INTEGRATED DISEASE SURVEILLANCE AND RESPONSE SYSTEMS IN RESOURCE-LIMITED SETTINGS

Zacharia John Mtema

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UNIVERSITY OF GLASGOW
INSTITUTE OF BIODIVERSITY, ANIMAL HEALTH AND COMPARATIVE MEDICINE, COLLEGE OF MEDICAL, VETERINARY & LIFE SCIENCES

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Abstract

Infectious diseases are a major public health burden causing millions of deaths every year. Government authorities need to be able to monitor disease incidence and evaluate their interventions for disease control. Monitoring the status of infectious diseases is one of the most challenging problems facing the public health sector, and epidemiological surveillance systems for infectious diseases, particularly notifiable diseases are essential. Despite initiatives to encourage reporting of infectious diseases, underreporting and poor surveillance are on-going challenges for many developing countries. Most surveillance systems in these settings use traditional paper-based methods, which are both inefficient and impractical. There is a need for alternative tools to strengthen infectious disease surveillance systems in resource-limited settings.

The remarkable progress made in mobile computing technology has the potential to improve infectious disease surveillance systems. However, user experience in digital technologies and infrastructure needs to be given greater attention. My study investigated the use of mobile phone devices as surveillance tools in health information systems. A mobile phone-based surveillance system was developed and applied in Tanzania as an alternative approach to traditional paper-based systems. Using this system different factors that affect the usability of mobile phone-based systems were investigated, by examining the quality of surveillance data in the context of completeness, timeliness and costs. After two years of operation in twenty-eight districts in southern Tanzania, numerous factors were identified that affect user accuracy and speed of use of the mobile phone-based surveillance. These include user experience in digital technology, particularly mobile device ownership; digital technology literacy, such as access and use of SMS and user's age. The mobile phone-based surveillance system was more accurate compared to the traditional paper-based system with greater data reporting, more complete data and timelier reporting. Initially the mobile phone-based surveillance system required more capital investment, although the running costs of paper-based surveillance were greater.

The utility of the mobile phone-based surveillance in monitoring and evaluating large-scale rabies control interventions was examined and the data produced was used to analyse the impacts of interventions on reducing disease incidence. Significant relationships were detected between the incidence of reported bite injuries in the focal district the previous month and in neighbouring districts that month, with more injuries detected in mainland Tanzania than on the island of Pemba. The relationship between bite injuries and

vaccination coverage was complicated, with some evidence that vaccination reduced bite incidence. However, more data and a better model are needed to fully understand the impact of vaccination on bite incidence. The system provided timely information on the implementation of control measures and incidence of bite injuries, vital for improving control efforts.

Use of automated short text messages (SMS) as part of the mobile phone-based surveillance was assessed to determine whether they could improve patient's adherence to treatment regimens. Patients who received SMS reminders had significantly better compliance than those who did not, with attendance improved by at least 10%. Use of SMS reminders has the potential to improve patients' compliance in other treatment regimens that require repeat clinic visits or administration of medicines.

This thesis documented how the use of mobile phone devices can be used to improve surveillance in resource-limited settings. The use of effective integrated surveillance system could empower major stakeholders concerned with public health problems by providing them with appropriate real-time information on disease incidence and control interventions. In the final chapter the challenges encountered and insights gained in the application of mobile computing in strengthening infectious diseases surveillance are discussed. Despite infrastructural challenges such as unreliable power and Internet, mobile computing technologies can improve patient care and authorities can be prompted in a timely manner about infectious disease outbreaks and of supply shortages. In conclusion, innovative tools that can strengthen and integrate human and animal surveillance can improve the control and prevention of infectious diseases. Mobile phones have great potential for this, and can be used to strengthen health information systems.

Candidate’s declaration

I declare that the work recorded in this thesis is entirely my own, except where otherwise stated, and that it is also my own composition. Much of the material produced in included in this thesis has been produced in co-authorship with others and some has been presented for publication. My contribution for each chapter is as follows.

