachea, progressed from 1871 onwards (Trendelenburg 1871; Mudry & Righini 2023). Inflatable cuffs to protect the trachea from aspiration were introduced in 1893 (Baker 1971), creating ETT reminiscent of the types in common use today.

Recognition of the ability of ETT to assist delivery of inhalational anaesthesia spurred further development from 1880 onwards (Macewen 1880). The accompanying advancement of laryngoscopy coupled to endotracheal intubation by Chevalier Jackson in 1913 (Phillips & Duerksen 1973; Burkle et al. 2004) eased the technical difficulties of oral intubation, that prior to this time had been performed blindly via manual palpation. In 1928, inhalational anaesthesia delivered through a homemade ETT composed of rubber was described by Ivan Magill (Magill 1928). By 1938, rubber ETT were being commercially manufactured. Use of cuffed rubber ETT became standard practice in anaesthesia from the 1950s onwards (Cook 2012). Polyvinyl chloride ETT were first produced in 1944 by Sidney Leader as an upgraded alternative to the rubber ETT (Featherstone et al. 2015).

2.4 Special types of endotracheal tubes

In addition to the standard Murphy ETT, a number of specialised designs exist to fulfil specific purposes or overcome particular challenges in unique clinical contexts.

2.4.1 Armoured endotracheal tubes

Reinforced or armoured ETT contain a spiral of wire or nylon embedded within the tube body wall. The body wall of the ETT can therefore be constructed from a much more flexible material than standard ETT. This design permits acute angling of the body of the tube whilst reducing the risk of kinking (Cook 2012), which can cause obstruction to gas flow.

Armoured ETT fulfil all the functions of standard ETT, but are less likely to kink in cases where special positioning of the head or neck of the patient is required (Hughes 2016). This benefit is due to the spiral of wire embedded in the ETT wall (see Figure 2-4).

Figure 2-4

Image showing an armoured endotracheal tube (ETT) in a patient requiring angled positioning of the head to facilitate surgical access. Significant curvature of the ETT is permitted without kinking due to the flexible tube material and spiralised reinforcing wire, preventing reduction in the ETT lumen cross-sectional area (CSA).

A disadvantage of the armoured ETT is the inability to adjust its length: because the spiralised wire cannot be cut, the ETT must remain at the length produced by the manufacturer. This may be too long for certain patients, risking inadvertent endobronchial intubation (if caudally mispositioned) or increasing dead space (if rostrally mispositioned).

An important risk associated with the use of armoured ETT is permanent obstruction of the lumen from deformation of the spiralised wire, which has been documented in humans (Spiess et al. 1991; Malhotra et al. 2007; Hosseinzadeh et al. 2015) and in the pig (Clutton & Lawrence 1997). Care must be taken to avoid excessive pressure on the wall of the armoured ETT, which may be caused by the patient biting the body of the tube or from personnel applying the securing tie too tightly. Armoured ETT should be carefully inspected before use.

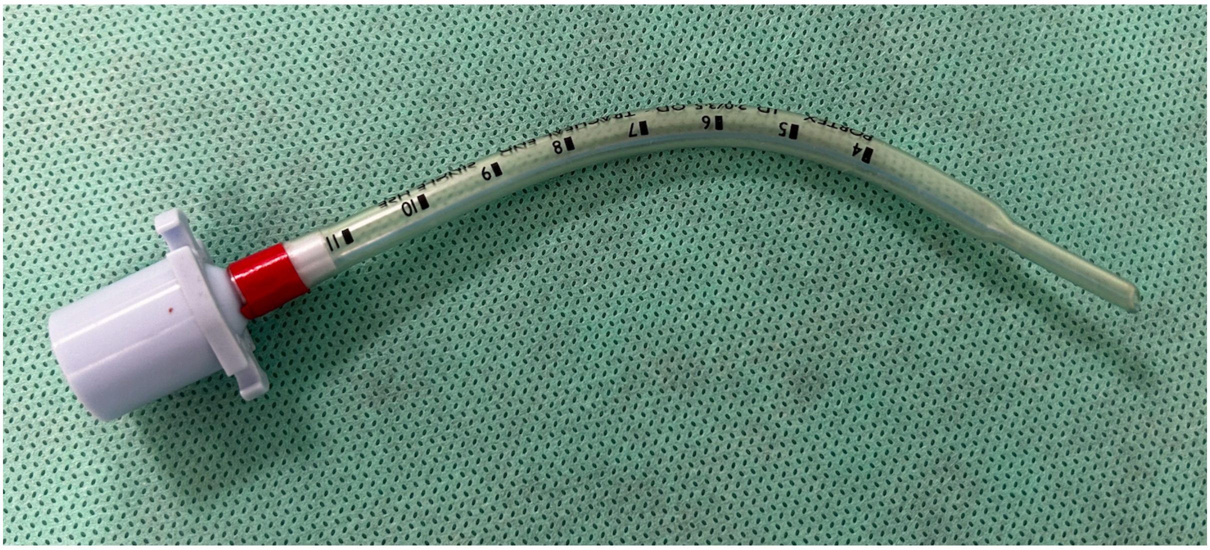
2.4.2 Other types of endotracheal tube

2.4.2.1 Cole pattern endotracheal tubes

Cole pattern ETT have a tapered shoulder construction at the distal end (Mosley 2015) (See Figure 2-5). Cole ETT do not possess cuffs. Instead, the tapered part seats onto the rima glottidis (Dugdale et al. 2020a), helping to prevent leaks. Cole ETT are classically used in avian anaesthesia (Degernes 2008). Studies in children show that Cole pattern ETT produce greater resistance and carry a higher risk of turbulent gas flow compared to Murphy ETT (Hatch 1978).

Figure 2-5

Image showing a Cole type endotracheal tube



2.4.2.2 Silicone endotracheal tubes with flexible baffles

Silicone ETT intended for use in animals are available with several silicone rings positioned at the distal end, called baffles, in place of an inflatable cuff (Dugdale et al. 2020a). The manufacturers of these ETT, called Safe-Seal™ Endo Tubes, state that the baffles prevent leakage of material around the ETT. The baffles also purportedly facilitate clearance of material from the trachea during extubation (IAP 2023). Additionally, the baffles are intended to allow escape of gas in cases of excessive intra-thoracic pressure (IAP 2023). No published studies are available to support these claims.

2.4.2.3 Pre-formed Ring, Adair & Elwin endotracheal tubes

Ring, Adair and Elwin (RAE) ETT are pre-formed with an extreme curve that directs the proximal part of the ETT and its connection to the breathing system away from the mouth when in position (Cook 2012). These ETT were designed to facilitate surgical access to the nose and mouth and are commonly used in children (Black & Mackersie 1991), but are not particularly common in veterinary anaesthesia. The pre-formed shape in conjunction with the size of the patient's oral cavity dictates the length of ETT that is available to pass through the larynx into the trachea. Endobronchial intubation has been demonstrated in children due to RAE tubes that are inappropriately long for the patient (Black & Mackersie 1991).

2.4.2.4 Endotracheal tubes for laser surgery

The use of surgical lasers carries a risk of fire if they inadvertently strike an ETT, due to the high temperatures caused and the presence of high oxygen concentrations within the ETT lumen (Fontenot et al. 1987). For this reason, ETT specifically intended for use in laser surgery have been developed. Such ETT may be constructed with a gas-tight metal helix, which reflects the laser beam, or wrapped in silver or copper foil to disperse the laser beam (Cook 2012). These ETT typically possess a double-cuff design, where the proximal cuff is intended to protect the distal cuff should an accidental laser strike occur, causing puncture. The double cuff should be inflated with dyed saline, rather than air, to prevent ignition in the case of a laser strike and to ensure early detection of a puncture through visualisation of the dye (Cook 2012).

2.4.2.5 Endotracheal tubes for isolation of a lung lobe

Endotracheal tubes for the specific purpose of isolating a lung lobe are available for humans (Cook 2012). They are designed to extend through and beyond the trachea into a bronchus. These ETT may be used in animals if careful consideration is given to the size (ID and length). These ETT facilitate certain types of thoracic surgery. The ETT options for isolating a lung lobe are broadly categorised into endobronchial tubes and double lumen tubes (Cook 2012).

Endobronchial tubes have a long length that extends into a bronchus, isolating the specific lung communicating with it (Cook 2012). Double lumen tubes are constructed from two tubes of different lengths adhered together, with individual cuffs and pilot balloons. The shorter of the two tubes sits in the trachea and the longer tube is designed to extend into a bronchus. Inflation of the respective cuffs of each of the two tubes seals off the trachea and bronchus, permitting isolation of one lung (Cook 2012). Double lumen tubes have been employed successfully in dogs for one-lung ventilation (Mayhew et al. 2009; Mayhew et al. 2012).

2.5 Alternatives to oral endotracheal tubes for inhalational anaesthesia

Although ETT are widely used in the general anaesthesia of cats and dogs, alternative equipment options exist for the provision of anaesthetic gases and vapours. These alternatives may be preferred in specific situations where endotracheal intubation may be difficult to perform due to the anatomy or size of the patient. Each of the alternatives is associated with their own unique advantages and disadvantages when compared with ETT.

2.5.1 Facemasks

Facemasks are available in a variety of different shapes and sizes to suit the patient (see figure 2-6). They are intended to sit outside the lower half of the face, covering the nose and mouth (Cook 2012). Some models include a flexible rubber 'diaphragm' that is intended to provide a tight seal around the face, whilst others have an inflated soft plastic membrane to perform this function.

Figure 2-6

Image showing a selection of different facemasks

Facemasks are typically used as an alternative to ETT for inhalational anaesthesia in neonatal or very small individuals. Anecdotally in these patients, endotracheal intubation is technically challenging due to the small size of the head and trachea. They may also be used in species where direct visualisation of the larynx is difficult, such as in rabbits (Bateman et al. 2005). When considering functionality with regards to inhalational anaesthesia, facemasks do not compare favourably with ETT (Fujita et al. 1991; Friembichler et al. 2011). Facemasks do provide a conduit for anaesthetic gases and vapours, but these are only delivered to the nose and mouth, not directly to the trachea as with ETT. Facemasks do not maintain upper airway patency or protect the respiratory tract from aspiration of foreign material, nor do they provide a reliable route for lung inflation. Facemasks may protect personnel from occupational exposure to waste anaesthetic gases, but only if they are tightly fitting. This may be difficult to achieve in cats and dogs due to the wide variety of anatomical conformation (Friembichler et al. 2011). External pressure should be applied to the facemask to ensure a good seal (McGowan & Skinner 1995) – this may be technically challenging to achieve consistently during the anaesthetic period and may cause discomfort for the patient.

2.5.2 Laryngeal Mask Airways

Laryngeal mask airways (LMAs) (see Figure 2-7) are designed to sit in the pharynx, over the outside of the larynx. A seal is formed around the larynx through inflation of a cuff (Hughes 2016). Unlike ETT, LMAs do not enter into the trachea. Their insertion does not require visualisation of the larynx, which may be of benefit in patients with limited access to the larynx (Reed & Iff 2012).

Figure 2-7

Image depicting laryngeal mask airways (LMA) intended for use in a cat (top) and rabbit (bottom)

Increased speed of placement, reduced anaesthetic requirements for tolerance of the LMA and lower frequency of coughing on emergence from inhalation anaesthesia are all reported benefits of the LMA when compared to ETT in humans (Brimacombe 1995).

In veterinary species, the use of LMA has been documented in dogs, cats, rabbits, sheep, pigs and deer (Vidricková & Boldižár 2020). In dogs, LMA are typically well-tolerated and their insertion requires less injectable anaesthetic than for the performance of endotracheal intubation (Wiederstein et al. 2006). The seal formed by the inflated cuff may be insufficient to perform IPPV effectively (Wiederstein & Moens 2008). In cats, IPPV may be performed when using LMA (Cassu et al. 2004). In rabbits, LMA perform better than facemasks for inhalational anaesthesia, maintaining normocapnia and higher partial pressures of oxygen (Bateman et al. 2005).

Problems with LMA include mispositioning of the device within the oral cavity, causing oropharyngeal leaks (Brimacombe 1998). Disruption of airway patency due to epiglottic folding, leading to increased work of breathing or complete airway obstruction, is reported in humans (Brimacombe 1998). Aspiration and gastric distension are also reported in humans (Takahata & Iwasaki 2006). This is due to exposure of the oesophageal inlet by the LMA. Protection of the respiratory tract from aspiration of foreign material is therefore not guaranteed by the LMA, unlike with an adequately cuffed ETT.

2.6 The process of oral endotracheal intubation

The technique of inserting an ETT (endotracheal intubation) into a cat or dog is largely consistent between individual patients and anaesthetists, with slight modifications made according to the clinical scenario. It is advisable to check the cuff of ETT prior to insertion by inflating it fully via the pilot balloon, then performing a visual and tactile check for partial deflation approximately five minutes later (Hughes 2016), which should reveal any leaks. Assessment of ETT cleanliness and patency is always recommended, particularly if an ETT has been previously used (and cleaned); this is commonplace in veterinary practice.

Following induction of anaesthesia, the cat or dog is typically placed into sternal recumbency. The head is elevated by an assistant, who supports the maxilla and the caudal skull to position the animal optimally as per the anaesthetist's preference (Hughes 2016). In this context, 'anaesthetist' refers to any clinical personnel performing tracheal intubation; this may be a veterinary surgeon, student or nurse. In the author's opinion, lateral recumbency may alternatively be preferable for tracheal intubation if there is any contra-indication to movement of the head, neck or forelimbs.

Examples of this include patients with suspected cervical spinal pathology or forelimb fractures. Lateral recumbency may also be preferred for reasons of convenience, for example in a very large dog where lifting of the head may cause discomfort for personnel.

The anaesthetist grips the tongue and retracts it rostrally, increasing visibility of the caudal pharyngeal structures by doing so. A laryngoscope is usually used to depress the base of the tongue, causing rostroventral movement of the epiglottis, thereby revealing the larynx (Hughes 2016). Anecdotally, some anaesthetists elect to intubate without the use of a laryngoscope, relying on manipulation of the tongue and using the ETT itself to obtain visual access to the larynx.

Cats are at risk of laryngospasm due to the heightened sensitivity of their laryngeal structures (Hughes 2016). Topical anaesthetic is typically applied by the author to the arytenoid cartilages and allowed to take effect before proceeding with intubation in this species.

The ETT is advanced caudally towards the larynx and through the arytenoid cartilages to pass into the trachea. Once advanced sufficiently, the ETT is secured, typically with a fabric tie, as described in section 2.7. The ETT cuff is inflated to produce a seal with the trachea. Correct placement of ETT should be confirmed via capnography where available. Alternatively, gas movement through the ETT (corresponding to breathing) can be confirmed via tactile assessment or observation of condensation on the inside of the tube (Hughes 2016). Providing a short period of manual IPPV and observing corresponding thoracic movements can also confirm correct ETT placement (Hughes 2016).

2.7 Options for securing endotracheal tubes

Securing endotracheal tubes in dogs and cats usually involves tying a length of fabric material around the body of the ETT or its proximal connector. This material is then knotted around the animal's ears, muzzle or mandible, depending on the type of surgical access and positioning required (see Figure 2-8). The incidence and types of complications caused by securement method are unknown in cats and dogs and there are no universally agreed best practice guidelines to advise. Choices are typically influenced by personal preference, immediate availability of materials and hospital policy. Recommendations pertaining specifically to the securement of ETT in cats and dogs made by textbooks are limited, with recommendations to choose a method and material that is suitable for the patient and clinical scenario (Mosley 2015; Dugdale et al. 2020a).

Figure 2-8

Image showing securement of an endotracheal tube (ETT) in a kitten by a length of fabric tied around the body of the ETT and the animal's head

Securing the ETT is required to avoid inadvertent tracheal extubation. This carries serious risks to patient safety and must be avoided; it has been associated with laryngeal oedema and aspiration in humans (Kiekkas et al. 2013). Improper fixation of ETT can be a causative factor (Kiekkas et al. 2013).

2.7.1 Unplanned tracheal extubation and the relationship to securement method

Studies with a specific focus on the methods of securement of ETTs are rare in the human medical literature. The existing evidence base primarily links securement method with its effect on unplanned extubation of the trachea (UE). This is a frequently reported event in human anaesthesia (Lucchini et al. 2018; Abbas & Lutfy 2019; Ferraz et al. 2020). Most UE occurs in the intensive care unit setting in mechanically ventilated patients, with a higher rate of occurrence in neonatal ICU populations (Merkel et al. 2014). Numerous patient movements during pre-hospital care were also associated with an increased risk of UE (Kupas et al. 2010). The pre-hospital setting refers to care orchestrated by paramedics, prior to hospital admission. This specific period is likely to approximate well to clinical veterinary practice, where movement of anaesthetised patients is frequently carried out. An overall accidental extubation incidence of 2.9% was found in 1732 patients in the pre-hospital setting, with woven twill tape performing best out of a variety of reported securement methods (Kupas et al. 2010). The analysis also evaluated manual holding of the tube by paramedics –this method was associated with the highest incidence of UE, accounting for 12.5% of total ETT dislodgements (Kupas et al. 2010). Incidence of UE varies widely for ICU settings, with reported rates ranging from 0.3 to 35.8% (Lucchini et al. 2018). There appears to be no consensus regarding best practice to reduce UE in human hospitals and little emphasis is placed on the methods used to secure endotracheal tubes.

A 2005 systematic review attempted to compare commonly used ETT securement methods in human ICUs including twill/cotton tape, gauze, adhesive tape and specially manufactured devices (Gardner et al. 2005). Performance was assessed with respect to ETT displacement, UE and facial skin and oral mucosal injury attributable to the presence of the ETT in the study. Due to large disparities in measured outcomes and interventions between studies, no one method could be reliably agreed upon to perform best. The review did comment on the large variation in clinical staff preference and experience regarding different securement methods (Gardner et al. 2005). This is certainly reminiscent of the situation in veterinary medicine.

Specific performance of ETT securing methods pertaining to their permittance of UE has been assessed in cadavers, comparing tape (the 'Lillhei' taping method, where adhesive tape encircles the body of the ETT as it exits the mouth and then continues around the head of the patient) and several commercially available devices (Carlson et al. 2007). The tape and Thomas Tube Holder device performed best out of the methods tested, requiring the most force on average to fail and permit a UE; 86.7 N and 164.6 N respectively (Carlson et al. 2007). The device consisted of a moulded plastic panel that sits over the mouth, with an adjustable clamp that secures the ETT. Another study showed the Haider Tube Guard, a commercial device, to compare favourably with adhesive tape (Buckley et al. 2016). The device, a silicone casing that sits around the ETT at the level of the mouth, better prevented displacement of an ETT when a force of 15 N was applied (Buckley et al. 2016). No such devices are available for use in cats and dogs, most likely because ETT are more commonly used as a temporary intervention, and long-term securement is infrequently required.

To the author's knowledge, studies evaluating methods of securement of ETTs in animals do not exist.

2.8 Selection of appropriate endotracheal tube size in animals

The best fit endotracheal tube for any individual is typically the largest size that fits through and advances smoothly into the larynx. Endotracheal tubes that are too large may delay tracheal intubation and cause laryngeal and/or tracheal trauma (Lish et al. 2008). An ETT that is too small may lead to leakage of anaesthetic gases, risk of aspiration and high resistance to gas flow (Park et al. 2022) . Selection of an appropriately sized ETT for an individual cat or dog is honed by clinical experience. Development of several estimation methods has been attempted to aid this process.

2.8.1 Estimating appropriate endotracheal tube internal diameter

Several methods have been proposed for approximating appropriate endotracheal tube internal diameter (ID) in dogs. A graphic chart was developed using body mass to estimate ideal ETT ID for dogs. The accuracy of prediction was demonstrated in mesocephalic dogs but estimations could not apply reliably to brachycephalic individuals (Haider et al. 2020). Large variations in anatomy between different dog breeds remains a significant challenge for choosing appropriate ETT sizes.

Two methods for estimation of 'best fit' ETT outer diameter used in clinical practice were examined (Lish et al. 2008). Digital palpation of the trachea performed best with 46% correct estimates, whilst pairing nasal septal width with ETT outer diameter produced only 21% correct estimates (Lish et al. 2008). However, it is pertinent to note that the cadavers used in this study were all of dolichocephalic conformation. Extrapolations to the general dog population, and particularly to brachycephalic dogs, should be made with caution.

Subjective scoring of resistance to passage of ETT through the trachea was used to quantify success of ETT size estimation in a population of mesocephalic dogs (Shin et al. 2018). The results suggested that choosing an ETT with an outer diameter of 70% of the internal tracheal diameter as measured by lateral cervical radiography provides the best fit (Shin et al. 2018). The practicality of this method may be low, because radiography is usually performed either under sedation or general anaesthesia, when an ETT would likely already have been placed. Additionally, this method necessitates exposure to radiation.

Reviewing a large variety of anatomical measurements, a study of 79 dogs concluded that calculating the cube root of body mass provides the best prediction of appropriate ETT size (Tong & Pang 2019). The authors alternatively proposed division of the nose width by 3. However, the study used the size of ETT placed in each dog by experienced technicians as the comparison for successful prediction, rather than measurements of tracheal diameter.

A formula used for ETT selection in children based on age (Khine et al. 1997) has been adapted for use in dogs, using body weight in place of age. The formula calculates the optimal ETT ID (mm):

$$\text{ETT ID} = (\text{Body weight (kg)} / 4) + 4$$

This formula is used by students in the Small Animal Hospital, University of Glasgow as a guide to ETT selection but has not been formally studied. Students are always encouraged to choose a selection of ETT, usually three different sizes, and to refine this selection following visualisation of the trachea.

2.8.2 Estimating appropriate endotracheal tube length

It is recommended that tubes should not extend distally beyond the thoracic inlet, nor should they emerge rostrally beyond the incisors (Mosley 2015). Long ETTs increase the risk of endobronchial intubation or carinal contact. Insufficiently long ETT could become dislodged or cause laryngeal trauma if a cuff is inflated too rostrally. If an ETT extends beyond the oral cavity, mechanical dead space is increased (Mosley 2015).

In cats, measurement of the distance between the larynx and first rib has been proposed as a guide for optimal ETT length selection (Rodriguez et al. 2022). Anecdotally, a popular method used in clinical practice for selecting an appropriate ETT length is to measure the intended ETT against the patient prior to tracheal intubation. This is performed by assessing the distance between the rostral tip of the nose and the point of the shoulder, which approximates to the thoracic inlet. An ETT of ideal length will extend beyond the level of the larynx and terminate before or at the point of the shoulder.

2.9 Physics related to gas flow through endotracheal tubes

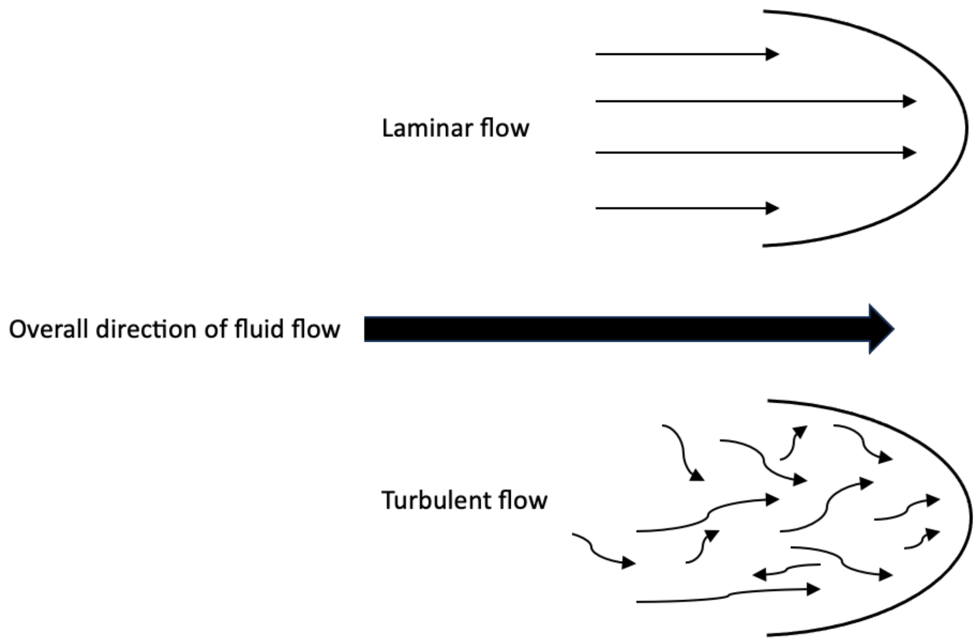
Gas flow through ETT is subject to the laws of fluid mechanics. In terms of clinical safety, the most important factor when considering the physics related to gas flow through ETT is resistance. Increasing resistance to gas flow increases work of breathing (WOB) through the ETT for the patient. An inappropriately high WOB predisposes to hypercapnia, hypoxaemia and respiratory fatigue (Moore & Binger 1927).

2.9.1 Nature of gas flow through the endotracheal tube

The applicable equations governing resistance to gas flow through an ETT are dependent on whether flow is laminar or turbulent (Bock et al. 2000) (see Figure 2-9). Laminar flow is described as the orderly movement of fluid (liquid/gas) in parallel layers, with the fastest velocity of flow in the centre of the fluid column (Middleton et al. 2012). Turbulent flow is by comparison disorderly, with multiple small irregularly arranged currents that contribute to an overall uniform direction of fluid flow (Middleton et al. 2012).

Figure 2-9

Schematic diagrams depicting laminar (top) and turbulent (bottom) fluid flow



Resistance to laminar fluid flow is described by the Hagen-Poiseuille equation.

$R = 8\mu L / \pi r^4$

Where R = resistance, μ = dynamic viscosity of fluid, L = length of tube, r = radius of tube.

For turbulent flow, resistance to gas flow in ETT is more appropriately determined using the Blasius formula, provided the Reynold's number lies between 4000 and 16000 (Lofaso et al. 1992) (see section 2.9.2):

$R = V^2 p f L / \pi r^5$ (Bock et al. 2000)

Where R = resistance, V = flow, p = density of fluid, *f* = frictional factor*,* L = length of tube, r = radius of tube.

In both equations, the radius of the ETT plays a significant role in determining resistance. Any reduction in the CSA of an ETT will decrease its radius, with a consequent inversely proportional increase in resistance. For laminar flow, resistance is proportional to the fourth power of the radius. For turbulent flow, resistance is proportional to the fifth power of the radius.

Whether a fluid exhibits laminar or turbulent flow is governed by the factors that dictate the Reynold's number (Re). The Reynold's number is a dimensionless characteristic as given by the following equation (Reynolds 1883):

$$Re = \nu \rho d / \eta$$

Where ν = linear velocity of gas, ρ = density of gas, d = internal diameter of ETT and η = viscosity of gas.

Laminar flow is likely if the Re <2000, whereas turbulent flow is likely at Re >4000 (Henderson & Runcie 2017). For a Re 2000-4000, flow is considered to be transitional and could exhibit both laminar and turbulent characteristics at different locations.

2.9.2 Reynold's number calculation in theoretical clinical scenarios

It is difficult to define the nature of flow in clinical scenarios, because many of the factors contributing to the Reynold's number are unknown, or difficult to calculate, in the clinical setting. For this reason, ten different example clinical scenarios are considered, with consequent calculation of the Re relating to each.

Units

Flow: cm^3/s (which is equal to ml/s)

Density: g/cm^3

Radius: cm

Viscosity: g/cm/s

Values for viscosity and density of pure oxygen at 23°C (Habre et al. 2001)

Density: 1.23 kg/m^3 → **0.00123 g/cm^3**

Viscosity: 0.00002 Pa s → **0.0002 g/cm/s**

RR = respiratory rate

bpm = breaths per minute

I:E = inspiratory:expiratory ratio

<u>Example 1</u>

20 kg dog, RR 20bpm, tidal volume 200ml, I:E ratio 1:2, ETT 7.0mm internal diameter

Flow: 1 respiratory cycle = 60/20 = 3 seconds, inspiratory time 1 second, so flow = **<u>200ml/s</u>**

Re = (2 x 200 x 0.00123) / (π x 0.35 x 0.0002) = 0.492 / 0.00022 = **2236** → **LAMINAR FLOW**

<u>Example 2</u>

10 kg dog, RR 16bpm, tidal volume 120ml, I:E 1:2, ETT 6m5mm

Flow: 1 respiratory cycle = 60/16 = 3.75s, inspiratory time 1.25s, flow = **<u>96ml/s</u>**

Re = (2 x 96 x 0.00123) / (π x 0.325 x 0.0002) = 0.236 / 0.000204 = **1157** → **LAMINAR FLOW**

<u>Example 3</u>

30 kg dog, RR 12bpm, tidal volume 400ml, I:E 1:2, ETT 11.0mm

Flow: 1 respiratory cycle = 60/12 = 5s, inspiratory time 1.7s, flow = **<u>235ml/s</u>**

Re = (2 x 235 x 0.00123) / (π x 0.55 x 0.0002) = 0.58 / 0.000346 = **1676 → LAMINAR FLOW**

Example 4

4 kg cat, RR 20bpm, tidal volume 40ml, I:E 1:2, ETT 4.5mm

Flow: 1 respiratory cycle = 60/20 = 3s, inspiratory time 1s, flow = **40ml/s**

Re = (2 x 40 x 0.00123) / (π x 0.23 x 0.0002) = 0.0984 / 0.000145 = **678 → LAMINAR FLOW**

Example 5

20 kg dog, RR 30bpm, tidal volume 300ml, I:E 1:3, ETT 9.5mm

Flow: 1 respiratory cycle = 60/30 = 2s, inspiratory time 0.5s, flow = **600ml/s**

Re = (2 x 600 x 0.00123) / (π x 0.48 x 0.0002) = 1.48 / 0.000302 = **4900 → TURBULENT FLOW**

Example 6

7.5 kg dog, RR 15bpm, tidal volume 150ml, I:E 1:2.5, ETT 7.0mm

Flow: 1 respiratory cycle = 60/15 = 4s, inspiratory time 1.1s, flow = **136ml/s**

Re = (2 x 136 x 0.00123) / (π x 0.35 x 0.0002) = 0.33456 / 0.00022 = **1520 → LAMINAR FLOW**

Example 7

55kg dog, RR 20bpm, tidal volume 825ml, I:E 1:2, ETT 14.0mm

Flow: 1 respiratory cycle = 60/20 = 3s, inspiratory time 1s, flow = **825ml/s**

Re = (2 x 825 x 0.00123) / (π x 0.7 x 0.0002) = 2.0295 / 0.00044 = **4613 → TURBULENT FLOW**

Example 8

1.6kg puppy, RR 35bpm, tidal volume 20ml, I:E 1:3, ETT 3.5mm

Flow: 1 respiratory cycle = 60/35 = 1.7s, inspiratory time 0.43s, flow = **46ml/s**

Re = (2 x 46 x 0.00123) / (π x 0.18 x 0.0002) = 0.11316 / 0.000113 = **1001 → LAMINAR FLOW**

Example 9

5.6kg cat, RR 24bpm, tidal volume 84ml, I:E 1:2, ETT 5.0mm

Flow: 1 respiratory cycle = 60/24 = 2.5s, inspiratory time 0.83s, flow = **101ml/s**

Re = (2 x 101 x 0.00123) / (π x 0.25 x 0.0002) = 0.248 / 0.000157 = **1579 → LAMINAR FLOW**

Example 10

40kg dog, RR 10bpm, tidal volume 680ml, I:E 1:2, ETT 12.0mm

Flow: 1 respiratory cycle = 60/10 = 6s, inspiratory time 2s, flow = **340ml/s**

Re = (2 x 340 x 0.00123) / (π x 0.6 x 0.0002) = 0.836 / 0.00038 = **2200 → LAMINAR FLOW**

Eight of the theoretical clinical examples would be expected to exhibit laminar flow, and two would exhibit turbulent flow. The actual nature of flow is likely to differ considerably in a real-life clinical scenario according to the pre-determined variables, as well as other influencing factors such as changes to angulation and CSA of breathing system tubing and the ETT. The examples chosen serve to demonstrate the potential variety in nature of flow in the clinical setting. This strongly suggests that accounting for both possibilities of flow type when considering the effect of fluid mechanics in ETT of cats and dogs is warranted.

2.10 Complications related to the use of endotracheal tubes in animals

Whilst endotracheal tubes are widely considered to contribute to the practice of safe general anaesthesia in animals, their use is not benign.

Endotracheal intubation has been linked to increased odds of peri-anaesthetic death in cats in a large-scale investigation (Brodbelt et al. 2007). This relationship was maintained even when accounting for health status and procedure. The authors proposed that the small size and sensitivity of the feline airway were possible contributing factors. They suspected that laryngeal oedema, trauma and spasm may have accounted for the relationship between endotracheal intubation and death in the cats studied (Brodbelt et al. 2007). However, the exact cause of death in the animals included in this study was not ascertained, and post-mortem examination was not carried out, so this theory remains unsubstantiated. Most of the cats died following tracheal extubation, suggesting that acute problems developing with the endotracheal tube in situ were less likely. To the author’s knowledge, Brodbelt et al. (2007) is the only large-scale investigation in veterinary species assessing ETT and their correlation with mortality. The remainder of the evidence base relating to complications with ETT in animals consists of case reports and series. The variety of problems documented suggests that the ETT is an important source of potential harm.

2.10.1 Complications associated with the process of endotracheal intubation

Endotracheal intubation can cause injury. Injuries attributed directly to tracheal intubation are described in a horse, where pharyngeal perforation occurred (Brock 1985). Laryngotracheal lesions as a direct result of orotracheal intubation, including abundant tracheal mucous, ecchymoses and basement membrane haemorrhage, were found in a large cohort of otherwise healthy horses (Heath et al. 1989). Tearing of the arytenoid cartilage associated with excessive force during tracheal intubation in the cat has been described (Hofmeister et al. 2007). Laryngeal perforation due to a difficult intubation in a pig is reported (Steinbacher et al. 2012). The pressure exerted on upper respiratory structures should be minimal during the tracheal intubation process. Optimal visualisation and positioning of relevant structures where possible promote gentle handling.

In cats and dogs, tracheal intubation is usually performed with direct visualisation of the larynx. Intubation without visualisation is typically performed in horses due to the small oral gape and length of the oral cavity. The appearance of blood in the upper airway, as previously reported (Hofmeister et al. 2007), is highly suggestive of iatrogenic injury and steps should be taken to assess and treat accordingly.

2.10.2 Tracheal rupture

Tracheal rupture in cats as a complication of endotracheal intubation is reported (Wong & Brock 1994; Hardie et al. 1999; Mitchell et al. 2000). Over-inflation of ETT cuffs is a speculated causative factor and has been shown experimentally to induce tracheal rupture in feline cadavers (Hardie et al. 1999). Traction on the trachea during recumbency changes and traumatic intubation are also proposed contributory factors (Mitchell et al. 2000). Rupture of the trachea due to ETT is also reported in the horse (Saulez et al. 2009; Miller & Auckburally 2020). Potential causes include traumatic intubation and excessive traction on the ETT due to inadvertent movement of the ETT within the trachea (Saulez et al. 2009), as well as extubation with the ETT cuff partially inflated (Miller & Auckburally 2020).

2.10.3 Tracheal mucosal injury

Injury to the tracheal mucosa is a possible consequence of the presence of an ETT. It has been shown experimentally that tracheal blood flow in dogs is significantly reduced when exposed to mucosal contact pressures of 20 mmHg from inflated ETT cuffs (Bunegin et al. 1993). Clinical cases of tracheal necrosis as a result of ETT are reported in the dog (Alderson et al. 2006; Manabe et al. 2021) and horse (Wylie et al. 2015). Tracheal injury and ulceration following orotracheal intubation has been shown in the rabbit, including two instances of death due to acute respiratory obstruction by necrotic tracheal debris (Phaneuf et al. 2006).

Tracheal stricture as a result of endotracheal intubation has been documented in the rabbit (Grint et al. 2006) and the dog (Manabe et al. 2021). It can result from excessive pressure or trauma to the tracheal mucosa, causing iatrogenic tracheitis. Chemical tracheitis from the presence of residual or inappropriate disinfection agent on the ETT has also been anecdotally reported.

Avoiding over-inflation of the ETT cuff and choosing an ETT of an appropriate size are recommended to reduce the risk of tracheal mucosal damage (Mosley 2015). Inflation of the ETT cuff may be achieved by inflating until cessation of an audible leak around the ETT during manual IPPV (minimal occlusive volume technique) (Hughes 2016). Alternatively, cuffs can be inflated with a manometer. Commercially manufactured inflation syringes are also available that contain a digital manometer. There is no current consensus on the best method for cuff inflation (Briganti et al. 2012; Hung et al. 2020)

2.10.4 Mispositioning of endotracheal tubes

Correct positioning of an ETT is important to reduce the risk of adverse effects. The ETT should extend from the oral cavity into the proximal/mid-trachea (Mosley 2015). Protrusion of the ETT beyond the mid-trachea may encroach upon the carina, causing irritation and possibly endobronchial intubation. Inadvertent endobronchial intubation is a recognised cause of hypoxaemia in humans (Bone et al. 1974). An ETT that protrudes rostrally beyond the oral cavity produces unnecessary apparatus dead space, predisposing to rebreathing of carbon dioxide and hypercapnia (King et al. 2017).

Caudal displacement of ETT within the trachea during flexion of the neck has been shown in dogs (Quandt et al. 1993). In the author’s experience in clinical practice, angled positioning of the head and neck is commonly performed to facilitate specific procedures such as ocular surgery and cerebrospinal fluid collection. The awareness of the potential for ETT to displace caudally in the trachea may be important for the prevention of iatrogenic endobronchial intubation when this type of positioning occurs.

2.10.5 Obstruction of endotracheal tubes

Obstruction of the respiratory tract can rapidly lead to fatality (Egger 2016). The ETT, once in situ, acts as the upper airway, and so any obstructions to its lumen effectively cause an upper respiratory obstruction. Reports in the literature of ETT obstruction can be broadly divided into two main causes: presence of material causing occlusion of the ETT lumen, and kinking of the ETT. Both scenarios cause a significant reduction in the CSA available for gas flow, imposing resistance to inspiration and expiration.

Severe flexion of the head and neck during pre-surgical positioning caused kinking of an armoured ETT in a dog, leading to complete obstruction of the ETT and failure of ventilation (Aguilar et al. 2017). Delayed onset pulmonary oedema and eventual respiratory arrest developed in this case causing a fatal outcome. The propensity of ETT to kink upon acute angling of the head and neck has been demonstrated experimentally in dogs (Campoy et al. 2003), with red rubber ETT showing increased vulnerability to constriction when compared to PVC ETT. However, this study only measured the changes to the ventrodorsal diameter of ETT, rather than the CSA, so the overall effect on gas flow was not measured. Occlusion of ETT due to kinking at the atlanto-occipital joint on neck flexion in dogs has been shown through review of x-rays from clinical cases (Quandt et al. 1993). This complication can occur with both armoured and non-reinforced ETT during any angled positioning of the neck.

Presence of blood clots in the ETT lumen, leading to obstruction of approximately 60% of the CSA, is reported in two dogs (Küls & Murison 2015). These cases experienced hypercapnia, respiratory acidosis and hypoxaemia, which resolved on tracheal extubation. In the author’s experience, the possibility of blood or other fluids accumulating in the ETT lumen is increased in cases where respiratory secretions or oral or respiratory bleeding are likely. Presence of haemorrhagic material in the ETT lumen has been observed at the Small Animal Hospital, University of Glasgow (see Figure 2-10).

Figure 2-10

Image showing presence of haemorrhagic material within the lumen of an endotracheal tube (ETT). This ETT was removed from a dog with suspected aspiration pneumonia.

Physical obstruction of the ETT due to tape acting as a one-way valve, impeding expiration, has been reported in one horse on two occasions (Gregson & Clutton 2012). The medical tape had been applied to the ETT connector to increase its outer diameter in an attempt to improve its fit within the ETT lumen. However, caudal displacement of the tape into the lumen of the ETT occurred, creating a unidirectional valve. This led to increasing thoracic distension of the horse and progressively increasing airway pressures due to prevention of exhalation. Anecdotally, makeshift solutions to repair breakages in breathing system equipment are relatively common in veterinary medicine. The case reported by Gregson and Clutton (2012) suggests that improvised repairs should be discouraged for safety reasons.

Experimental obstruction of an anaesthetic breathing system in seven anaesthetised dogs has been evaluated (Algren et al. 1993). The obstruction created constituted a 95% reduction in the CSA of the inspiratory limb of the breathing system. Maintaining this obstruction for three hours lead to development of pulmonary oedema in four of the seven dogs. Pulmonary vascular congestion occurred in six out of seven. These dogs were not recovered from general anaesthesia, so the speed of resolution or recovery was not determined. However, pulmonary oedema leading to fatal respiratory arrest in a clinical case following obstruction of the ETT has been reported (Aguilar et al. 2017). This report shares similarities with experimental findings in anaesthetised dogs subjected to progressive inspiratory obstruction, which produced pulmonary congestion and oedema as assessed histologically post mortem (Moore & Binger 1927). Interestingly, no characteristic pulmonary changes were observed in dogs subjected to expiratory obstruction (Moore & Binger 1927). Obstruction of the ETT lumen is likely to lead to both inspiratory and expiratory obstruction, however.