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I further declare that no part of this work has been submitted as part of any other degree

[redacted]

Zacharia John Mtema

University of Glasgow

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Glossary

ALU	Artemether Lumefantrine
B&MGF	Bill & Melinda Gates Foundation
BTS	Base transceiver station
CDC	Centers for Disease Control and Prevention
CP	Central point where mass vaccination campaign takes place
DFA	Direct Fluorescent Antibody test to detect rabies virus
DHIS	District Health Information System
DNA	Deoxyribonucleic acid
dRIT	Direct rapid immunohistochemical test to detect rabies virus
ELISA	Enzyme-linked immunosorbent assay
FAO	Food and Agriculture Organization
GAVI	Global Alliance for Vaccines and Immunisation
GLM	General Linear Models
GLMM	Generalized Linear Mixed Model
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HCI	Human–computer interaction
HIV/AIDS	Human immunodeficiency virus infection / acquired immunodeficiency syndrome
HMIS	Health Management Information System
ICT	Information and communications technology
ICT4D	Information and communication technologies for development
IDSR	Integrated Disease Surveillance and Response
IDWE	Summary of Infectious Disease Weekly Ending
IHI	Ifakara Health Institute
LFO	Livestock Field Officers
MOHSW	Ministry of Health and Social Welfare
MOLFD	Ministry of Livestock and Fisheries Development
NBS	National Bureau of Statistics
OIE	World Organisation for Animal Health
OMC	Open Mobile Consortium
PDA	Personal digital assistant
PEP	Post-exposure prophylaxis
PHP	Hypertext pre-processor, a server-side scripting language generally used for web-based systems.
RDT	Rapid Diagnostic Tests
SARS	Severe acute respiratory syndrome
SMS	Short Message Service
UTM	Universal Transverse Mercator
WHO	World Health Organization

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1.1 General introduction

Surveillance is the collection of information and the monitoring of a situation using that information [129]. In the context of health, surveillance is a tool for collection, collation and dissemination of data on disease incidence, treatment, prevention and control [58]. Routine disease surveillance is an essential tool for authorities to enable timely detection of and responses to disease outbreaks [46,129]. Without an effective surveillance system, it is difficult to know the true burden of disease, the source(s) of infection, and to characterise trends and patterns of infection. However, armed with this information, response systems and preventative measures can be developed and improved.

A surveillance system has to have a mechanism for collecting information, such as trained recording personnel or automated devices. This information needs to be reported to a central system where it is readily accessible [36,63]. Data needs to be collected from all the places where the program is operating, which is dependent upon the scale of the surveillance system. This may vary from a small well-defined geographical area (e.g. urban malaria control in Dar es Salaam) to the global community (e.g. swine-flu and SARS) [38]. Depending upon the disease(s) of interest, the type and extent of information that needs to be collected will vary and a surveillance system needs to be capable of dealing with this variation [15,99,133]. For example, detailed information may be collected on biological samples such as the number and species of malarial mosquitoes, different types of molecular data or laboratory results such as ELISA and DNA extractions (e.g. images and quantitative information), to personal information from patients, or the use of drugs, diagnostic tests, and vaccines [11,125,127]. Integrated disease surveillance and response systems can support health facility-based surveillance such as reporting the results of check-ups, which for malaria may include Blood Smear slides and Rapid Diagnostic Tests [68,119]. However, two-way communication and response is critical for surveillance to ensure that data collectors are incentivised, and to recognize their role within the system and how it can contribute to improving health outcomes. These responses from the responsible authorities include the provision of vaccines at clinics, distribution of larvacide to malaria-endemic areas, or the restocking of rapid diagnostic tests and so on.