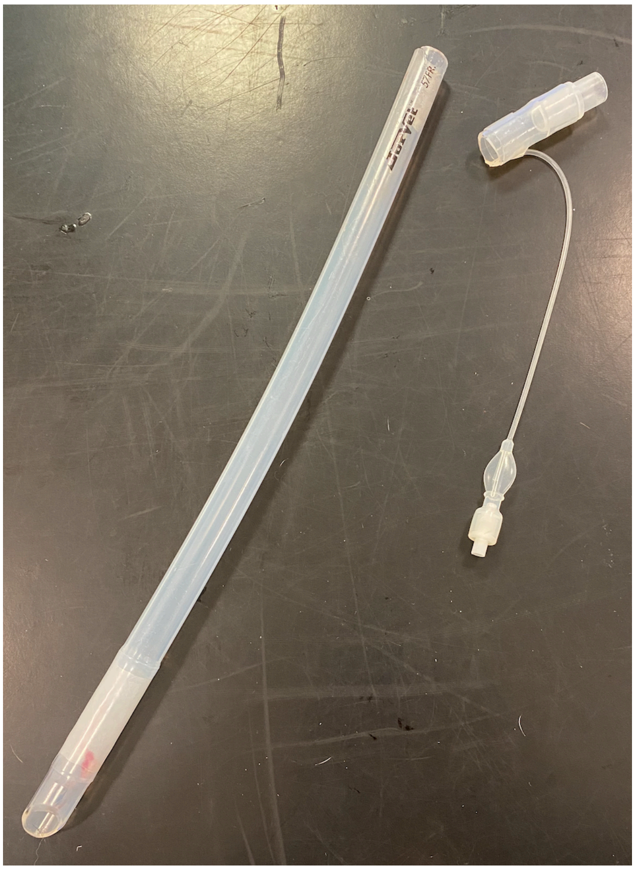
The obstruction of ETT, whilst infrequently reported in the veterinary literature in comparison to other complications, perhaps exerts the most detrimental physiological effects, and can be fatal. Its occurrence and any possible contributory factors therefore warrant investigation.

2.10.6 Breakage of endotracheal tubes

Breakage of silicone ETT in situ, leading to aspiration of the distal part, has been reported in the dog (Niimura del Barrio et al. 2015) (see Figure 2-11). Progressive degradation of the ETT material due to repeated cleaning and sterilisation, as well as biofilm formation, were proposed contributory factors. Breakage of ETT in situ caused by the patient biting and severing the body of the tube is reported in cats, dogs (Thomas 1975; Nutt et al. 2014), sheep (Lipiski et al. 2018) and pigs (Clutton & Lawrence 1997). Most of these instances occurred at the recovery phase, with the animal recovering rapidly or prematurely. Severing the ETT can result in aspiration of the distal tube and requires further anaesthesia and retrieval. In the pig, biting of an armoured ETT at recovery lead to a fatal outcome through maintenance of luminal obstruction by the reinforcing wire (Clutton & Lawrence 1997). Accidental aspiration of the ETT has also been reported in the rabbit, where the body of the tube became detached from the proximal connector (Lipiski et al. 2018). This particular case led to death due to failure of ETT retrieval, highlighting the importance of secure attachment of connectors to the ETT body.

Figure 2-11

Image showing a severed silicone endotracheal tube (ETT). The ETT was broken in situ during recovery by a dog biting the ETT body



2.10.7 Problems occurring at tracheal extubation

The tracheal extubation process should be performed quickly and gently. In the author's experience, delayed tracheal extubation may result in irritation to the tracheal mucosa and/or larynx, coughing and distress for the patient. Failure of tracheal extubation due to problems with the ETT cuff has been reported in the cat (Sanchis Mora & Seymour 2011) and dog (Norgate & Jimenez 2017). Both case reports describe gathering of the deflated ETT cuff material at one end, causing impedance to extubation. Both HVLP and LVHP cuff types were implicated, suggesting that this complication is possible in any cuffed ETT. Failure of tracheal extubation of silicone ETT with deflated LVHP cuffs has occurred in three dogs (Romano & Portela 2020). Inappropriately large sized ETT were postulated to have contributed to these cases and all required lubrication of the ETT for successful removal. Dehydration of mucous membranes causing adhesion of the cuff material to the tracheal mucosa may also contribute to this problem and is anecdotally reported.

Accidental iatrogenic fixation of the ETT cuff into a tracheal laceration repair is reported in the dog leading to an inability to perform tracheal extubation (Miller et al. 2020). The same complication has also been clinically observed in a dog undergoing surgical treatment of laryngeal paralysis. These reports serve to highlight the potential interference that surgical procedures involving the head and neck may pose to ETT.

2.11 Use of computed tomography imaging to assess endotracheal tubes

Computed tomography is an advanced imaging modality, using rotating x-ray beams to create cross-sectional images. The ability of computed tomography imaging to accurately detect reductions in ETT CSA has been shown in non-clinical equipment studies.

An experimental study demonstrated acceptable correlation of CT-derived assessments of reduced ETT CSA with changes to resistance to gas flow through ETT (Mietto et al. 2014). The non-clinical study subjected ETT to reductions in CSA through application of varying amounts of silicone to the internal surface, simulating respiratory secretions. The siliconised ETT then underwent CT for measurement of CSA reduction, and subsequent pressure-drop testing to determine resistance. The authors propose high-definition CT as a technique for the evaluation of ETT patency in intubated human patients (Mietto et al. 2014). Accurate detection of mucous accumulation in previously-used ETT by high-definition CT has also been demonstrated (Pinciroli et al. 2013).

Computed tomography imaging provides an appropriate resource for the assessment of ETT luminal patency and mispositioning. Anecdotal observations of ETT CSA reductions visible on CT images of clinical cases were made on a fairly frequent basis at the Small Animal Hospital, University of Glasgow.

Chapter 3

Aims of thesis

The aims of this work can be summarised with the following research questions.

1. What is the prevalence of ETT constriction in anaesthetised cats and dogs?

2. What is the prevalence of rostral and caudal mispositioning of ETT in anaesthetised cats and dogs?

3. What are the risk factors associated with ETT constriction and rostral and caudal mispositioning in anaesthetised cats and dogs?

4. How do ETT material, ETT size and securing tie material affect the minimum force required to produce ETT constriction through application of the securing tie?

Questions 1-3 were answered through a retrospective investigation of clinical cases at the Small Animal Hospital, University of Glasgow. Question 4 was answered through the performance of an experimental non-clinical equipment study.

Chapter 4

Preface to retrospective study

Bone et al. (1974) stated "We must be sure to give sufficient emphasis to the problems involved in endotracheal intubation and its hazards. It is a manoeuvre so commonly employed as to diminish both the respect it deserves and the care it demands".

Cats and dogs are endotracheally intubated with ETT daily at the Small Animal Hospital, University of Glasgow. Observations of constriction of ETT, as revealed by CT imaging for various clinical purposes, sparked an interest in undetected ETT complications. A thorough literature search failed to elicit any large scale investigations focussing on ETT complications in animals. With the aim of contributing to the evidence base, a retrospective review of ETT in cats and dogs was conducted, resulting in the following piece of original research.

The database of CT images of canine and feline patients at the Small Animal Hospital, University of Glasgow provided a readily available resource for the review of ETT positioning and complications. Cats and dogs undergo CT imaging regularly at the hospital, for a variety of diagnostic purposes. A significant proportion of these animals require general anaesthesia for the safe completion of CT imaging and to ensure excellent quality images through the reduction of movement. Any animal undergoing general anaesthesia will have an ETT in situ during the CT.

The inclusion criteria for the retrospective study were any cat or dog undergoing CT imaging of the head and/or neck and/or thorax for any reason, with an oral ETT in situ, from 2017 to 2019 inclusive. These criteria provided a study population of 670 dogs and 146 cats.

A review of the CT images was conducted to evaluate any and all complications that were visible. This included problems with mispositioning (if the ETT was positioned too rostrally or too caudally) and constriction of the ETT lumen. Causes of constriction were appraised and categorised. Analysis of the results revealed both mispositioning and constriction to be present with substantial frequency.

It is sincerely hoped that the results of this retrospective investigation serve to increase awareness of the prevalence of problems with the use of ETT in cats and dogs. The information gained from this investigation could possibly contribute towards the creation of evidence-based guidelines for ETT use in veterinary anaesthesia.

Chapter 5

Retrospective study manuscript

5.1 Title

Retrospective computed tomography analysis of endotracheal tube constriction & mispositioning in cats & dogs

5.2 Abstract

5.2.1 Objectives

This study aimed to discover the prevalence of endotracheal tube (ETT) constriction and rostral and caudal mispositioning in anaesthetised cats and dogs, and to identify associated risk factors.

5.2.2 Study Design

Retrospective analysis

5.2.3 Animal population

146 cats, 670 dogs

5.2.4 Methods

Computed tomography images of the head/neck/thorax from orotracheally intubated cats and dogs were visually assessed for constriction or mispositioning of the ETT. If constriction was present, measurements of the cross-sectional area (CSA) of the ETT lumen at constricted and un-constricted locations were compared. Location and cause of constriction was noted and expected increase in resistance to gas flow was calculated. Patient information was collected from clinical records. Normality of continuous variables was assessed via the Shapiro-Wilk test. Chi square tests examined associations between variables. Kendall's tau-b test was performed between measured ETT size and degree of constriction.

5.2.5 Results

The ETT extended rostrally beyond incisors in 52% of cases; the connector was within the oral cavity in 19% of cases. The ETT extended beyond the first rib in 25.5% of cases. The prevalence of ETT constriction was 22.7%. Median reduction in CSA was 7.68% (0.14 – 64.19%). Median increase in resistance assuming laminar and turbulent flow was 16.5% (0.3 – 680%) and 21% (0.3 – 1200%), respectively. The most common cause of constriction was the presence of a radiotherapy mouth gag. Significant associations existed between presence of constriction and rostral mispositioning, and caudal mispositioning and extreme brachycephaly. Increased severity of constriction was more likely in smaller ETT.

5.2.6 Conclusions and clinical relevance

Constriction and mispositioning of ETT occurred very commonly in this population. Checking the ETT within the oral cavity for constriction and mispositioning is recommended. Radiotherapy mouth gags increase the risk of ETT compression. Smaller ETT are at greater risk of severe constriction. Brachycephalic dogs are at particular risk of caudal mispositioning.

5.3 Introduction

Orotracheal intubation is standard practice in canine and feline anaesthesia. Endotracheal tubes (ETT) facilitate the delivery of anaesthetic gases and oxygen, ensure patency of the upper airway and can protect the respiratory tract from aspiration of gastric contents (Mosley 2015; Hughes 2016). However, endotracheal intubation is not a benign procedure. In humans, iatrogenic tracheal mucosal damage and stenosis are risks of orotracheal intubation (Evans et al. 2015), and obstruction of ETT and endobronchial intubation are reported (Bone et al. 1974).

Complications with ETT may result in a risk to patient safety. A reduction in the size of the ETT lumen increases resistance to gas flow and consequently the work of breathing (Shapiro et al. 1986), and may lead to hypercapnia, hypoxaemia (via hypoventilation) and pulmonary oedema if severe (related to negative pressure in the alveoli) (Dicpinigaitis & Mehta 1995; Bhaskar & Fraser 2011). Endobronchial intubation can cause hypercapnia and hypoxaemia (Owen & Cheney 1987; Bissinger et al. 1989). An ETT that protrudes rostrally beyond the oral cavity produces unnecessary apparatus dead space, predisposing to rebreathing of carbon dioxide and hypercapnia (King et al. 2017). Conversely, an ETT with the connector residing within the oral cavity may cause handling difficulties for personnel when connecting breathing systems.

Case reports in cats and dogs describe incidents of tracheal injury from orotracheal intubation and ETT cuff overinflation (Alderson et al. 2006; Hofmeister et al. 2007). Tracheal rupture as a result of orotracheal intubation is also reported in the cat (Mitchell et al. 2000). There are relatively few reports of ETT constriction and mispositioning in animals: ETT obstruction due to kinking (Aguilar et al. 2017) and occlusion from blood clots (Küls & Murison 2015) is reported in dogs.

The utility of computed tomography (CT) imaging in assessment of ETT patency and detection of reductions in ETT cross-sectional area (CSA) has been demonstrated (Pinciroli et al. 2013; Mietto et al. 2014). Diagnostic CT imaging of the head, neck and thorax of orotracheally intubated cats and dogs provides a readily available resource for the evaluation of ETT constriction and mispositioning.

Knowledge of the prevalence of mispositioning and constriction of ETT in cats and dogs may inform clinical management. Awareness of the causes of ETT constriction presents an opportunity for prevention. The objectives of this study were to discover the prevalence of ETT constriction and rostral and caudal mispositioning in anaesthetised cats and dogs, and to ascertain risk factors for these problems. The authors expected to find rostral mispositioning and constriction caused by ETT ties in some cases (as observed clinically).

5.4 Materials and methods

This study received ethical approval from the Research Ethics Committee at the University of Glasgow (reference EA17/20). Retrospective analysis of CT images of anaesthetised cats and dogs from one University referral hospital from 2017-2019 inclusive was performed. A 3-year period was chosen to provide a representative sample of the hospital caseload and provide large numbers of images for analysis. Images were produced by a multislice scanner (Somatom Spirit, Siemens Healthineers, Germany) as Digital and Communication in Medicine (DICOM) files and reconstructed with bone windows for analysis by specialised medical imaging software (Clear Canvas, Synaptive Medical, Canada). Inclusion criteria comprised any cat or dog undergoing CT imaging of the head and/or neck and/or thorax for any reason with an ETT in situ. A single observer (veterinary anaesthesia resident, trained in use of the software and targeted image interpretation by a Diplomate radiologist) assessed all images and performed all measurements in a transverse plane via the imaging software.

Rostral positioning was assessed in image sets of the entire head that included the tip of the nose and mouth. An ETT was defined as ‘too rostral’ when the body of the ETT extended beyond the incisors. Connectors of ETT positioned within the oral cavity were noted. An ETT was considered to be optimally rostrally positioned if the connector was present at the level of the incisors. Caudal mispositioning was assessed in image sets of the thorax showing the caudal tip of the ETT, and was so defined if this extended beyond the first rib. The number of ribs each caudally mispositioned ETT extended to was counted, and ETT reaching the carina were noted. The ETT lumen was visually assessed for any constriction and the location and apparent cause were noted. For cases showing constriction, measurements of the CSA of the ETT lumen were performed at the narrowest location and a normal (non-constricted) location that was free of image artefact. Degree of constriction was calculated as a percentage reduction in CSA between the two measurements. In cats, presence of a cuffed ETT was defined according to the detection of a pilot balloon or inflation tube within the ETT wall. A case was categorised as ‘radiotherapy planning’ if characteristic oral inserts/‘gags’ and a moulded plastic mask were visible in CT images of the head (see supplementary material 2). This category was defined to facilitate separate analysis because in the majority of these cases, the ETT extended beyond the incisors deliberately to permit connection to the breathing system through a moulded mask.

For ETT exhibiting constriction, the expected increase in magnitude of resistance to gas flow was calculated. This was achieved by comparing the constricted CSA with the non-constricted CSA, as an effect on ETT radius. The measured CSA was converted to a theoretical ETT radius via the following equation:

Radius = $\sqrt{(CSA/\pi)}$

Using the calculated radius, the expected change in magnitude of resistance was then estimated for both laminar and turbulent flow using the following equations:

For laminar flow: Resistance increase (%) = $((\frac{1}{x})^4)$ x 100 - 100

For turbulent flow: Resistance increase (%) = $((\frac{1}{x})^5)$ x 100 - 100

Where x = reduction in (calculated) radius due to (measured) constricted CSA.

Clinical and anaesthetic records were searched for species, breed, age, body weight, presenting complaint, procedure, ETT size and recorded complications. French bulldogs, pugs and bulldogs were classified as 'extreme brachycephalics' (Ladlow et al. 2018).

5.5 Statistics

Data were analysed using SPSS Statistics for Mac 28.0 (IBM, United States). Continuous variables were assessed for normal distribution using the Shapiro-Wilk test. Median (range) values and 95% confidence intervals (CI) are reported. Chi square tests (χ^2) were used to assess for associations between too rostral and caudal mispositioning with species, constriction and extreme brachycephaly, constriction with radiotherapy planning status, and constriction with cuffed tube status in cats. Radiotherapy cases were excluded from the association between too rostral positioning and constriction. Strength of association is reported as φ. Kendall's tau-b test (τb) was performed between measured ETT size and degree of constriction. Statistical significance (p) was set at 0.05.

5.6 Results

The total number of cases meeting the inclusion criteria was 816, comprising 146 cats and 670 dogs. Across all cases, 380 imaging sets of the head region, 438 of the neck region and 523 of the thoracic region were available for evaluation. Of the head image sets, 277 permitted assessment of the rostral ETT. Of the thoracic image sets, 515 permitted assessment of the caudal tip of the ETT (see supplementary material 1). Assessment of both the rostral and caudal ETT was possible in 65 cases. No continuous variables showed normal distribution and so are presented as median (range). Bodyweight was 14.5 (1.5 – 77.7) kg, 95% CI: 12.9 – 16.7 kg. Age was 8 (0.3 – 19) years; 95% CI: 8 - 9 years. Included dog and cat breeds are summarised in Table 5-1. Extreme brachycephalic breeds comprised 14% of all dogs. There were 59 radiotherapy planning cases identified.

Table 5-1

Breeds and number of individual animals represented in a retrospective cohort of 816 cats and dogs undergoing CT imaging of the head/neck/thorax with endotracheal tubes in situ from 2017-2019 inclusive at one University referral hospital. 'Other breeds' include those represented by fewer than 3 individuals.

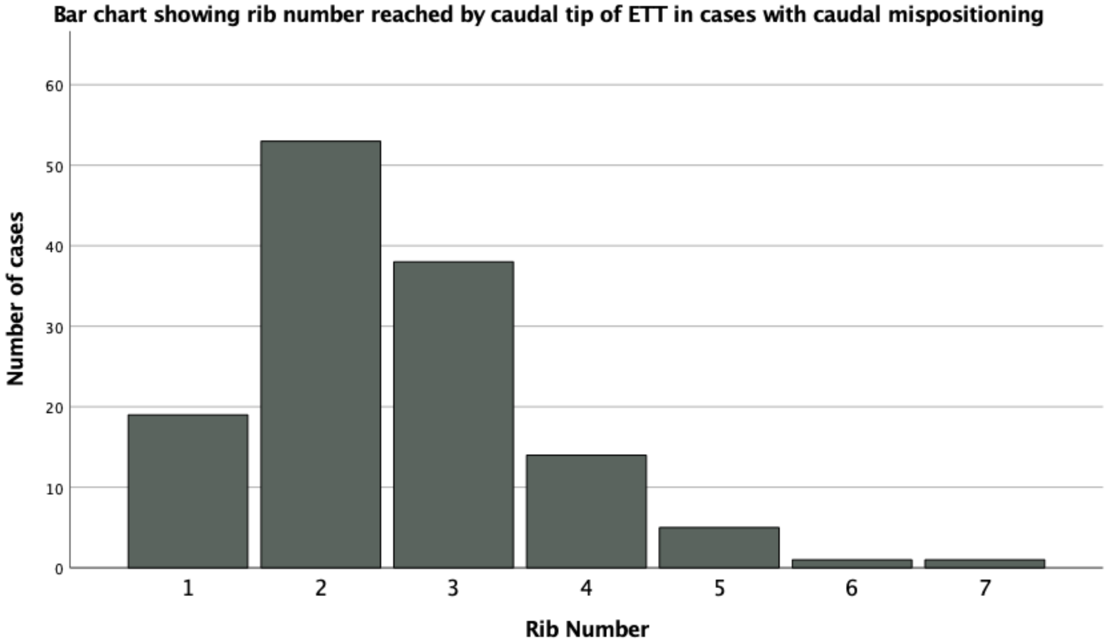
Dogs	**Number of individuals**
Labrador Retriever	78
Pug	50
Cocker Spaniel	38
Border Collie	30
French Bulldog	28
Staffordshire Bull Terrier	24
Springer Spaniel	24
Boxer	22
Labradoodle	19
Jack Russell Terrier	19
Golden Retriever	18
West Highland White Terrier	18
British Bulldog	18
Cavalier King Charles Spaniel	13
Lhasa Apso	13
Border Terrier	11
Siberian Husky	11
German Shepherd	11
Shih-Tzu	10
Rottweiler	10
Miniature Schnauzer	8
Chihuahua	8
Whippet	7
Pomeranian	7
Bernese Mountain Dog	6
Yorkshire Terrier	6
Beagle	6

Bull Mastiff	6
German Pointer	6
Rhodesian Ridgeback	5
Bichon Frise	4
Weimaraner	4
Bearded Collie	3
Cairn Terrier	3
Miniature Poodle	3
Tibetan Terrier	3
Hungarian Viszla	3
Bassett Hound	3
Munsterlander	3
Other	41
Cats	
Domestic Shorthair	92
Persian	5
Bengal	4
Crossbreed cat	5
Domestic Longhair	8
British Shorthair	8
Maine Coon	6
Ragdoll	4
Havana	3
Unspecified	7
Other	12

The overall prevalence of too-rostral mispositioning was 52% (145/277) for the entire population and 44% (95/218) excluding radiotherapy cases. Fifty (85%) radiotherapy planning cases exhibited too-rostral mispositioning. The overall prevalence of ETT connectors residing within the oral cavity was 19% (52/277). Optimal rostral positioning was exhibited in 29% (80/277) of cases. The overall prevalence of caudal mispositioning was 25.5% (131/515) - see Figure 5-1 for the distribution of rib numbers reached by the caudal tip of the ETT. Three ETT reached the carina (0.6%), which was present at rib 5, 6 and 7 in these animals. No instances of endobronchial intubation were found.

Figure 5-1

Bar chart showing rib number reached by caudal tip of endotracheal tube in 131/515 cats and dogs undergoing CT imaging of the head/neck/thorax from 2017-2019 inclusive at one University referral hospital. In 384 cases the caudal tip of the ETT did not extend beyond the first rib.



There was no statistically significant association between rostral mispositioning and species (p = 0.244) or extreme brachycephaly (p = 0.148). With radiotherapy cases excluded, there was a statistically significant association between rostral mispositioning and presence of constriction, $\chi^2 = 34.45$, $\varphi = 0.398$, $p < 0.001$. See Table 5-2 for the distribution of causes of constriction in this cohort.

Table 5-2

Causes of constriction of endotracheal tube (ETT) lumen with concurrent rostral mispositioning (ETT extends beyond rostral incisors) in 94/816 cats and dogs undergoing CT imaging of the head/neck/thorax from 2017-2019 inclusive at one University referral hospital.

Site/cause of constriction		**Number of cases**
'Oral' (unidentified)		18
Larynx		10
Tie		11
Gag		20
Teeth	Incisors	16
	Canines	1
	Molars	18

There was a statistically significant association between caudal mispositioning and species, with dogs being more likely to have too-caudally positioned ETT, $\chi^2 = 6.168$, $\varphi = 0.109$, $p = 0.013$. There was a statistically significant association between caudal mispositioning and extreme brachycephaly, $\chi^2 = 14.232$, $\varphi = 0.183$, $p < 0.001$. There was no statistically significant association between caudal mispositioning and constriction ($p = 0.345$).

Apparent constriction was present in 191/816 ETT, however in 6 of these cases, no actual reduction in cross sectional area was found, so they were excluded from all further analyses. The overall prevalence of true ETT constriction was 22.7% (185/816); with a prevalence of 22.4% in dogs (150 /670) and 24% in cats (35 /146). There was no statistically significant association between species and presence of constriction ($p = 0.679$). The frequency of constriction was similar in cuffed and plain ETT in cats. Constriction was exhibited in 46 (78%) radiotherapy planning cases. Prevalence and severity of constriction according to cause is presented in Table 5-3. The most common site for ETT lumen constriction was within the oral cavity, caused by the presence of a radiotherapy mouth gag, compression from the ETT tie or teeth. The larynx was the site of constriction in 27 cases. Severity of constriction for all causes is presented in Figure 5-2. See Figure 5-3 for example images (at end of manuscript).

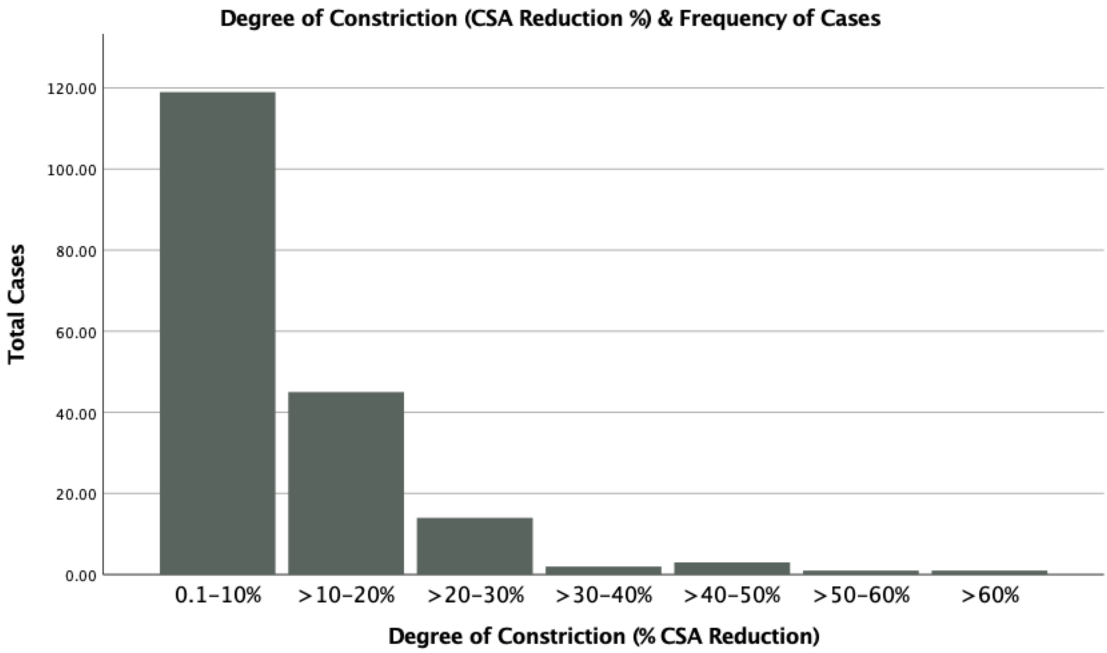
Table 5-3

Causes of constriction of endotracheal tube (ETT) lumen in 185/816 cats and dogs undergoing CT imaging of the head/neck/thorax from 2017-2019 inclusive at one University referral hospital with prevalence (total cases = number of cats and dogs) and severity of constriction as measured by percentage reduction in ETT cross sectional area (CSA), with associated expected increase in resistance assuming laminar and turbulent flow. In 631 cases there was no constriction of the ETT lumen. CI = confidence interval.

			Reduction in CSA (%)			Increase in resistance assuming laminar flow (%)			Increase in resistance assuming turbulent flow (%)		
Type	Cause	Total Cases	Median	Range	95% CI	Median	Range	95% CI	Median	Range	95% CI
All	All	185	7.9	0.1 – 64.2	6.0-9.0	16.5	0.1-680	12.2-19.2	21.0	0.3-1200	15.5-24.5
Intra-luminal	Material in ETT	6	14.6	8.4 – 64.2	8.4-64.2	37.6	19-680	19-680	49.1	25-1200	25-1200
Extra-luminal	Radio-therapy mouth gag	40	8.0	0.8 – 43.3	4.1-9.2	18.2	2-211	8.7-21.2	23.3	2-313	11-27.2
	Oral (unidentified)	39	11.1	0.6 – 36	4.8-14.6	26.8	1-144	10.4-37.2	34.5	2-206	13.1-48.5
	Tie	37	9.2	0.6 – 45.8	6.0-14.5	21.4	1-240	13.1-36.8	27.4	2-362	16.6-47.9
	Teeth	35	6.7	0.1 – 42.9	3.6-9.9	14.7	0.1-206	7.6-23.3	18.7	0.3-305	9.6-29.9
	Larynx	27	3.3	0.3 – 56.8	1.8-4.7	7.0	0.1-435	3.7-10.1	8.8	1-714	4.6-12.8

Figure 5-2

Bar chart showing severity of constriction of endotracheal tube (ETT) lumen in 185/816 cats and dogs undergoing CT imaging of the head/neck/thorax from 2017-2019 inclusive at one University referral hospital. Degree of constriction measured by percentage reduction in ETT cross sectional area (CSA). In 631 cases there was no constriction of the ETT lumen.



There was a significant association between severity of constriction and ETT size, $\tau b = -0.111$, $p < 0.001$: smaller ETT showed increased severity of constriction. See Table 5-4 for median reductions in CSA and expected increase in resistance according to ETT size category. There was a statistically significant association between presence of a radiotherapy mouth gag and presence of constriction, $\chi^2 = 107$, $\varphi = 0.362$, $p < 0.011$.

Table 5-4

Average constriction of endotracheal tube (ETT) lumen in 185/816 cats and dogs undergoing CT imaging of the head/neck/thorax with from 2017-2019 inclusive at one University referral hospital as measured by percentage reduction in ETT cross sectional area (CSA) with associated expected increase in resistance assuming laminar and turbulent flow, according to size category of ETT. In 631 cases there was no constriction of the ETT lumen. CI = confidence interval.

Size Category (ETT Internal Diameter, mm)	Median (range) Reduction in CSA (%)	95% CI for median reduction in CSA (%)	Median (range) increase in resistance assuming laminar flow (%)	95% CI for median increase in resistance assuming laminar flow (%)	Median (range) increase in resistance assuming turbulent flow (%)	95% CI for median increase in resistance assuming turbulent flow (%)
<4.0	18.6 (1.9 – 43.5)	4.0 – 28.7	52.0 (4.0-210.0)	8.0-97.0	69.0 (5.0-313.0)	11.0-133.0
4.0 - 6.5	10.8 (0.4 – 45.8)	8.0 – 13.9	26.0 (1.0-240.0)	18.0-35.0	33.0 (1.1-362.0)	23.0-45.0
>6.5 – 9.0	8.2 (0.3 – 56.8)	5.7 – 10.1	19.0 (1.0-435.0)	13.0-24.0	24.0 (1.1-714.0)	16.0-31.0
>9.0	4.5 (0.1 – 64.2)	3.5 – 7.1	10.0 (0.1-680.0)	7.0 – 16.0	12.0 (0.3-1200.0)	9.0-21.0

The median decrease in CSA due to constriction was 7.9% (0.14 – 64.2%), 95% CI: 6.0 - 9.0%. The median increase in expected resistance due to ETT constriction at laminar flow was 16.5% (0.3 – 680%); 95% CI: 12.2 - 19.2%, and at turbulent flow was 21% (0.3 – 1200%); 95% CI 15.5 – 24.5%.

5.7 Discussion

Constriction and mispositioning of ETT were observed very commonly in this population of cats and dogs.

Caudal mispositioning of ETT risks endobronchial intubation, which can cause significant morbidity including hypoxaemia (Bissinger et al. 1989), hyperinflation of the intubated lung and pneumothorax (McCoy et al. 1997). The basis for defining caudal mispositioning in this study comes from the description of proper placement of an ETT in animals as outlined by Lumb & Jones (Mosley 2015). According to this description, the ETT should not extend beyond the thoracic inlet. The first rib designates the thoracic inlet and was easy to identify on CT imaging. It was uncommon for the caudal tip of the ETT to reach the carina, and most of the caudally mispositioned ETT extended only to the second rib. However, caudal movement of ETT within the trachea equalling the distance of up to 6 vertebral bodies has been demonstrated with neck flexion in dogs (Quandt et al. 1993), so any ETT could migrate caudally, especially when a patient is re-positioned.

Caudal mispositioning was more common in dogs, suggesting better estimation of appropriate ETT length in cats. This may be explained by the greater variability in body size and tracheal length in dogs, making ETT length selection more difficult. Measurement of the larynx to first rib distance is proposed for optimal ETT insertion length in cats (Rodriguez et al. 2022), but considerable variation in head and/or nose size might reduce the applicability of this measure for dogs. Pugs, French bulldogs and bulldogs collectively showed a greater prevalence of caudal mispositioning. This may be a result of the combination of relatively larger heads and shorter noses and necks typical of these breeds leading to overestimation of appropriate ETT length. Assessing intended ETT against the nose to thoracic inlet distance is especially advised in these dogs.

Rostral mispositioning could only be assessed in cases including complete imaging of the oral cavity, therefore the true prevalence could differ from our findings. The description of ETT placement in Lumb & Jones recommends that ETT do not emerge beyond the incisors (Mosley 2015). In practice, an ETT emerging rostrally from the oral cavity may facilitate handling and connection of the breathing system. This was indeed the case in the majority of the radiotherapy planning cases, where presence of a plastic head mask (see Supplementary material) necessitated protrusion of the ETT beyond the incisors to facilitate connection to the breathing system. However, the convenience of rostral mispositioning should be weighed against the clinical implications of increased apparatus dead space, which increases as more of the ETT protrudes out of the oral cavity, predisposing to the rebreathing of carbon dioxide and hypercapnia (King et al. 2017). It was not possible to quantify the length of ETT protruding in our study, as many of the CT head images did not include the rostral part of the ETT. If the connector of the ETT is situated within the oral cavity, as exhibited by 51 cases in this study, handling may be difficult when connecting breathing systems and accidental disconnection may be more likely.

An association between too rostral positioning and constriction of ETT was demonstrated in this study. Endotracheal tubes emerging from the mouth are more at risk of compression by teeth. Molars and incisors were responsible in similar frequencies for constriction of ETT exhibiting too-rostral positioning, suggesting that rostrally mispositioned ETT may also be predisposed to lateral displacement. Aiming for optimal rostral positioning by ensuring the ETT connector is situated centrally within the oral cavity (thereby avoiding the molars), and sits at the level of the incisors, eliminates the risk of compression from teeth and minimises apparatus dead space, whilst optimising handling. A visual check of the ETT for optimal rostral positioning should be performed in every patient.

Severity of constriction of ETT (CSA percentage reduction) varied considerably both within and between cause categories. It is difficult to predict the clinical effects of a reduction in ETT CSA, as this is dependent on individual patient characteristics, but the implications are likely to be dictated by the effect on resistance to gas flow. Calculation of the expected increase in magnitude of resistance was therefore performed to illustrate a theoretical correlation between constriction and clinical implications. In laminar gas flow, resistance is proportional to the fourth power of the radius of the ETT lumen (Bock et al. 2000) whereas in turbulent flow, resistance is proportional to the fifth power of the radius (Lofaso et al. 1992). Nature of gas flow is predicted by the Reynold's number (Re), a dimensionless characteristic as given by the following equation (Middleton et al. 2012):

$$Re = \nu\rho d / \eta$$

Where ν = linear velocity of gas, ρ = density of gas, d = internal diameter of ETT and η = viscosity of gas.

If Re <2000, flow is likely laminar; turbulent flow is likely at Re >4000 (Henderson & Runcie 2017). Due to the retrospective nature of this study, exact values for the Reynold's number are unknown, although it is assumed that tracheal gas flow is likely turbulent (Dekker 1961). Sites of constriction further increase the likelihood of turbulent flow (Ahmed & Giddens 1983). Calculations were performed for each case of constriction assuming both laminar and turbulent flow to cover both possible scenarios.

Using experimentally derived data from El-Khatib et al. (2008), ETT 7.5 – 8.0 mm internal diameter (ID) showed a baseline resistance of ~15 cm H_2O at the proximal end, and a clinically significant increase in resistance was designated as > 5 cmH_2O. With these figures, an increase in resistance of approximately 33% (i.e., from 15 to 20 cmH_2O) would be considered 'clinically significant'. Using this definition, 24% of cases in this study exhibiting constriction assuming laminar flow and 32% of cases exhibiting constriction assuming turbulent flow would qualify as having a 'clinically significant' increase in resistance. Many cases had expected resistance increases of much more than 33% (the highest being a 1200% increase for one individual), despite modest median increases in resistance for the population. It is important to state that the calculations for resistance are theoretical and unlikely to reflect the true reality, as the radius measurement derived from the measured CSA assumes a circle, which was not the case for constricted ETT as constriction was not perfectly concentric. Additionally, the range of ETT sizes in this study was much wider than those tested by El-Khatib et al. (2008), therefore the parameters for clinical significance may differ considerably. Clinically, even modest increases in resistance could exert deleterious clinical effects, and any degree of constriction of an ETT is undesirable (Redding et al. 1979). If very severe, complete obstruction of the ETT may occur, leading to hypoxaemia, pulmonary oedema (Dicpinigaitis & Mehta 1995; Bhaskar & Fraser 2011) and possible fatality.

Measured ETT size was negatively associated with severity of constriction: ETT with smaller ID are more vulnerable to higher degrees of constriction (ETT ID was calculated from the measured non-constricted CSA). Table 5-4 shows the median decreases in CSA according to ETT size category: ETT <4.0 mm ID showed the highest median reduction in CSA, and this decreased as ETT ID increased. Smaller diameter ETT are already associated with increased work of breathing (WOB) (Bolder et al. 1986). Reducing the tube radius further in small sized ETT is therefore likely to have a considerable impact on WOB and produce a clinically detrimental effect.

Maximising the diameter of ETT placed in every patient would reduce the risk of constriction as well as the WOB exerted by the ETT itself, but this must be balanced against the risk of tracheal mucosal damage. The larynx was the site of constriction in 27 cases, suggesting insertion of an ETT that was too large in these individuals. Prediction of ETT size has received considerable attention in the veterinary literature, with several methods of estimation proposed including using body mass (Haider et al. 2020), nasal septal width, tracheal palpation (Lish et al. 2008) and cervical radiography (Shin et al. 2018) to inform choice. None of the methods tested produced perfect results and differences in suitability were evident between breeds, particularly for brachycephalic dogs. Using an ETT that fits through the larynx and advances into the trachea comfortably remains the most sensible approach to tracheal intubation.

In 6/816 cases, there was a change in shape of the endotracheal tube lumen, which gave an initial impression of constriction. However, subsequent measurements of normal and misshapen sections of these ETT had the same CSA. In 5/6 cases this occurred within the oral cavity and represents a distortion of the ETT lumen without any associated effect on lumen CSA. Distortion of the ETT is therefore possible without accompanying constriction of the lumen. However, this remains an uncommon finding.

A variety of causes for a reduction in ETT CSA were identified. The largest median CSA reduction (and hence largest expected increase in resistance) was caused by the presence of material within the ETT lumen, but this was also the least frequent cause. The retrospective nature of this study meant the material identified on CT was unknown, but it is likely to have been respiratory secretions or possibly saliva aspirated during induction. Identifying patients at risk of this, auscultation to identify airway fluid and suction of the ETT if appropriate are recommended to reduce the adverse effects of this complication.

The most common cause of ETT constriction was the presence of a radiotherapy mouth gag within the oral cavity. This finding represents a specific sub-population of animals in this study, undergoing CT planning for radiotherapy treatment of intra-cranial, intra-nasal or oral tumours. Solid plastic inserts (‘gags’) are placed in the mouth to separate out the soft tissues in the oral cavity and create a uniform tissue field for the radiotherapy beam to penetrate through (Withrow et al. 2013). Additionally, custom-moulded plastic head ‘masks’ are applied, ensuring uniform positioning for each radiotherapy session - see supplementary material 2. The combined presence of both structures poses a significant risk of compression of the ETT. These tools are required for successful and safe radiotherapy, but the ETT should be checked for constriction. Use of metallically reinforced (‘armoured’) ETT could be considered, but distortion of the metal structures can lead to permanent constriction (Aguilar et al. 2017) which could in itself pose an additional risk. Armoured ETT may also cause artefact in CT images, making them unsuitable for the planning stage.

Compression of ETT by the securing tie is avoidable, and personnel applying the tie should be mindful of its potential to constrict the tube. In 39 cases exhibiting constriction within the oral cavity, the cause was not evident from evaluation of the CT images and the cases were categorised as ‘oral’ (unidentified). In these cases, there was no contact from teeth and no gag was present. The most plausible cause is therefore the ETT tie, but this could not be confirmed due to lack of visual evidence: the prevalence of ETT tie constriction is therefore possibly higher than reported. Performing a visual check of the ETT once the tie is in place is recommended.