1.2 Health surveillance in developing country settings

In developing countries, infrastructure is generally poor, power may be unreliable and much of the population may be based in remote areas with little access to modern computing technology. Due to these constraints, many studies have reported challenges to the evaluation of infectious diseases in instances when passive surveillance efforts are ineffective, resulting in high underreporting [22,71,76,116]. Infectious disease surveillance systems, though available, are often not well implemented and may be poorly designed, providing little incentive for compliance [116]. Although infectious disease reporting is mandated by law, many of the rural and remote areas cannot abide by the rules due to difficulties of reporting [66]. Many studies have enumerated the challenges that exist in resource-limited settings, not only to detect or report infectious disease outbreaks in time but also in healthcare delivery and monitoring. The lack of reliable infrastructure, human resource capacities and poor policy are frequently mentioned as key challenges [13,18,46,64,74,109]. Most surveillance systems in resource-limited settings are paper-based, which are more prone to error accumulation from transcription. Paper records can also be easily damaged or destroyed, and, for monitoring and evaluation of biomedical interventions, are difficult to compile, particularly those operating across large areas and populations [64,116].

Health surveillance efforts in developing countries have been demonstrated to be inaccurate, suffering from shortcomings such as data incompleteness, a lack of timeliness, and inability to detect events (collectively known as “under-reporting”) [136]. These surveillance systems lack mechanisms to share feedback with local communities, resulting in unidirectional flow of information that provides no incentives to users [46,71,93,109,116,117]. A lack of up-to-date data both in human and animal surveillance increases these challenges, and increases the vulnerability of human populations to zoonotic diseases [46]. For example, accessing paper records is time-consuming but moving records to electronic surveillance in developing countries is often difficult because of unreliable power supplies, lack of computer facilities, Internet access and trained people capable of using these technologies [74]. Therefore, epidemiological surveillance systems for infectious diseases, particularly notifiable diseases, have failed to monitor and respond to communities most in danger of infectious disease outbreaks, due to lack of data that can potentially narrow down the problem [66].

1.3 Mobile computing technologies in developing countries

Mobile computing technologies, also known as mobile device technology, is a generic term which refers collectively to portable technology devices capable of operating, executing and providing services and applications like a typical computing device, an alternative to desktop computers. Mobile computing technology includes: notebook computers, personal digital assistants (PDAs), smart and standard mobile phones. In developing countries mobile phones have become ubiquitous, with cell phone subscriptions exceeding the number of fixed landlines and computers with Internet access [30]. Mobile phones are easy to use, requiring just a basic knowledge to operate, and are inexpensive, making them available in limited-resource settings, and driving exceptional growth in ownership [93]. Despite the challenges of illiteracy in digital technology and poor digital infrastructure that exists in these settings, mobile phones have successfully emerged and promise to be a quick fix for digital communication in developing countries [117].

Mobile computing technologies are increasingly being deployed in developing countries for a variety of purposes [33]. Mobile phone-based systems are used to monitor water infrastructure in rural areas where most engineers are based in urban locations [19]. Elsewhere mobile phones are being used to empower communities to improve water services by reporting their complaints to authorities in real-time [1]. The use of mobile phone-based systems has enabled rural and remote communities to access banking services, which used to only be available in cities. Money can be sent and received and bills paid (water, electricity, satellite television, etc.) in remote locations via mobile phones [94,109]. Mobile computing technology is removing the barrier of communication from otherwise isolated communities. For example, up-to-date information on trading prices can be easily accessed on mobile phones or through tools such as SMS Tips [57]. Mobile phones are being trialled to track large numbers of patients and materials across health facilities [96].

A number of digital devices are available and have been used for surveillance (e.g. desktop computers, laptops, tablet computers, personal digital assistant (PDAs), digital recorders, cameras, smart phones and mobile phones). However, the utility of these devices varies in developing countries depending on their price, availability, acceptability, and ease of use, including operating language and dependence on infrastructure such as power supplies.