At the hospital where the study was conducted, ETT are typically secured with stretch bandage material that is knotted onto the ETT or connector and then secured around the muzzle or behind the ears of the animal. There is no standard operating procedure for ETT size (ID) or length selection and approaches to choice of ETT and orotracheal intubation differ between personnel. Management of ETT and tracheal intubation practices may differ amongst other institutions, which could result in different complication rates with ETT and reduce the applicability of the findings of this study to wider populations.

An important limitation of this study is that the entire length of the ETT could not be assessed in all animals due to a lack of CT images of all anatomical areas. As a result, findings for rostral and caudal mispositioning and constriction may not reflect the true prevalence in this population. Additionally, it was not possible to assess the impact of the rostral ETT connector on CSA reduction because this was infrequently included in the available images. Connectors insert into the ETT lumen, thereby reducing the CSA at this location. It is possible that the connector itself presented a greater impact on resistance than some of the more modest reductions in CSA found in this study, rendering them clinically insignificant when compared to an un-constricted ETT.

The material composition of ETT may influence their vulnerability to constriction. At the hospital where the study was conducted, silicone, polyvinyl chloride and (infrequently) red rubber tubes are utilised. Information regarding ETT material was not available for individual cases, and it was not possible to identify through CT imaging, although no armoured ETT were found.

The identification of constriction was made before measurements were taken, but the detection of very small CSA reductions suggests an adequate visual sensitivity for subtle cases. There were missing patient data for many cases in this study (such as body weight, procedure and presenting complaint), preventing meaningful assessment of these variables. Although no complications recorded were directly attributed to the ETT, clinical abnormalities noted on the anaesthesia records such as hypercapnia and hypoxaemia were not assessed, preventing the opportunity to link observed constriction and mispositioning of ETT with potential clinical effects.

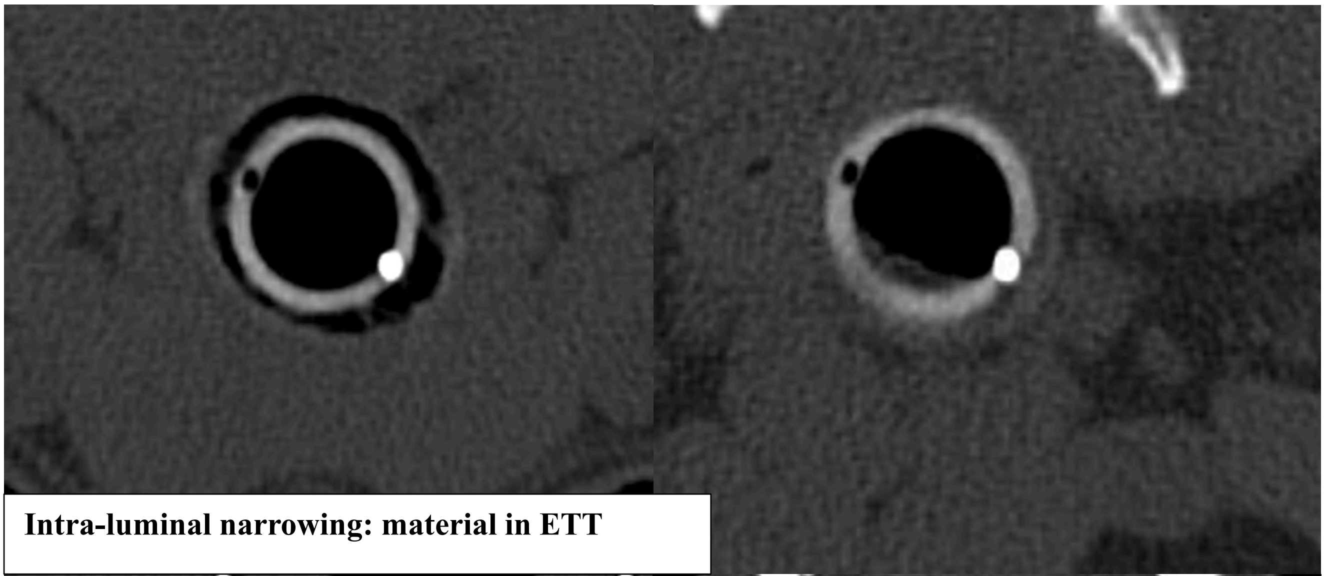
The images evaluated in this study only represent a single point in time that is not necessarily reflective of the entire anaesthetic period, so results are unlikely to reflect the true prevalence of complications in the population studied. Although the prevalence of tube tie compression is unlikely to have changed after CT imaging, intraluminal narrowing could occur later in anaesthesia with accumulation of respiratory secretions, and dental compression could occur or resolve following patient repositioning. Gradual warming of ETT from body temperature could lead to softening of the tube material (Busaidy et al. 2011), which may predispose to deformity from compressive forces. Tube constriction associated with gag placement will have resolved on removal.

5.8 Conclusions

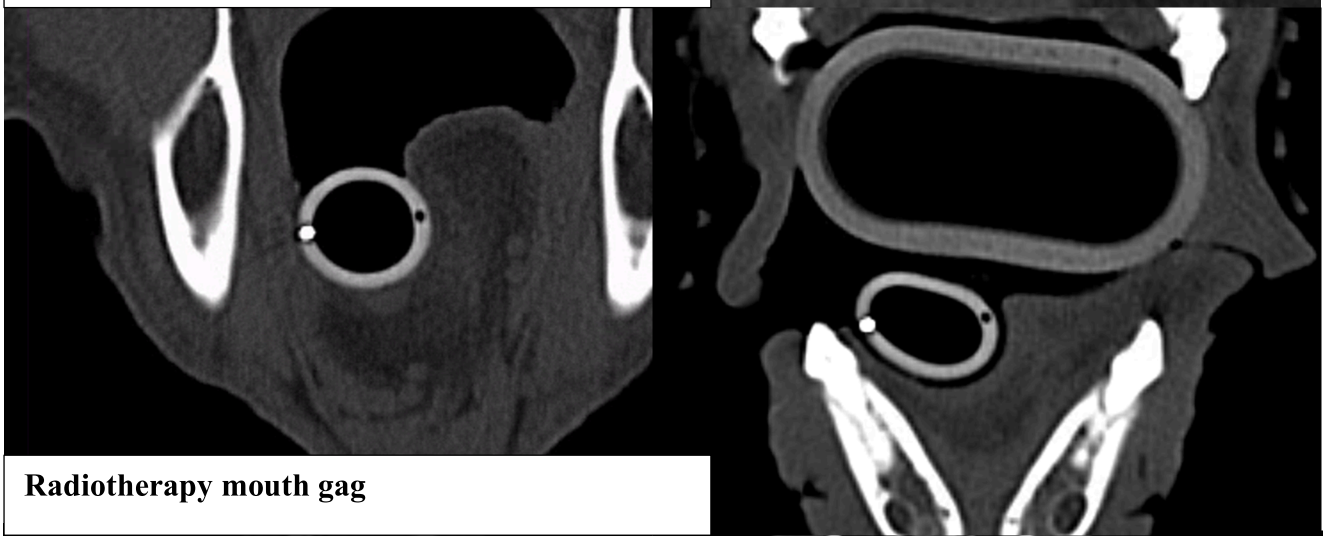
Constriction and mispositioning of endotracheal tubes occurred very commonly in this population. The use of radiotherapy mouth gags carries a significant risk of ETT compression. Smaller ETT carry a greater risk of severe constriction. Brachycephalic dogs are at particular risk of caudal mispositioning of ETT.

Figure 5-3 (see next page)

Example images of different causes of constriction of endotracheal tubes (ETT) found in 185/816 cats and dogs undergoing CT imaging of the head/neck/thorax with from 2017-2019 inclusive at one University referral hospital. In 631 cases there was no constriction of the ETT lumen. Left: normal un-constricted ETT, right: constricted ETT

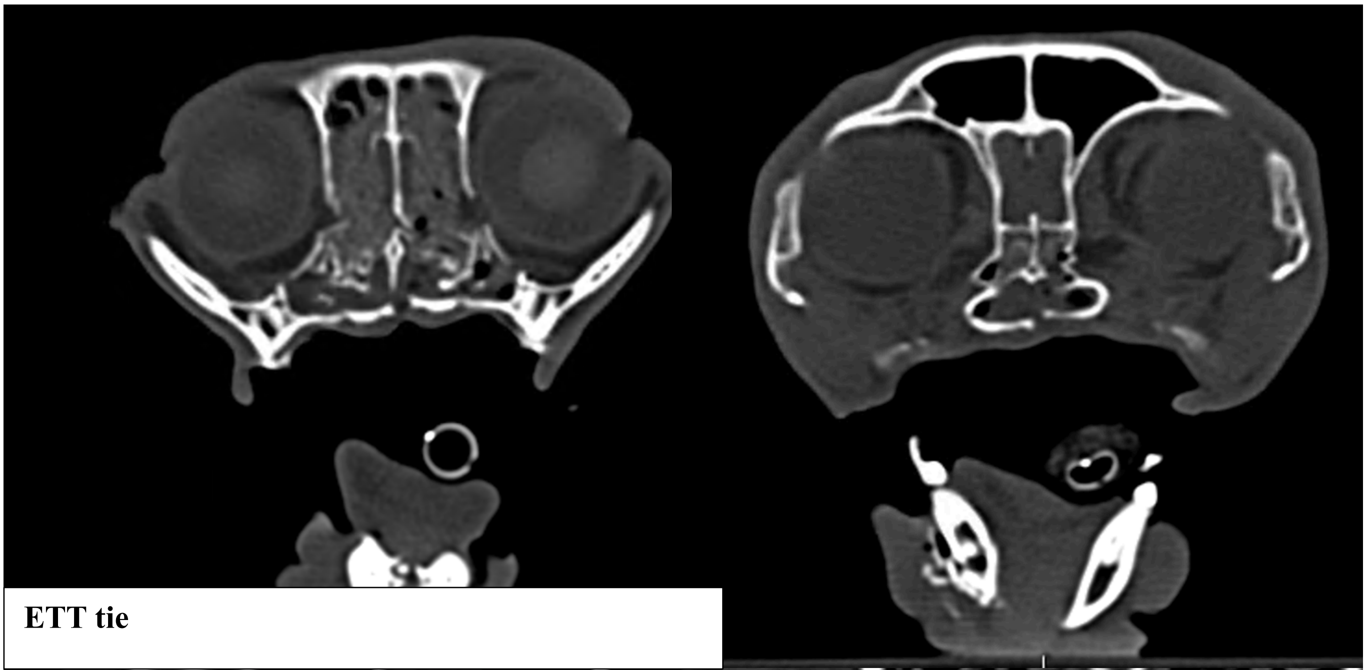


Intra-luminal narrowing: material in ETT

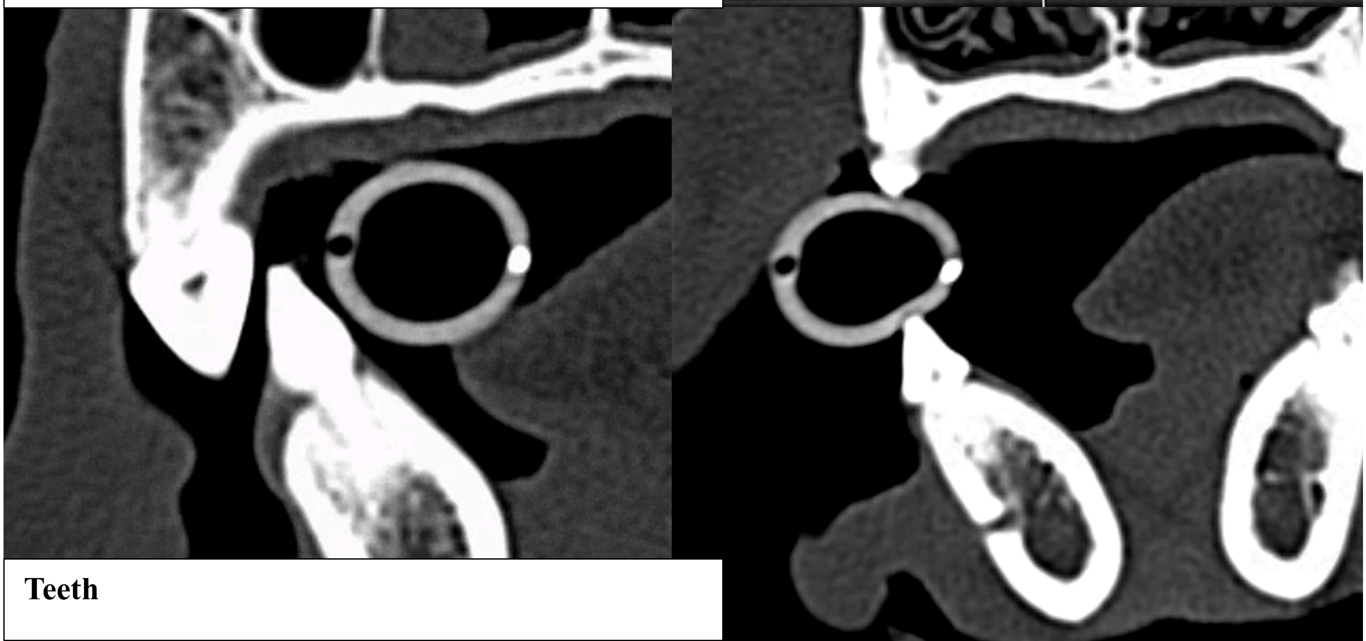


Radiotherapy mouth gag

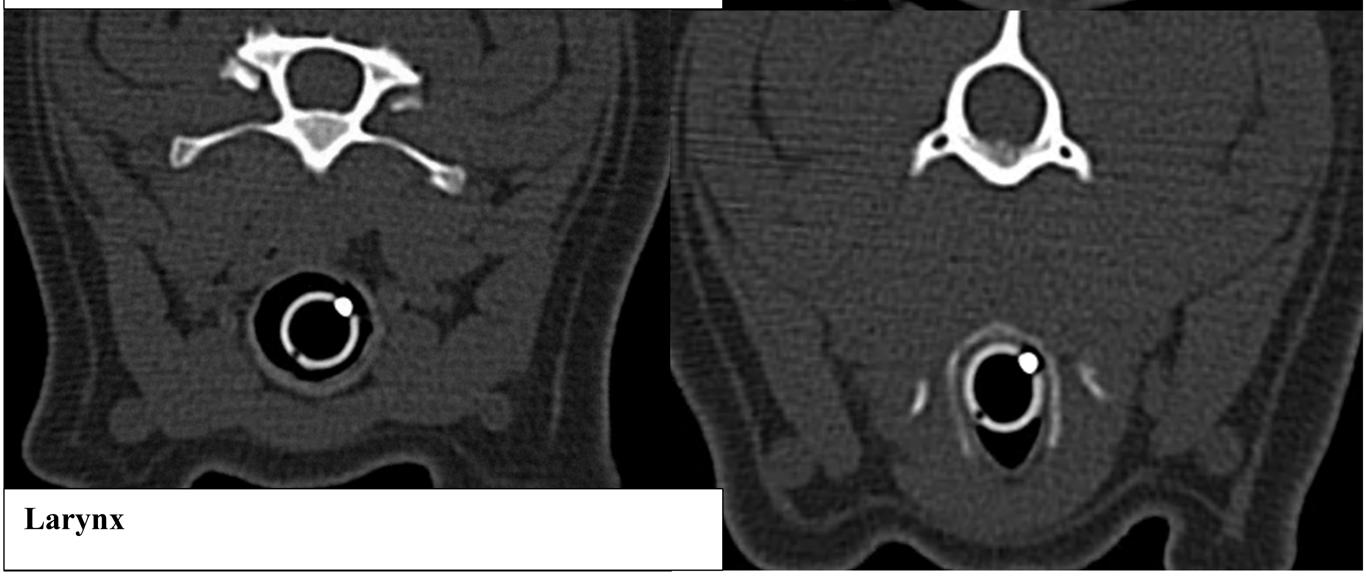
Oral (exact cause unidentified)



ETT tie



Teeth



Larynx

5.9 Supplementary Material

Supplementary Material 1

Data flowchart showing assessment of rostral & caudal mispositioning of endotracheal tubes (ETT) in 816 cats and dogs undergoing CT imaging of the head/neck/thorax from 2017-2019 inclusive at the University of Glasgow Small Animal hospital. Too rostral positioning = ETT extended beyond incisors; too caudal positioning = ETT extended beyond first rib.

ALL cases: **816**

Cases including HEAD image set: 380

↓

Cases including rostral head: 277

↓

Too rostral positioning: 145 (52%)

Optimal rostral positioning: 80 (29%)

Too short positioning: 52 (19%)

Cases including THORAX image set: 523

↓

Cases including caudal tip of ETT: 515

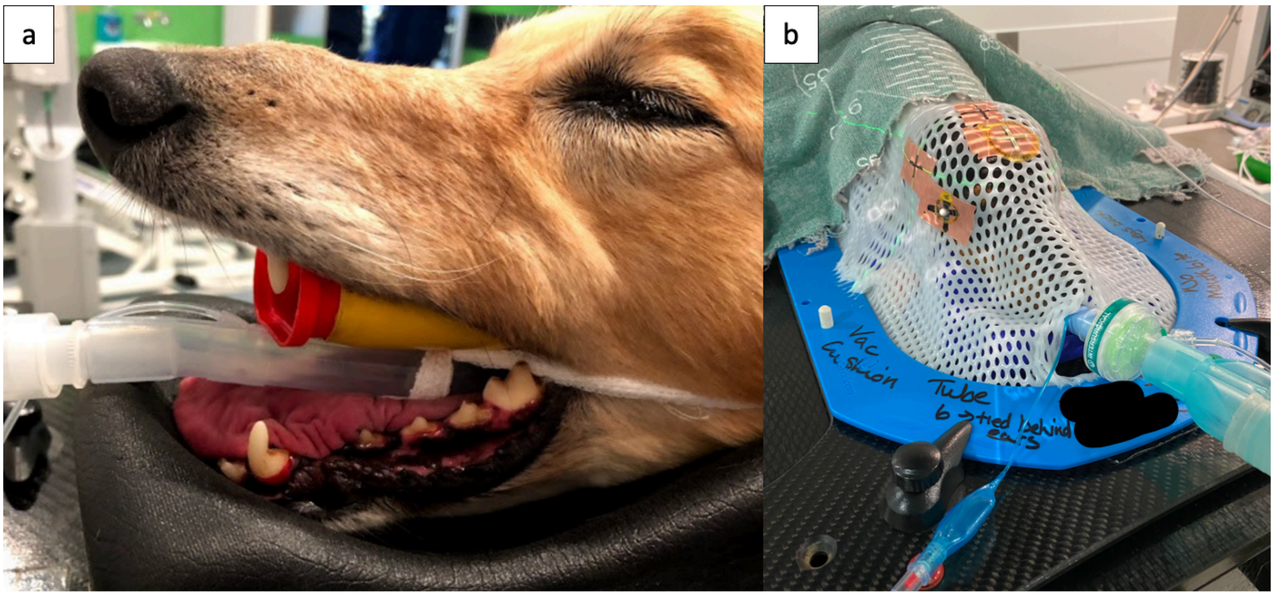
↓

Too caudal positioning: 131 (25.4%)

Optimal caudal positioning: 384 (74.6%)

Supplementary Material 2

Photographs of dogs undergoing radiotherapy treatment for oral/intra-cranial/intra-nasal tumours. A: plastic mouth gag overlying the endotracheal tube. B: custom-moulded plastic face mask applied to patient with endotracheal tube exiting through specially made hole. Photographs courtesy of Shona Burnside.



Chapter 6

Preface to experimental study

One of the complications revealed by the retrospective investigation into ETT problems was the issue of ETT lumen compression by the securing tie material. This occurred with surprising frequency in both cats and dogs: it was the responsible cause in 20% of the instances of ETT constriction found. Recognition of the securing tie as the presiding cause for constriction was made through visualisation of the knot overlying the body of the ETT, with a reduction in lumen CSA at the same location.

Another notable finding of the retrospective investigation was the vulnerability of smaller sizes of ETT to more severe constriction.

Application of a securing tie onto the ETT is common practice in veterinary anaesthesia. It is intended to ensure consistent positioning of the ETT within the oral cavity and trachea, and to prevent displacement of ETT during re-positioning or moving of the patient within the hospital, which occurs frequently over the course of a period of general anaesthesia in many patients.

Choices regarding ETT securing tie material at the institution where this study was conducted are made according to personal preference of the anaesthetist and immediate availability of materials. The most common options for the tie material are stretch fabric and non-stretch (woven) fabric bandage material. A third less common option is a non-stretch specially-manufactured plastic tie: this is typically chosen for patients requiring longer periods of general anaesthesia (for example, patients requiring long term mechanical ventilation) or for procedures where oral secretions or bleeding is expected, due to its non-absorbent properties. It may also be the preferred choice in smaller patients, where the narrow diameter of the material provides a benefit.

Choices regarding ETT material at the institution where this study was conducted are generally made according to personal preference of the anaesthetist and size selection according to the patient. Silicone and PVC ETT are the most common options available; silicone ETT are only typically available in larger sizes at the hospital so tend to be chosen more often for larger dogs (from 11.0 – 14.0 mm ID).

It was decided to investigate some of the notable findings from the retrospective study in an experimental manner, resulting in the following non-clinical research study. The experiment was designed to assess different ETT materials, ETT sizes and securing tie materials with regards to their propensity to cause constriction of the ETT lumen. It is hoped that the results will contribute to the evidence base informing guidelines for the securement of ETT in cats and dogs.

Chapter 7

Experimental study manuscript

7.1 Title

Investigation into factors affecting forces required to produce constriction of an endotracheal tube lumen by application of a securing tie.

7.2 Abstract

7.2.1 Objectives

This study investigated how endotracheal tube (ETT) material (polyvinyl chloride (PVC) and silicone), ETT size (4.0, 7.0 and 11.0 mm internal diameter) and securing tie material (stretch, woven and plastic) affected the force required to cause constriction of the ETT by application of a securing tie.

7.2.2 Study Design

Experimental non-clinical study

7.2.3 Animal Population

N/A

7.2.4 Methods

Stage 1: each combination of ETT material, size and tie material was tested. A length of securing tie was fixed at one end and a loop created at the other. An overhand knot was created around the ETT. A luggage scale was hooked into the loop of tie and pulled, causing visible constriction of the ETT lumen. The maximum force applied was recorded. Constriction was verified and reduction in the ETT lumen was measured by computed tomography.

Stage 2: The process was repeated, with the force applied decreasing by 9.81 N each time, or halved if the preceding force was ≤9.81 N, until no constriction was detected.

Stages 1 and 2 were repeated 3 times in total.

7.2.5 Results

The median minimum force required for constriction of silicone and PVC ETT was 9.8 and 28.4 N, respectively. The median minimum force required for constriction of the small, medium and large ETT was 6.9, 18.6 and 37.3 N, respectively. The median minimum force required for constriction by the stretch and woven materials was 14.7 and 22.6 N, respectively. The plastic securing tie loosened spontaneously in all combinations prior to CT.

7.2.6 Conclusions and clinical relevance

Silicone ETT required less force to produce constriction by application of a securing tie than PVC ETT. Smaller ETT constrict at lower forces than larger sizes. Stretch material requires a lower force during application to cause constriction of the ETT than woven. Plastic securing ties may loosen around the ETT body.

7.3 Introduction

The endotracheal tube (ETT) is a widely used piece of equipment in the anaesthesia of cats and dogs. The main functions of ETT are to maintain upper airway patency, protect the respiratory tract from aspiration of gastric contents, saliva and blood and provide a conduit for oxygen, anaesthetic vapours and gases (Hughes 2016). Multiple options exist for ETT material, size and method of securement. Decisions for each category are usually driven by personal preference or practice policy, as well as immediate availability.

Concerning the choice of ETT material, practicality may influence decision-making. Metallically reinforced (armoured) ETT are preferred for procedures where kinking of the ETT due to special positioning is possible, but the most common types of ETT used in clinical practice are made from silicone or polyvinyl chloride (PVC) (Mosley 2015). These ETT are predominantly manufactured for single use in humans, but are commonly re-used in cats and dogs. Reusable red rubber ETT are also available, but their opacity prevents thorough inspection of the lumen (Mosley 2015), which may lead to undetected obstructions and contamination.

For an ETT to successfully fulfil its many functions, it must remain securely in place throughout general anaesthesia. Accidental displacement of the ETT may occur during repositioning of the animal or movement between different locations in the peri-anaesthetic period if it is not secured effectively. Unintended tracheal extubation is a documented problem in humans (Lucchini et al. 2018). The incidence of this is currently unknown in veterinary species. In cats and dogs, securing the ETT is typically achieved via knotting a length of securing tie material around the body or connector of the ETT, and then placing a second knot around the animal’s maxilla or back of the head. It is recommended that the tie is tied tightly, without occluding the lumen of the ETT (Hughes 2016).

The choice of tie material for securing ETT in cats and dogs is typically dictated by personal preference of the anaesthetist or practice policy. Fabric bandage material is commonly used for this purpose in veterinary practice, likely due to its widespread availability. Both knitted stretch and non-stretch versions are used, in a variety of widths. Thin, non-stretch plastic material may be preferred for smaller animals due to its narrow width, or in procedures where significant oral secretions or oral/facial bleeding are expected due to its non-absorbent qualities. The ideal tie material sits securely on the body or connector of the ETT without becoming displaced, is easy to apply, does not cause injury to the animal and does not affect the integrity of the ETT itself.

Although the use of ETT in general anaesthesia confers many theoretical safety benefits, iatrogenic obstruction of the ETT lumen has been reported in humans (Davies & Templeton 2021) and animals (Gregson & Clutton 2012; Aguilar et al. 2017). Constriction of the ETT lumen by application of the securing tie is a known complication in anaesthetised cats and dogs. In a retrospective analysis of CT images from 816 cats and dogs under general anaesthesia, the ETT securing tie was the cause of constriction in 20% of cases showing a reduction in ETT lumen cross-sectional area (CSA) (Lloyd et al. in press) The securing tie was associated with a median ETT CSA reduction of 9.2%. Any reduction in CSA of the ETT lumen will result in increased resistance to gas flow, which may have detrimental clinical effects for the animal, including an increase in the work of breathing (Shapiro et al. 1986).

Computed tomography (CT) imaging provides an effective and accurate method to evaluate distortions of the ETT lumen (Pinciroli et al. 2013; Mietto et al. 2014).

It is not known if or how ETT material, ETT size or securing tie material affects the risk of lumen constriction. Gaining insight into how these factors influence ETT constriction may guide recommendations for clinical practice.

This study aimed to find which combination of ETT material, ETT size and tie material was most likely to produce constriction of the ETT lumen. This was achieved by measuring the minimum force required to produce constriction for each combination, as evaluated via CT imaging.

It was hypothesised that silicone ETT would require lower forces to produce constriction than PVC ETT, smaller ETT would require lower forces than larger ETT and there would be no difference in force required between the tie materials.

7.4 Materials and methods

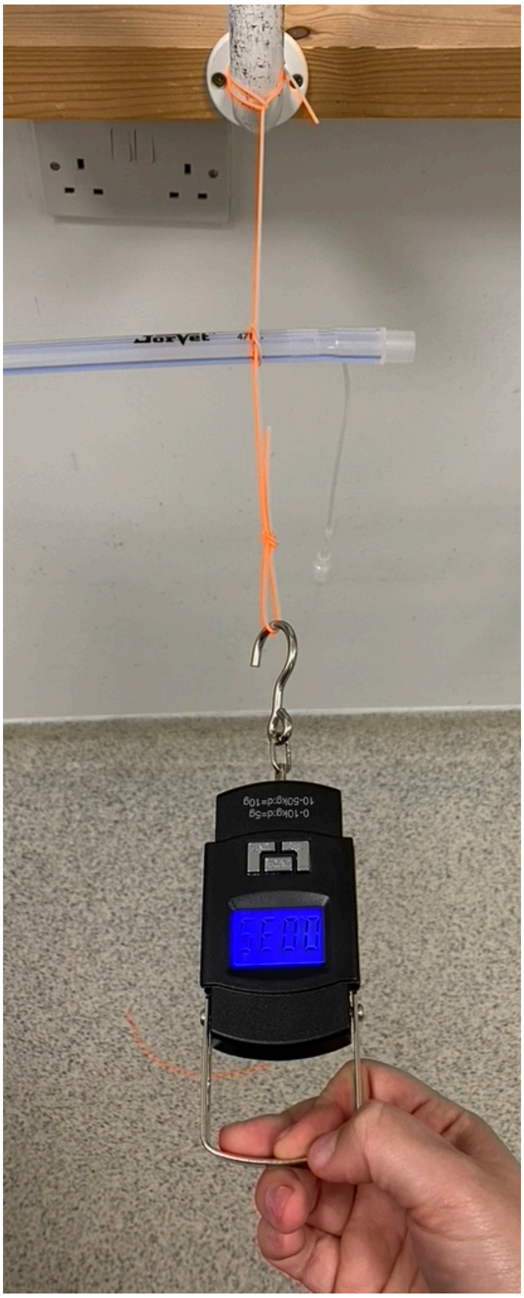
An experimental, non-clinical equipment study was performed testing silicone (Silicon Endotube, Jorvet, CO, USA) and PVC (Endotracheal tube PVC cuffed, J.A.K Marketing Ltd, UK) ETT in three different sizes of internal diameter (4.0, 7.0 and 11.0 mm). A new, unused ETT was used for each of the different tie materials at the beginning of the study. Three different tie materials were tested: plastic non-stretch specialised ETT ties (‘plastic’, Anesthesia Tube Ties, iM3 Dental Ltd, Ireland), 2.5 cm wide white open weave bandage (‘woven’, Reliwow Wow Bandage BP, Reliance Medical Ltd, UK), and 5 cm wide knitted stretch conforming bandage (‘stretch’, Knitfirm, Millpledge, UK). A new piece of tie material was used for each test.

The precision of a commercial hanging luggage scale (Portable Luggage Scale, Hyindoor, China) was evaluated by weighing two objects of known weights (object 1 = 0.43 kg, object 2 = 0.16 kg) six times each.

The study was conducted in two stages. In stage 1, two figure-of-eight knots with loops were tied at each end of a 30 cm length of tie material. At one end, the loop was passed around a metal pipe fixed to a wall, with the trailing end threaded through the loop, anchoring the material. An overhand knot was loosely applied around the ETT body in the middle of the 30 cm length of tie material, 4 cm distal to the end of the ETT connector. All ETT were the full length, as produced by the manufacturer, with plastic connectors inserted fully into the lumen. The luggage scale was hooked into the free looped end of the tie material (see Figure 7-1). Operator 1 pulled on the luggage scale perpendicular to the body of the ETT to tighten the overhand knot around it. The knot was tightened until visible constriction of the ETT body was apparent, as assessed by operator 1. Concurrently, operator 2 steadied the ETT at the distal end and recorded a video of the luggage scale reading during the test. The maximum force applied to the tie was recorded from the video of the scale read-out: this was defined as the ‘starting force’.

Figure 7-1

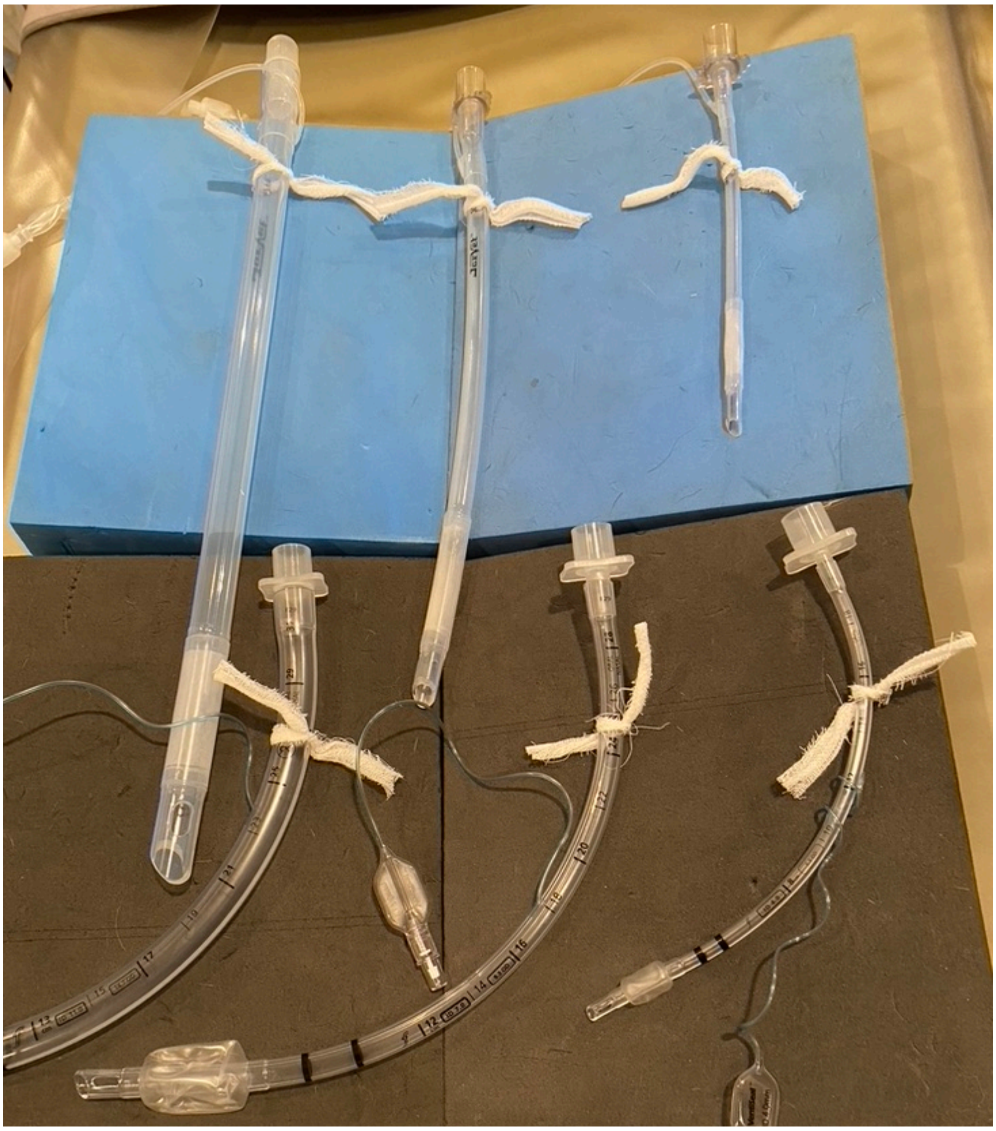
Image depicting set up for an experimental non-clinical equipment study assessing force required to cause constriction of the ETT lumen through application of a securing tie. ETT materials tested: silicone and polyvinyl chloride (PVC). ETT sizes tested: 4.0, 7.0 and 11.0 mm internal diameter (ID). Tie materials tested: non-stretch woven fabric (woven), specialised plastic tie (plastic) and stretch knitted fabric (stretch). Tie material secured to wall-mounted pipe via looped knot at one end, with portable luggage scale hooked into loop at other end. Overhand knot applied over ETT body with 30 cm length of tie, 4 cm distal to rigid plastic connector.



Once the knot was applied, the long ends of the tie material were cut to free the ETT from the metal pipe. The ETT with knotted tie material then underwent CT imaging by a radiographer using a multislice scanner (Lightning Aquilion, Canon Medical Systems Ltd, UK) (see Figure 7-2), after which the tie material was removed and the body of the ETT was inspected. The ETT was reused in the study provided there was no visible indentation of its body wall following removal of the tie. Three individual ETT of each material and size were available for use in the study.

Figure 7-2

Image depicting set up prior to computed tomography (CT) imaging for an experimental non-clinical equipment study assessing force required to cause constriction of the ETT lumen through application of a securing tie. ETT materials tested: silicone and polyvinyl chloride (PVC). ETT sizes tested: 4.0, 7.0 and 11.0 mm internal diameter (ID). Tie materials tested: non-stretch woven fabric (woven), specialised plastic tie (plastic) and stretch knitted fabric (stretch). ETT with knotted tie material subsequently underwent CT imaging for measurement of lumen constriction.



For the woven material, a double layered strip was used, as breakage of a single strip of material occurred before constriction of the ETT could be caused in many of the combinations. The force at which a 30 cm single layer of woven material broke apart was tested by securing it as for stage 1 (without the ETT). The luggage scale was hooked into the free loop and traction applied until breakage occurred. The maximum force applied was recorded. This process was repeated 6 times.

During stage 2 of the study, the equipment set-up was as described for stage 1. The force applied to each combination was pre-determined, initially being 1 kg (9.81 N) less than the ‘starting force’ ascertained for that combination during stage 1. The ETT underwent CT imaging to detect and measure constriction of the lumen. The process was repeated for each combination, with the force applied decreasing by 1 kg each time, or halved if the preceding force was ≤1 kg, until no constriction of the ETT lumen was detected on review of the CT images.

Stages 1 and 2 were repeated three times in total for each combination of ETT material, ETT size and tie material.

Computed tomography images were reviewed as Digital and Communication in Medicine (DICOM) files, reconstructed with lung windows for analysis by medical imaging software (Clear Canvas, Synaptive Medical, Canada). A single trained observer assessed all images and performed all measurements in a transverse plane. The CSA of the ETT lumen at the constricted location was measured and compared to an un-constricted location as assessed visually. Degree of constriction was calculated as a percentage reduction in CSA between the two measurements. The wall thickness of each ETT was measured and recorded.

For each combination, the minimum force producing constriction was defined as the half-way point between the lowest force applied causing no constriction, and the preceding (i.e. second lowest) force that caused constriction, as assessed by CT. Degree of CSA reduction reported corresponds to the second lowest force applied.

Weight as measured by the luggage scale in kilograms (kg) was converted to Newtons (N) for all major results (1 kg = 9.81 N).

7.5 Statistics

Continuous variables were assessed for normal distribution using the Shapiro-Wilk test. Clustered bar charts illustrate relationships between minimum force required to produce constriction with ETT material and tie material (except for plastic), and between minimum force and ETT size and

ETT material. Minimum force is reported both for each combination of independent variables and according to each of the independent variables alone.

7.6 Results

Starting force (results of stage 1), breaking force for woven material, ETT wall thickness and measured weight of objects (results of luggage scale precision test) exhibited normal distribution and are reported as mean (± standard deviation, S.D.). Minimum force and associated ETT CSA reduction (results of stage 2) did not exhibit normal distribution and are reported as median (range).

The force causing breakage of a single layer of the woven material was 2.6 kg ± 0.3 kg (25.5 N, ± 2.9 N).

The luggage scale demonstrated acceptable precision. The measured weight of object 1 was 0.44 kg (± 0.01 kg). The measured weight of object 2 was 0.17 kg (± 0.01 kg).

See Table 7-1 for results of stage 1 testing. Constriction was verified for all combinations by CT imaging except for those involving the plastic tie. It was possible to cause a visible constriction in all combinations of ETT material, ETT size and tie material tested. For all ETT, the knots over the ETT body created by the plastic tie material spontaneously loosened once tension was released, (see Figure 7-3), resulting in no visible constriction on subsequent CT imaging. Stage 2 testing was consequently not carried out for the plastic material and constriction could not be verified by CT for stage 1.

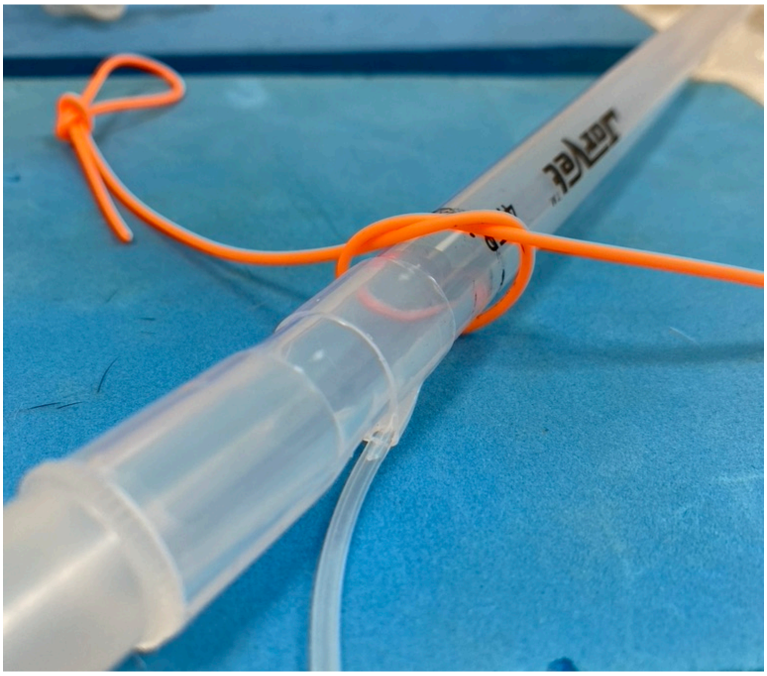
Table 7-1

Mean minimum force (N) required to produce a visually appreciable constriction of the endotracheal tube (ETT) lumen according to ETT size, ETT material and tie material in an experimental non-clinical equipment study assessing force required to cause constriction of the ETT lumen through application of a securing tie. ETT materials tested: silicone and polyvinyl chloride (PVC). ETT sizes tested: 4.0, 7.0 and 11.0 mm internal diameter (ID). Tie materials tested: non-stretch woven fabric (woven), specialised plastic tie (plastic) and stretch knitted fabric (stretch). Constriction was verified using computed tomography imaging except for combinations involving the plastic tie.