Mobile phones show particular potential, as they are now accessible and affordable in developing countries, are well accepted and have user-friendly interactive interfaces, which mean that end users do not require extensive training.

Use of open source software is recognized as an important means of reducing the digital divide between developed and developing countries. Open source software is computer software with an open license, whereby source code is made available for free and the copyright holder provides the rights to study, change and distribute the software to anyone and for any purpose [79]. Technical experts have come together under the umbrella of open source software within the Open Mobile Consortium (OMC). OMC aims to provide a development platform applicable across mobile computing technologies [78]. Moving to open source has a number of advantages. There is rapid turnover in technological applications and a common development environment, meaning that developers do not need to learn new languages for different devices and as technology varies. As a consortium there is a more rapid uptake of technological ideas and shared experiences, costs are reduced because there is no need to outsource consulting to private companies for particular expertise, and the progress made is freely available to those who might otherwise not have access. Furthermore, open source development means that applications are not restricted to a particular manufacturing company; there are no license fees for software users and tools can be easily and cheaply tailored to specific needs and localized, smaller scale (non-commercial) activities. However, open source software came with number of drawbacks, which includes not being straightforward particularly for beginners, lack of incompatibility among hardware and lack of working across platforms for example the applications software that runs open source software wont run on proprietary software's.

1.4 The growth of 'mHealth': examples and lessons learned

Mobile health (mHealth) is defined as medical and public health practice supported by mobile phone devices, such as mobile phones, patient monitoring devices, tablets, PDAs, and other wireless devices [57]. The emergence of mobile computing technologies in both developed and developing countries presents an opportunity to improve health outcomes through the innovative delivery of health services and information. Despite challenges in the developing world that prevented acquisition of digital technology, Information and Communication Technologies for Development (ICT4D) have shown promise [98,109].

Reports from the World Bank have shown increasing evidence that ICT4D have the capability to improve the efficiency of healthcare delivery, transforming knowledge through communication across rural and remote communities [4].

Mobile phone software designed for public health applications is one of the fastest growing and most successful examples of mobile computing in action under ICT4D. In the developing world, many products have been created under the open source software framework and pioneered in developing countries. Examples of mHealth from developing countries include: ‘Freedom HIV/AIDS’, a mobile phone game to create and spread awareness through SMS about HIV, which was developed by an Indian non-governmental organization (NGO) [20,124]. ‘Learning about Living’ is a Nigerian m-Health program based on questions and answers via mobile phone funded by the charities OneWorld and ActionAid International Nigeria. ‘HIV Confidant’ is another mobile application developed by a private US software company for PDAs and mobile phones that has been used in South Africa since 2003 [20]. There are numerous similar on-going projects globally that use either PDAs or mobile phones, including systems for monitoring malaria in Mozambique and Rwanda (TRACnet), telemedicine systems in Indonesia, health systems infrastructure in Rwanda (Phones for Health), dengue surveillance in Brazil (Nokia Data Gathering), tools to improve maternal health (Nacer) and patient compliance with treatment regimens (Colecta-PALM) in Peru, and for childhood illness in Tanzania (Mobile E-IMCI) [124] and ReliefWeb, a humanitarian information hub designed to share and exchange information among governmental and non-governmental agencies [75]. During the 2008 Kenya elections violence, “Crisis mapping” through Ushahidi, an SMS based system, was used to map the incidence of violence [6]. Recently, mobile phone-based systems have proven useful during and after natural disasters including: the 2010 earthquake in Haiti and the 2008 Chengdu-Sitzuan earthquake in China [75].

These examples demonstrate the potential that exists in mHealth, particularly in resource-limited settings where challenges to implement reliable and sustainable digital health surveillance can be accommodated. This potential to improve medical and public health practice is through the systematic collection, analysis and timely sharing of information between local sectors and international stakeholders. Moreover, several mHealth innovations can be integrated into a single system that can contribute to the remote monitoring and evaluation of biomedical interventions for disease control. The successful implementations of mHealth innovations can potential bridge developed and developing countries through sharing of knowledge and data, essential for diseases elimination.

However rigorous research is needed to evaluate this potential and challenges of using mobile technologies to improve health information systems.

1.5 Challenges for infectious disease surveillance systems in resource-limited settings

1.5.1 Digital divide

The digital divide is the gap that exists between individuals or communities describing differences in their ability to access and control technology, mainly caused by digital inexperience, lack of possession of appropriate technologies, poor technology design/lack of user friendliness, or differences in the support of the devices or technology itself [10,34,60,111]. Many African nations and Arab states are considered to be limited in terms of digital technologies due to the lack of reliable and supportive infrastructure, such as power and Internet [10].

During the last two decades, the growth of mobile phone subscriptions in the developing world has been broadly discussed as the bridge that will eliminate the digital divides in many of these nations [70]. However, this potential has not been fully explored to demonstrate how it can accommodate the challenges that face resource-limited settings. Some of the available systems rely on sophisticated software and technical language, which are not suitable for developing countries.

Many studies have revealed that local end-users experience frustration and feelings of incompetence when operating information technology systems, and those encountering problems have insufficient local support from experts. In particular, the lack of availability of software engineers is thought to contribute to these frustrations [74,116].

In the developing world, ICT technical experts are few and mostly employed by commercial companies; it is rare to find them in health sectors [66]. The lack of ICT experts is a problem because the end-users for surveillance generally require products that may need adapting to varying needs. In general, commercially available software does not have this flexibility and end-users do not have the capability to develop the software themselves or the resources to constantly buy newer products.

1.5.2 Lack of Digital infrastructure

Research and investment in sustainable digital infrastructure has been abandoned to private sectors; the lack of awareness of innovation that exists among policy makers has eliminated motivation for public investment in infrastructure development [115]. Moreover, the lack of reliable electricity hinders the growth of digital technology in developing countries, forcing communities to rely on traditional methods for health surveillance systems. The existing Internet and network infrastructure are mainly based in capital cities, while the majority of developing countries' inhabitants live in rural areas. This prevents the sharing of resources and expertise that could otherwise serve a wide area. With proper network infrastructure, for instance in Tanzania where health facilities are managed at a district-level, a wide intranet could improve their resource management. More universal Internet access could generally speed up the process of data sharing and dissemination of health information on, for example, raising awareness or responding to an outbreak of infectious disease. The Internet should also make it possible to share human resources, such as making doctors accessible to serve more than one health facility, and community transparency on price and resource allocations from the central government. Computers and Internet would also allow clinicians and nurses to obtain online training and to share knowledge from elsewhere in the world.

Despite the remarkable progress made by the software industries, research organizations and institutions have struggled to find tailored yet flexible and user-friendly tools for data collection in remote areas. Some of the adopted industry tools have been unsatisfactory, failing to accomplish the necessary tasks. It is difficult for computer scientists to understand the nature of public health research without having a background in this area. With a fuller understanding of the problem, appropriate solutions can be designed.

The following table (Table 1.1) summarizes different stakeholders that would benefit from reliable active disease surveillance systems. Typical examples are given for two major infectious diseases that are widespread in developing countries and whose prevention would benefit from the development of effective surveillance systems. I have developed mobile phone-based surveillance systems in Southern Tanzania used during large-scale domestic dog vaccination campaigns to evaluate their impacts on reducing human rabies (described in this thesis) and applied to community-based routine monitoring of mosquito populations to improve urban malaria control (e.g. larvacide delivery). The urban malaria control study aimed to develop an affordable and quality-assured community-based system for high-resolution entomological surveillance of vector mosquitoes to reflect human malaria infection risk patterns [12]. Drawing on practical experience from these case studies I describe the requirements of surveillance systems and the challenges that need to be fulfilled to meet these requirements.