Results for Stage 1: Starting force causing visible constriction			
ETT Material	**ETT Size (internal diameter, mm)**	**Tie Material**	**Mean** (± S.D) **Starting Force (kg)**
Silicone	4.0	Woven	**2.0** (± 0.4)
Silicone	7.0	Woven	**3.4 (**± 0.2)
Silicone	11.0	Woven	**4.0** (± 0.4)
Silicone	4.0	Stretch	**1.9** (± 0.4)
Silicone	7.0	Stretch	**2.9** (± 1.1)
Silicone	11.0	Stretch	**3.9** (± 0.7)
Silicone	4.0	Plastic	**2.4** (± 0.3)
Silicone	7.0	Plastic	**3.3** (± 0.1)
Silicone	11.0	Plastic	**3.8** (± 0.1)
PVC	4.0	Woven	**3.0** (± 0.1)
PVC	7.0	Woven	**4.3** (± 0.2)
PVC	11.0	Woven	**5.7** (± 0.1)
PVC	4.0	Stretch	**3.2** (± 0.9)
PVC	7.0	Stretch	**4.3** (± 0.2)
PVC	11.0	Stretch	**6.5** (± 0.3)
PVC	4.0	Plastic	**4.1** (±0.4)
PVC	7.0	Plastic	**4.6** (± 0.3)
PVC	11.0	Plastic	**6.2** (± 0.3)

Figure 7-3

Image depicting spontaneous loosening of overhand knot made with specialised plastic securing tie over endotracheal tube body. This was part of an experimental non-clinical equipment study assessing force required to cause constriction of the ETT lumen through application of a securing tie.



Minimum forces (results of Stage 2) required to cause a detectable constriction on CT for all ETT sizes, materials and woven and stretch tie materials with associated CSA reduction are presented in Table 7-2.

Table 7-2

Minimum force required to produce constriction of the endotracheal tube (ETT) lumen in an experimental non-clinical equipment study assessing force required to cause constriction of the ETT lumen through application of a securing tie. ETT materials tested: silicone and polyvinyl chloride (PVC). ETT sizes tested: 4.0, 7.0 and 11.0 mm internal diameter (ID). Tie materials tested: non-stretch woven fabric (woven) and stretch knitted fabric (stretch). Reduction in cross-sectional area (CSA) of ETT lumen was measured via computed tomography (CT).

ETT Material	**ETT Size (internal diameter, mm)**	**Tie Material**	**Median** (range) **Minimum Force (kg)**	**Median** (range) **Minimum Force (N)**	**Median** (range) **% CSA reduction of ETT lumen**
Silicone	4.0	Woven	**0.4** (0.4-0.5)	**3.9** (3.9-4.9)	**12.9** (6.2-18.2)
Silicone	7.0	Woven	**1.6** (1.1-2.0)	**15.7** (10.8-19.6)	**11.8** (9.6-13.2)
Silicone	11.0	Woven	**3.1** (2.2-3.3)	**30.4** (21.6-32.4)	**3.0** (2.4-6.8)
Silicone	4.0	Stretch	**0.2** (0.2-0.4)	**2.0** (2.0-3.9)	**12.2** (7.1-31.3)
Silicone	7.0	Stretch	**0.8** (0.8-0.9)	**7.8** (7.8-8.8)	**2.7** (2.4-8.1)
Silicone	11.0	Stretch	**2.4** (2.1-2.8)	**23.5** (20.6-27.5)	**3.0** (1.0-7.1)
PVC	4.0	Woven	**1.6** (1.5-2.3)	**15.7** (14.7-22.6)	**15.7** (9.2-26.2)
PVC	7.0	Woven	**3.0** (2.8-3.6)	**29.4** (27.5-35.3)	**9.7** (6.7-9.9)
PVC	11.0	Woven	**5.1** (4.2-5.4)	**50.0** (41.2-53.0)	**3.3** (3.1-3.8)
PVC	4.0	Stretch	**0.9** (0.8-1.3)	**8.8** (7.8-12.7)	**8.6** (2.4-9.5)
PVC	7.0	Stretch	**2.5** (1.7-3.1)	**24.5** (16.7-30.4)	**1.2** (1.1-9.4)
PVC	11.0	Stretch	**4.9** (4.7-5.4)	**48.0** (46.1-53.0)	**6.6** (4.2-14.2)

See table 7-3 for results of stage 2 from each individual repetition.

Table 7-3

Median minimum force (kg) required to produce constriction of the endotracheal tube (ETT) lumen according to ETT size, ETT material and tie material in 3 repetitions of an experimental non-clinical equipment study assessing force required to cause constriction of the ETT lumen through application of a securing tie. ETT materials tested: silicone and polyvinyl chloride (PVC). ETT sizes tested: 4.0, 7.0 and 11.0 mm internal diameter (ID). Tie materials tested: non-stretch woven fabric (woven) and stretch knitted fabric (stretch).

ETT Material	**ETT Size (internal diameter, mm)**	**Tie Material**	**Minimum Force (kg)**			**% CSA Reduction of ETT lumen**		
			Repeat 1	**Repeat 2**	**Repeat 3**	**Repeat 1**	**Repeat 2**	**Repeat 3**
Silicone	4.0	Woven	0.4	0.4	0.5	12.9	6.2	18.2
Silicone	7.0	Woven	1.6	1.1	2	13.2	9.6	11.8
Silicone	11.0	Woven	3.1	2.2	3.3	6.8	3.0	2.4
Silicone	4.0	Stretch	0.38	0.2	0.2	12.2	7.1	31.3
Silicone	7.0	Stretch	0.9	0.8	0.75	2.4	2.7	8.1
Silicone	11.0	Stretch	2.4	2.1	2.8	1.0	3.0	7.1
PVC	4.0	Woven	2.3	1.5	1.6	26.2	9.2	15.7
PVC	7.0	Woven	2.8	3.6	3	9.7	6.7	9.9
PVC	11.0	Woven	5.1	4.2	5.4	3.8	3.1	3.3
PVC	4.0	Stretch	0.9	0.8	1.3	8.6	9.5	2.4
PVC	7.0	Stretch	3.1	1.7	2.5	1.1	1.2	9.4
PVC	11.0	Stretch	5.4	4.7	4.9	14.2	6.6	4.2

See table 7-4 for median minimum forces required to produce constriction of the ETT lumen according to ETT size, ETT material and tie material, ignoring the impact of the other independent variables.

Table 7-4

Median minimum force required to produce constriction of the endotracheal tube (ETT) lumen according to ETT size, ETT material and tie material in an experimental non-clinical equipment study. ETT materials tested: silicone and polyvinyl chloride (PVC). ETT sizes tested: 4.0, 7.0 and 11.0 mm internal diameter (ID). Tie materials tested: non-stretch woven fabric (woven) and stretch knitted fabric (stretch).

Stage 2 results according to category: minimum force required to cause constriction of ETT lumen			
		Median (range) minimum force (kg)	**Median (range) minimum force (N)**
ETT Size (internal diameter, mm)	**4.0**	0.7 (0.2-2.3)	6.9 (2.0-22.6)
	7.0	1.9 (0.8-3.6)	18.6 (7.8-35.3)
	11.0	3.8 (2.1-5.4)	37.3 (20.6-53.0)
ETT Material	**Silicone**	1.0 (0.2-3.3)	9.8 (2.0-32.4)
	PVC	2.9 (0.8-5.4)	28.4 (7.8-53.0)
Tie Material	**Woven**	2.3 (0.4-5.4)	22.6 (3.9-53.0)
	Stretch	1.5 (0.2-5.4)	14.7 (2.0-53.0)

Wall thickness of each ETT as measured by CT according to material and size is presented in table 7-5.

Table 7-5

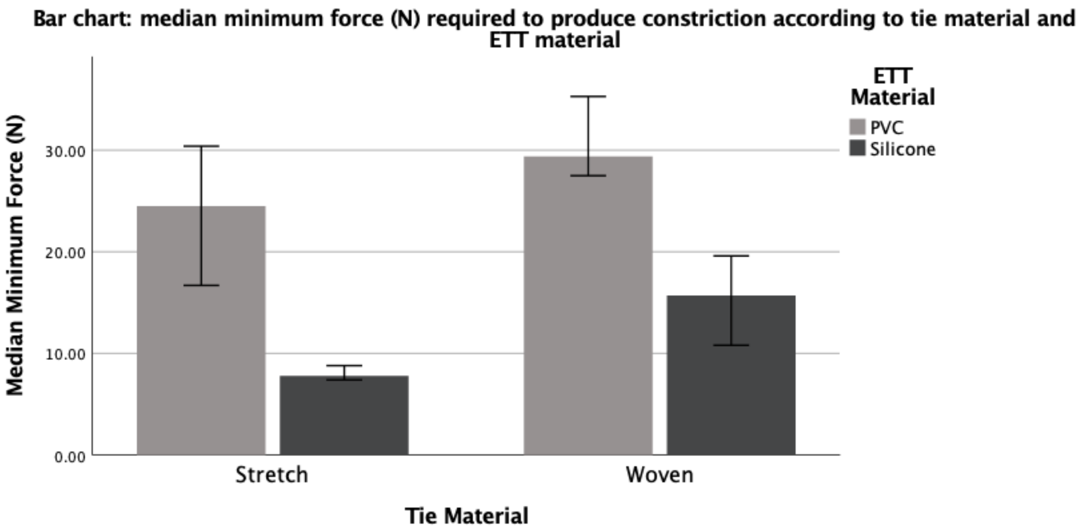
Wall thickness (mm) of endotracheal tubes (ETT) participating in an experimental non-clinical equipment study assessing force required to cause constriction of the ETT lumen through application of a securing tie. ETT materials tested: silicone and polyvinyl chloride (PVC). ETT sizes tested: 4.0, 7.0 and 11.0 mm internal diameter (ID). Wall thickness measured via computed tomography (CT) imaging.

Mean (± S.D) of measured ETT wall thickness (mm)			
		PVC	**Silicone**
ETT Size (internal diameter, mm)	**4.0**	**1.4** (± 0.1)	**1.5** (± 0.2)
	7.0	**1.6** (± 0.2)	**1.7** (± 0.1)
	11.0	**1.7** (± 0.0)	**2.8** (± 0.1)

Median minimum force required to produce a constriction across all ETT sizes according to ETT and tie material is presented in Figure 7-4.

Figure 7-4

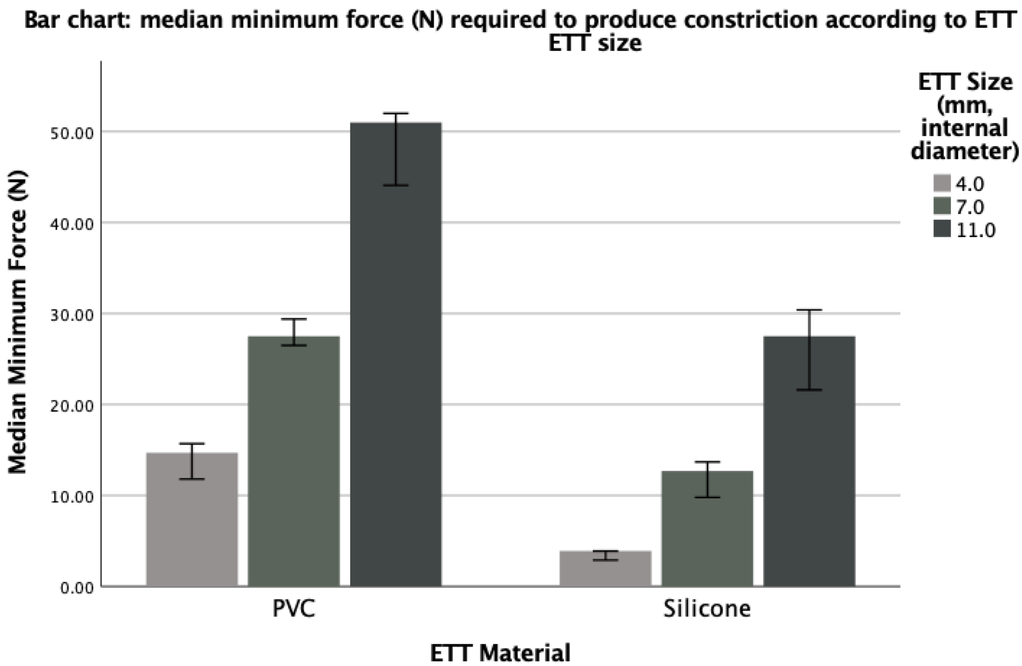
Clustered bar chart showing median minimum force required (N) to produce a constriction in endotracheal tubes (ETT) according to securing tie material and ETT material in an experimental non-clinical equipment study assessing force required to cause constriction of the ETT lumen through application of a securing tie. ETT materials tested: silicone and polyvinyl chloride (PVC). ETT sizes tested: 4.0, 7.0 and 11.0 mm internal diameter (ID). Constriction was assessed via computed tomography imaging. Error bars represent 95% confidence interval.



Median minimum force required to produce a constriction across all tie materials according to ETT material and size is presented in Figure 7-5.

Figure 7-5

Bar chart showing median minimum force required (N) to produce a constriction in endotracheal tubes (ETT) according to ETT material and ETT size in an experimental non-clinical equipment study assessing force required to cause constriction of the ETT lumen through application of a securing tie. ETT materials tested: silicone and polyvinyl chloride (PVC). ETT sizes tested: 4.0, 7.0 and 11.0 mm internal diameter (ID). Constriction was assessed via computed tomography imaging. Error bars represent 95% confidence interval.



7.7 Discussion

This study evaluated ETT material, ETT size and securing tie material in relation to the minimum force required to cause constriction of the ETT lumen through application of a securing tie. Whilst decisions regarding the three variables tested may often be taken automatically in clinical practice, the results of this study show that these choices deserve consideration on an individual basis. In all combinations tested, it was possible to cause a visible constriction of the ETT lumen.

Visual appraisal is a less sensitive method for the detection of ETT lumen constriction than CT evaluation, as evidenced by the results of Stages 1 and 2 in this study. The 'starting forces' for every combination produced constriction verified by CT. However, despite application of increasing force until constriction was visible in Stage 1, lower forces applied in Stage 2 continued to produce constriction detectable on CT. A visual check of the ETT should always be performed. In addition, when available, CT imaging is a valuable opportunity for further evaluation.

The associated CSA reductions in ETT from application of the minimum constrictive force showed a high degree of variability, both between different ETT sizes and repetitions. This may be a result of an inconsistent rate of increase of force application: the luggage scale reading changed rapidly, making it challenging to reliably apply the pre-determined forces in stage 2. Consequently, the median CSA reduction reported for each combination may not accurately reflect what would be expected in a real-life clinical scenario. However, it does indicate that some degree of constriction is to be expected following application of the minimum force. The clinical effect of any reduction in ETT lumen CSA is dependent on several individual patient factors and was not possible to calculate in this study. The variability in the range of reported CSA reductions for each combination may also reflect a true variability between the propensity for constriction between individual ETT of the same material and size.

The three different sizes of ETT in this study were chosen to provide an appropriate spectrum reflective of clinical practice. The available size range of ETT typically spans 2.5 mm ID to 14.0 mm ID. Whilst it was not possible to test every available size, the representatives of ‘small’, ‘medium’ and ‘large’ sizes in this study effectively show the relationship between internal diameter and propensity for constriction.

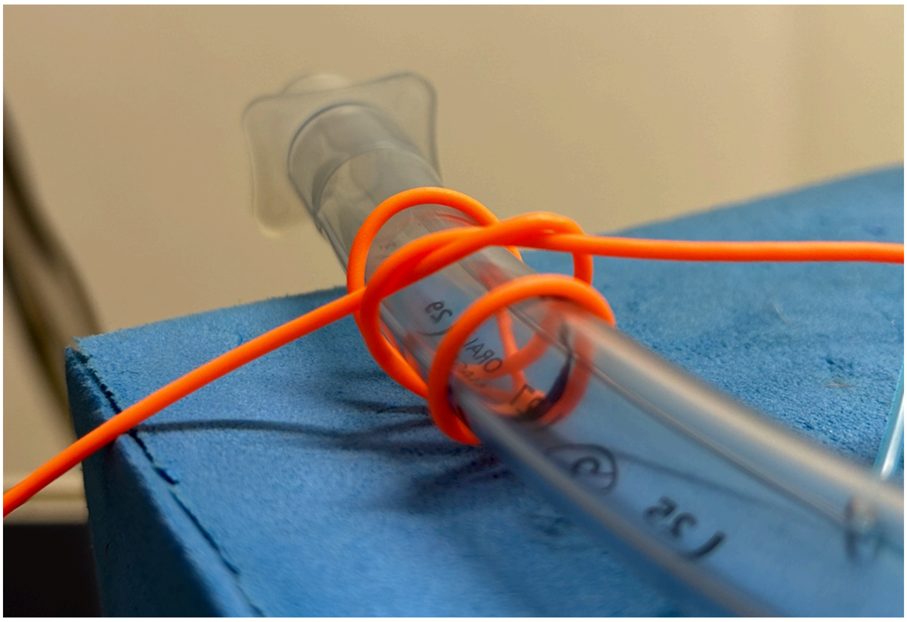
Smaller ETT had thinner walls than the larger ETT, which is likely responsible for their increased vulnerability to constriction. An inversely proportional relationship between internal diameter of ETT and severity of constriction has been demonstrated (Lloyd et al. in press). Smaller sized ETT are therefore not only at higher risk of constriction of the lumen, but the constriction itself is more likely to be of higher severity. Many animals such as cats and small dogs require ETT of 4.0 mm ID or smaller. An awareness of the increased risk of constriction in these ETT is important, and may lead to improvements in safety if heightened care is taken when applying the securing tie.

The greater rigidity of the PVC ETT in comparison to their silicone counterparts is evident on palpation. It was consequently expected that the silicone ETT would require lower forces to produce constriction. This hypothesis proved true. When evaluating the choice of ETT material in relation to the risk of constriction from a securing tie alone, PVC is the preferred choice. However, the decision to choose a silicone or PVC ETT may be influenced by numerous other factors, including but not limited to the overall shape of the ETT, cuff type and immediate availability. The rigid curvature of PVC ETT may make them easier to insert in cats and dogs when compared to straight, more compliant silicone ETT. However, the stiffness of the PVC ETT may make trauma to the tracheal mucosa more likely (Joo et al. 2002). If a silicone ETT is chosen for an individual animal, vigilance regarding the increased risk of constriction from application of the securing tie is warranted.

The intended assessment of securing tie materials in this study was not complete, due to spontaneous loosening of the plastic tie material once tension on the securing knot was released. This is likely a result of this material's high tensile strength and low friction, properties that are apparent on handling. Evaluation of the true minimum forces required for this tie material was consequently prevented. However, this finding does have clinical relevance: the plastic tie material may fail to secure an ETT in situ if a traditional overhand knot is tied. Overhand knots were applied in this study because of their ubiquity in clinical practice, but the manufacturer of the plastic ties recommends an alternative method of application. This method involves folding the length of material in half and looping this double length around the ETT body, threading the loose ends through the loop and then using these loose ends to tie an overhand knot, creating a 'triple loop' construction. (JAKMarketing 2022). To maintain standardisation for comparison the same knot was chosen for all ties. The effect on the force required to produce constriction of the ETT lumen if using this method is therefore unknown. Attempts to use this knot application method demonstrated a similar propensity for the knot to spontaneously loosen (see figure 7-6).

Figure 7-6

Image depicting spontaneous loosening of overhand knot over endotracheal tube body, tied with a specialised plastic tie material applied using the manufacturer-recommended method.



The effect on ETT security of using the manufacturer-recommended knot application method is unknown. The presence of two circumferential loops in addition to the central knot may reduce rostral and caudal movement of the ETT in situ, despite spontaneous loosening. If this was the case, the plastic material may present an attractive option for securing ETT, as the risk of constriction is minimised, but ETT security is maintained. Further work is required to assess this hypothesis.