Table 1.1. Different stakeholder requirements from infectious disease surveillance systems and the key challenges in meeting those requirements. Here we highlight empirical examples illustrating each concept with two case studies (malaria and rabies) in Tanzania.

Stakeholders	**Requirements from IDSR**	**Challenging facing stakeholders**	**Empirical examples**	
			Malaria	Rabies
Infected patients/ individuals exposed to infection	Provide information about risks of disease, appropriate treatment, costs and availability of treatment and consequences if not treated.	i) Poor understanding of risks and means of prevention, ii) Costly treatment and travel to obtain treatment, iii) Local treatment shortages, iv) Complicated multiday/ multi-dose treatment regimens	i) Importance of RDT in early malaria treatment, ii) Effective drugs (e.g. ALU) are not well known or accessible in rural areas, iii) Poor awareness about free prescription drugs (rather than expensive privately bought drugs), iv) poorly regulated drugs (fake drugs readily available) [73]	Following a rabid animal bite, immediate wound washing and prompt PEP is the only means to prevent fatal onset. PEP shortages are common; patients spend time travelling to clinics, but delays increase risks causing anxiety and expense (sometimes giving up) [49]. PEP requires 3-5 clinic visits (reminders necessary), must be administered by a clinician, and stored in well maintained, cold facilities [126].
Communities living in areas where disease is endemic	Access to up-to-date accurate information on prevention measures and sources of help (clinics, vets etc.)	Unaware of preventive measures and how these can be accessed	Distribute information on the importance of: i) insecticide-treated nets to prevent transmission, ii) environmental management (drainage, larvicidal spraying etc).	Disseminating information on i) animal vaccination campaigns (location, date, why) and ii) first aid and clinics with PEP (following an exposure)

Local clinicians/ HWs/ LFOs/ Fieldworkers responsible for control and prevention	Tools for data collection and submission and incentives for compliance.	Reporting is paper-based and slow. There is often no feedback from reports, which is demotivating (no job satisfaction) and results in overall poor service	Drug resistance increases are reported, but no changes to drug supplies for the clinic[107]. Fieldworkers report high mosquito densities, but larvicides are not promptly delivered.	Animal vaccinations used up during campaigns, but not resupplied. PEP expired or out of stock, but not resupplied. Doctors witness rabies deaths, and cannot advise on nearest sources of PEP [49]. No information received (medics to vets and vice versa) to understand status of disease.
Laboratory technicians responsible for surveillance and diagnostics	i) Automated notification of submissions, ii) incentives to conduct tests and report results, iii) maintained lab supplies for continued quality service provision	Inadequate mechanisms for reporting results to public/fieldworkers/higher authorities. Poor delivery, handling and labelling systems to ensure accurate data identification.	Mismatched samples (such as mosquito species identification and laboratory results) due to poor labelling (illegible handwriting). Delayed notifications of sample submission, resulting in less effective diagnostic tests.	Technicians not notified of samples, which deteriorate and cannot be tested. No means of reporting positive brain samples back to veterinary offices (who could carry out swift outbreak response vaccinations), and doctors (who could treat bitten patients).
District & regional health/ veterinary officers/ supervisors	To provide timely results and activity summaries to enable effective report writing and supervision of control programmes.	Difficulty in i) monitoring employees, ii) relating field/clinic activities to progress/results (incidence), iii) improving management based on results.	Hard to monitor field employees schedules without real-time communication. Delays in receiving results mean intervention responses are poorly timed (larvicide spraying).	Late estimates of animal populations (reported by LFOs) means insufficient vaccines are ordered. Vets do not receive reports from medics on animal bite injuries, so cannot evaluate dog vaccination effectiveness.