The woven material in this study required use of a doubled layer to prevent breakage of the material when applying the securing knot. The force at which breakage of a 30 cm single strip of this material occurred was lower than that required to cause a constriction of the ETT lumen in the majority of the ETT materials and sizes tested. It was therefore necessary to use a double layer to permit comparison between materials. Using a single strip of the woven material in silicone size 4.0 and 7.0 (mm, internal diameter) and PVC size 4.0 (mm, internal diameter) ETT may represent a useful safety mechanism, as breakage of the securing tie would be expected to occur before constriction of the ETT is caused in these combinations.

The knitted stretch material tested in this study required lower forces overall to produce a constriction than the non-stretch woven fabric, irrespective of ETT size or material. It consequently appears to be the higher risk material to use as a securing tie. This may be due to the stretch quality of the material causing additional compression of the ETT lumen once the maximum force has been applied: releasing the tension on the stretch material causes it to relax, consequently decreasing the circumference of the knot and causing further constriction. This finding is despite the larger width of the knitted fabric in comparison to the woven fabric, which would be expected to reduce the pressure exerted by the tie for any given force due to the increased area of coverage of the ETT body. This relationship is given by the equation:

$P = F/A$

Where P = pressure, F = force, A = area.

The significance of the difference in minimum force between the woven and stretch materials could be questioned. In one of the repetitions of this study, the overall median minimum force for the woven material was lower than for the stretch material, in disagreement with the overall findings from all repetitions. This uncertainty is illustrated by the relatively large 95% confidence interval for the minimum force by stretch material in PVC ETT, which overlaps with the 95% confidence interval for the woven material. This may suggest that in reality, there is little difference in propensity for constriction between the woven and stretch tie materials, at least for PVC ETT.

There were several limitations to this study. Endotracheal tubes were re-used on multiple occasions in Stage 2 testing. Progressive weakening of the ETT body could have occurred with repeated application of the tie materials, lowering the force required to produce constriction of the lumen. This may also be a contributory factor to the wide variety of CSA reductions found between repetitions in Stage 2. However, there was no consistent pattern of increasing CSA reduction with progressive repetitions which would be expected if this were the case. Whilst repeated use of ETT is reflective of clinical veterinary practice, further work is warranted to assess the potential effects on ETT material integrity.

Defining the 'minimum force' for each combination of ETT material, ETT size and tie material was intended to facilitate comparisons between choices faced by the anaesthetist. Those combinations with a lower minimum force are at higher risk of causing ETT constriction, as less force is required to compress the lumen. The definition of 'minimum force' in this study is not an exact reflection of the true minimum force, as this lies somewhere between the lowest force applied that did not cause constriction, and the stepwise-increased force above it that did. The choice to use the halfway point between these two forces was an attempt to report results as close to this true minimum force as possible. The 1 kg increments between the reducing forces applied during stage 2 were chosen to facilitate accurate force application. The sensitivity of the luggage scale meant that readings changed quickly; 1 kg differences were deemed a feasible target when performing testing.

The application of the securing ties in this study was not a true replication of the method typically used in clinical practice. Usually, an overhand knot is applied with traction on both ends of the tie material, rather than applying traction on one end and having a fixed source of tension on the other. However, adhering to the typical clinical method made accurate measurement of total force impossible, due to unequal distribution of tension and direction of force. The study method as described allowed consistent application and measurement of force. This in turn made valid comparisons between variables possible. It is hoped that the method of force measurement during knot application in this study provides a reasonable approximation of the total force applied during knot application in real-life scenarios.

Constriction of ETT is likely more severe in clinical practice than was demonstrated in this study. Securing ties are usually knotted around the head or nose of the animal once the overhand knot onto the ETT is applied: this may alter the tension applied to the knot over the ETT lumen, resulting in tightening or loosening. The weight of oral structures and the maxilla may exert additional force onto the ETT wall, worsening constriction. Progressive warming of the ETT from body temperature, a reported risk factor for compression (Busaidy et al. 2011), may reduce the force required to produce constriction.

The findings of this study demonstrate that constriction of the ETT lumen through the application of a securing tie is a potential hazard. The anaesthetist should be mindful of this possibility, and take care to avoid overtightening when applying the securing tie onto the ETT body. The minimum force which reliably secures the ETT should be used. Applying the knot over the rigid plastic ETT connector may be a safer alternative but how this might affect the risk of displacement of the ETT and the connector is unknown.

7.8 Conclusions

It is possible to cause constriction of the lumen of both silicone and PVC ETT from application of a securing tie. Silicone ETT are more vulnerable to constriction than PVC ETT, and smaller sized ETT require lower forces to produce constriction than larger sizes. Knitted stretch fabric is more likely to cause constriction of the ETT lumen compared to non-stretch woven fabric. Plastic securing ties may fail to adequately secure the ETT body.

Chapter 8

Discussion

8.1 Relationship between studies & shared themes

The overarching intention of this work was to contribute to the evidence base regarding ETT complications in cats and dogs. With the retrospective investigation, information collection regarding the current state of ETT use and their problems was performed. The inclusion criteria for the study population were kept intentionally general, with the aim of finding broad-ranging complications. Analysis of the data collected facilitated associations to be made between specific ETT-related problems and contributory factors. The experimental equipment study focussed specifically on constriction of ETT by application of a securing tie. The aim of this study was to replicate and further investigate one of the causes responsible for 20% of all cases of constriction found in the retrospective study population. The findings of the retrospective study therefore led directly to the conception of the experimental study.

The findings of both studies could contribute to improvements in safety regarding ETT use in cats and dogs. The retrospective study highlighted some potential problems that can occur with ETT in animals and the relative frequency of these problems. The experimental study defined the parameters within which constriction of an ETT by application of a securing tie is possible. The information discovered by both studies could influence the decision-making process of the anaesthetist when selecting, placing and securing ETT in cats and dogs.

Both studies utilised CT as an evaluation tool for ETT CSA reduction. The use of this imaging modality for measuring ETT and detecting reductions in ETT CSA has been demonstrated in the literature. Its integration into both studies is a key theme. Assessment and measurement of ETT lumens was performed in a transverse plane. Lumen reduction was therefore readily detectable, as any deformation of the ETT wall was immediately visible when moving along the ETT body. This concept is shown through the successful detection of CSA reductions as small as 0.14% in the retrospective study and 1% in the experimental study.

8.2 Integration of findings

The retrospective study showed a statistically significant relationship between severity of constriction and ETT size. Smaller ETT showed more severe reductions in lumen CSA. The experimental study demonstrated that smaller sized ETT require lower forces to cause constriction by application of a securing tie than larger sizes. Both discoveries are likely to be, at least in some part, explained by the finding that smaller ETT sizes also have thinner walls, as shown through the experimental study. The proportion of ETT sizes found in the retrospective population was not analysed. However, given that the experimental study showed that smaller ETT sizes are more likely to constrict, the proportion of small and large sized ETT in the retrospective population will have influenced the prevalence of constriction found. It may therefore be expected that different clinical populations would have a different constriction prevalence, with populations of larger dogs showing less and smaller dogs and cats showing more constriction.

Visualisation of the securing tie material via CT was key in determining it as a specific cause for ETT constriction in the retrospective study. In many cases, the material was obvious, presenting as a knotted structure with a fabric-like appearance, surrounding the ETT body. If there was a concurrent reduction in the ETT lumen CSA at the same location, the cause of constriction was easily assigned. However, some cases of constriction in the retrospective study were not straightforward to assign, because there was no visibly obvious inciting cause. In many of these cases, the constriction occurred in the oral cavity, resulting in the inclusion of the 'oral' cause category. The variety in appearance of the three different securing tie materials assessed in the experimental study was evident on CT image evaluation. Whilst the securing tie material was visible surrounding every ETT, the knitted stretch material was subjectively easier to detect. This was due to its distinctive thread pattern and increased radiopacity compared to both the woven and plastic materials. Additionally, different types or brands of stretch material, which were used in the hospital over the inclusion period for the retrospective study, may appear differently on CT review. These differences could account for some instances of ETT constriction due to a securing tie being missed, and being placed into the 'oral' category in the retrospective study. The prevalence of this complication may therefore be higher than reported.

The influence of ETT material on constriction prevalence is unmeasured for the retrospective study. This information is not routinely recorded and was unavailable for the population studied. Results from the experimental study show silicone ETT to be more vulnerable to constriction from the securing tie, requiring lower minimum forces than PVC ETT. In the retrospective population, the relationship between ETT size and material was skewed. This is because silicone ETT were only stocked in larger sizes (11.0-14.0 mm, internal diameter) at the hospital during the time period studied. However, the larger sizes of silicone ETT are more likely to constrict than PVC ETT of the same size range.

Securing tie material was not recorded for cases in the retrospective study population. The experimental study states that the stretch material was more likely to cause constriction than the woven material as it required an overall lower minimum force, however there was a large degree of variability. Although there was no official hospital policy dictating securing tie material during the inclusion period for the retrospective population, only stretch fabric was stocked for this purpose. This will have influenced the prevalence of constriction found. Changing the availability of securing tie materials in the hospital in favour of woven fabric could contribute to decreasing this complication.

The three independent variables assessed in the experimental study are likely to have influenced the reported prevalence of constriction due to the securing tie in the retrospective study. The individual contribution of each factor is unknown because of missing information. However, focussing specifically on constriction due to the securing tie, sub-populations within the retrospective study that were at higher risk were those animals with silicone ETT, smaller sized ETT and where stretch material was used. Of course, any tie applied with a high force would also cause constriction: any force above the reported minimum for each combination in the experimental study carries the risk of compressing the ETT body. Retrospective cases showing other causes of ETT constriction, such as presence of a radiotherapy mouth gag, compression from teeth and compression at the larynx may have been influenced by ETT material and size. If a silicone ETT becomes constricted at a lower force applied by a securing tie than a PVC ETT, then it would be reasonable to assume that lower forces from any external source would have the same effect. Similarly, smaller ETT are probably more likely to become constricted from forces exerted by teeth, mouth gags and the larynx than larger ETT.

8.3 Clinical recommendations based on findings

The most valuable outcome of the two studies is the ability to make evidence-based recommendations for the use of ETT in cats and dogs. Based on the results of the retrospective study, the veterinary anaesthetist should be aware that rostral and caudal mispositioning of ETT and constriction of the ETT lumen are common occurrences. Reasonable steps taken to reduce the occurrence of these problems are likely to improve patient safety and should be followed where appropriate.

Adhering to the current guidelines for ETT size selection in terms of internal diameter and length is advisable to prevent constriction of the ETT from the larynx and caudal mispositioning, respectively. Special attention should be paid to the assessment of ETT length for brachycephalic breeds, as these dogs showed a higher prevalence of caudal mispositioning than others in the retrospective study.

An appreciation by the anaesthetist that any ETT may be constricted by the securing tie if a high enough force is applied is important. Choosing the ETT with the largest suitable internal diameter for each patient helps to reduce the risk of constriction as shown through the experimental study. The retrospective study additionally shows that any constriction of larger ETT sizes is likely to be of lesser severity. Patients that require ETT of internal diameters ≤4.0 mm are at highest risk of constriction of the ETT through application of the securing tie and special care should be taken when applying the tie, using the lowest possible force. There is always a balance to strike between securing the ETT sufficiently, and avoiding constriction of the lumen. The experimental study provides the numerical values for force to prevent the latter, but force values to ensure the former are unknown.

The material used for the securing tie may influence the propensity for constriction. Choosing woven material may reduce the risk of ETT compression, but regardless of material, always using the lowest force possible to achieve securement is advised.

Recording the ETT and securing tie material on the anaesthetic record, whilst not routinely practised, may provide a valuable opportunity to investigate complications in future and should therefore be encouraged.

Although visual inspection of ETT is always recommended, CT provides a more sensitive method for the detection of ETT lumen CSA reduction, as shown through the comparison of results of stage 1 and 2 in the experimental study. If a patient is undergoing CT of the head/neck/thorax for any reason with an ETT in situ, the anaesthetist should use this as an opportunity to evaluate the ETT. If any complications are appreciated, corrective action should be taken.

8.4 Limitations

8.4.1 Shared limitations

Although CT evaluation provided a convenient method for detection of ETT lumen constriction in both studies, the precision and accuracy of measurements via the specialised imaging software imposed a limitation. Measurement repeatability was not assessed prior to the retrospective study, but repeating measurements of ETT wall thickness and CSA reduction in the experimental study shows some variability. These differences may be true and due to individual ETT characteristics. Different ETT (but of the same size and material) were measured between repeats of the experimental study. Additionally, the resolution of the CT image decreased noticeably when magnifying it to measure the smaller ETT sizes, causing some pixelation of the image, thereby impacting the accuracy of measurements. This could have affected measurements of both ETT lumen CSA and wall thickness in the smaller ETT sizes.

8.4.2 Retrospective study limitations

The retrospective study is subject to a number of limitations which may impact the relevance of its findings. All data was collected from a single hospital. The population studied was subject to specific policies, staff and equipment. These factors are likely to differ amongst clinical institutions, and may influence the types and frequencies of the complications identified. However, the population studied was relatively large, and there are no specific protocols governing ETT selection, tracheal intubation and ETT securement at the hospital. Consequently, diversity of approach is expected.

Each case was matched with its respective anaesthetic record where possible, but there were large amounts of missing data. This prevented meaningful evaluation of variables such as body weight, procedure and presenting complaint, so the opportunity to search for associations between these patient factors and complications was missed. There were no adverse anaesthetic events directly attributed to the ETT in the anaesthetic records found. This could suggest that no clinical problems were caused by the complications found in the study, or that the clinical sequelae of mispositioning and constriction of ETT were misattributed to a different cause. Highlighting the prevalence and potential for such complications is important in increasing their likelihood of being added to the list of differentials by the anaesthetist when problems arise.

The influence of ETT material and securing tie material on constriction and mispositioning was not possible to assess, because this information is not typically recorded on the anaesthetic record. This prevented evaluation of these factors. An attempt to address this limitation was made through performance of the subsequent experimental study.

The precision of measurement of the imaging software imposed a limit on the accuracy of the reported CSA reduction. Every effort was made to perform measurements in as high a resolution as possible, but all measurements were made manually. Human error is therefore likely to have contributed to inaccuracy. Repetition of the measurements by the same operator, with calculation of an average, may have increased measurement accuracy and allowed assessment of intraobserver consistency. However, this was deemed unfeasible due to the large number of measurements made.

The lack of availability of complete imaging of the head, neck and thorax in many cases limited the evaluation of prevalence of all complications: the true prevalence of both mispositioning and constriction of ETT in the population studied may indeed be higher or lower than reported.

8.4.3 Experimental study limitations

The repeated use of ETT in the experimental study imposes a limitation on the validity of the minimum forces reported. Whilst a new ETT was used for each different tie material in the first performance of stage 1 of the study, the individual ETT were re-used throughout stage 2 testing and subsequent repetitions. Progressive weakening of the ETT at the site of securing tie application may be expected, which could have lowered the forces required to produce constriction. Progressively decreasing minimum forces between repetitions of the study were not found, however, suggesting that if weakening of ETT with repeated use does occur, it requires reuse above the total number of tie applications performed in this study. Re-use of ETT is a common practice amongst veterinary hospitals so it was deemed appropriate to re-use ETT in this study. It must also be borne in mind that there may be inherent differences between the vulnerability to constriction in individual ETT of the same material and size. This could be due to manufacturing inconsistencies in ETT material composition and/or wall thickness.

The application of the securing tie as prescribed by the study method does not match the method used in clinical practice. Typically, an overhand knot is applied through tension on both ends of the tie material, rather than just one as in the study. The reason for this was to facilitate accurate measurement of total force, but the difference in technique may have affected the validity of the minimum forces found for each combination of materials and ETT size. In addition, in the clinical setting the securing tie is typically tied around the head or muzzle of the patient following knotting of the material onto the ETT body. This may alter the tension applied to the knot over the ETT lumen, resulting in tightening or loosening. The weight of the maxilla may also contribute to additional compression of the ETT in situ, through transmission of pressure onto the knot of securing material. Considering this, the true minimum forces required to cause a reduction in ETT CSA may be even lower than reported.

8.5 Proposed further work

Both the retrospective and experimental studies lend themselves to further work, in the interests of expanding the relevance and clinical applicability of the results.

Conducting the retrospective study method with different clinical populations could provide an interesting comparison, as well as increase the volume of evidence for ETT-related complications and their associations with patient factors. Different referral hospitals would be a convenient next step for this study, but non-referral populations would provide a valuable addition. In this type of veterinary practice, CT imaging is rare, so the study methodology may need to be amended. Radiography could represent a suitable alternative resource to evaluate the ETT. Mispositioning would be easy to assess with this imaging modality using lateral views. Constriction would likely be possible to detect using a lateral radiographic view of the ETT in situ, but severity of constriction would be challenging to measure without the ability to compare ETT CSA, which requires access to images in a transverse plane.

The differences in complication rate may be significant between referral and non-referral institutions. The presence of a dedicated anaesthesia team in a referral hospital may be expected to produce a lower complication rate. This is because insertion of the ETT is performed or supervised by personnel with specialised knowledge and experience in this intervention. Until comparisons with non-referral institutions are possible, however, this hypothesis remains unsubstantiated.

An important improvement factor to consider for further work based on the retrospective study would be to fully match cases with information from anaesthetic records. This would allow assessment of specific patient factors and their influence on complications. Designing a prospective iteration of the study would facilitate this, with anaesthesia records to be completed with compulsory inclusion of this information. This would allow evaluation for specific relationships between patient body weight and ETT constriction and mispositioning.

A knowledge of patient body weight would also permit relation of this variable to ETT size, which could contribute to the production of evidence-based guidelines on ETT size selection.

The ability to match presenting complaint with prevalence of ETT-related complications would enable discovery of any at-risk patient groups based on clinical signs. This valuable information could contribute to the prevention of ETT mispositioning and constriction in future patients by increasing risk awareness.

Looking for respiratory abnormalities would enable discovery of the clinical impact of the complications found in the retrospective study. Searching for hypercapnia, hypoxaemia and changes in respiratory rate would require a detailed inspection of anaesthetic records. Such a process would require strict definitions of hypercapnia and hypoxaemia applied to the entire population but may involve species differentiation. Significant changes in respiratory rate would likely need to be defined according to percentage changes from the pre-anaesthetic examination. This would be more feasible in a prospective study design where completeness of relevant information is explicitly required.

Further work based on the experimental study could involve assessing the effect of re-use of ETT on minimum force required to produce a constriction. The effect of re-sterilisation could also be evaluated given its purported association with damage to silicone ETT in the veterinary literature (Niimura del Barrio et al. 2015). Findings may lead to the prevention or encouragement of an already well-established practice.

Proper assessment of the plastic tie material, by adhering to the manufacturer's recommendation for knot application, would allow a fair test of this material and its minimum force required to produce a constriction. A study of this type would then permit a fair comparison of the plastic tie material with the stretch and woven fabric materials, allowing evidence-based selections to be made on the basis of patient safety.

Attempting to simulate unplanned extubation would allow evaluation of the security provided by each tie material. Measuring the force required to produce displacement of the ETT when secured by different materials would show which material performs best in this regard. The use of cadavers would provide the best ethical assimilation to clinical practice. Displacement could be assessed by applying traction to the ETT in both rostral and caudal directions. Performance of the tie material in this situation would be dictated by the security of the knot created by each material, as well as the friction applied by it to the ETT body. The results of such a study would be a valuable adjunct to the existing findings, facilitating a balanced evaluation between each tie material's ability to both constrict and secure the ETT.

Chapter 9

Conclusions

The two studies presented in this work aim to provide a well-rounded insight into the issues encountered with ETT in cats and dogs. It is hoped that the findings from both studies can inform clinical practice, by increasing awareness of the problems already occurring, and by testing common variables so that the occurrence of further problems may be reduced.

Constriction and mispositioning of ETT occurred very commonly in the retrospective study population. Assessment of the ETT within the oral cavity for constriction and mispositioning is recommended. Radiotherapy mouth gags increase the risk of ETT compression. Smaller ETT are at greater risk of severe constriction. Brachycephalic dogs are at particular risk of caudal mispositioning. Evaluation of CT images of the head, neck and/or thorax of a patient presents an opportunity to check for ETT mispositioning and constriction.

It is possible to cause constriction of the lumen of both silicone and PVC ETT from application of a securing tie, as shown through the experimental study. Silicone ETT are more vulnerable to constriction than PVC ETT. Smaller sized ETT require lower forces to produce constriction than larger sizes. Knitted stretch fabric is most likely to cause constriction of the ETT lumen compared to non-stretch woven fabric. Plastic securing ties may fail to adequately secure the ETT body.

Chapter 10
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