Researchers Scientists at Institutions (e.g. IHI, SUA, UDSM etc)	An interface to monitor ongoing activities and to collate data from across sites.	Difficult to monitor and evaluate multisite project in remote locations.	Field experiments for mosquito control or clinical trials require real-time monitoring and accurate data collection (affected by poor labelling). Paper based methods are too slow to allow design changes.	Unable to develop adaptive management programme because data on dog vaccination and incidence of disease are recorded only in local record books.
Responsible Ministries (MoLDF, MoHSW, MoE)	To provide i) current information on disease/health status, ii) overview of activities, iii) progress reports of funded projects.	Unable to allocate (or argue for) sufficient budget if no data available on disease problem.	Inappropriate drug distribution (parasites are resistant to certain drugs but this information is not available at ministry levels)	Unable to request donor support for rabies control because reported cases to do not reflect actual burden. Difficult to track PEP stock to prevent national/regional shortages.
International organisations and donors (WHO, OIE, FAO, B&MGF, GAVI etc)	To provide i) current information on disease/health status, ii) overview of activities, iii) progress reports of funded projects.	Budgeting, monitoring and planning large-scale/ international health policies and priorities without accurate information on disease and effectiveness of interventions.	B&MGF funds larvicide programmes, but need information to distinguish between poor implementation and biological resistance to chemicals to determine funding priorities.	WHO needs to evaluate effectiveness of dog vaccination campaigns for regional planning purposes, but cannot do so without accurate information.
Politicians and policy-makers	To provide up-to-date accurate information and summary statistics to inform decision making.	Lack of information on research and local level government activities on disease burden and control.	Information required on the effectiveness of community-based programs to control malaria.	No information about burden of rabies within political units.

Computer scientist/system developer	To be a reliable, portable, secure system, with automated error log, able to show the status (success/failure) of information retrieval.	Poor understanding of biological problems, technical experiments and biomedical language. Few resources on development of mobile computing tools for health.	i) Experiments are variable and require flexible tools, ii) Entomological/ molecular biology vocabulary is non-intuitive.	Lack of experience in field vaccination. Need to overcome both medical and veterinary language barriers and communication divide.

1.5.3 Traditional paper-based approaches

Use of paper-based tools for data collection is costly, inefficient, and decreases the reliability of information. Compared to digital technology, which can be monitored remotely, it is hard to control the validation of data collected on paper. This correspondingly increases the chance of incorrect data accumulating (see chapter 3). When data is being collected from a wide range of environments, it is time consuming and difficult to monitor a large number of users with differing abilities. Often data collectors are deployed after only a short training period, without on-going feedback once data collection has started (see chapter 2). Timely validation that controls the individual accuracy of data collection from the primary surveillance sources is difficult to implement and frequently delayed until data analysis, meaning that such mistakes may not be identified until much later. Numerous studies have reported inaccuracies and inconsistency of data collected through this approach. When changes are made to update the paper-based approaches to surveillance systems it take quite a long time to take effect and requires lots of financial resources to be put in place in the surveillance system, therefore major inconsistency of data collection is avoided in these approaches [71,74].

The primary objective for health surveillance systems is continuous data collection, and its analysis with timely interpretation and dissemination of health information. However, many difficulties result from a paper-based approach, where timeliness and incompleteness of data are major problems. Lack of timeliness and completeness associated with paper-based surveillance is due to a lack of mechanisms to report and share information compared to a digital approach. Moreover, the process of data transcription (from paper to digital) is slow, labour-intensive and expensive. Data storage and transport can be difficult, and there is a risk of data damage and loss. All these reasons become particularly problematic for health surveillance, because delays in reporting, inaccurate data recording, and costly processing can result in ineffectual medical systems, translating into human deaths. For policy makers and stakeholders who are relying on paper-based surveillance, their decisions might be inappropriate because of inaccurate and out-dated information.

1.6 Potential of mobile phones for health surveillance

Exceptional growth of mobile phones and mobile networks (GSM) can be found even in remote villages where local inhabitants have never seen computers. By 2011, estimates predicted 500 million subscriptions, almost 50% of the total population in Africa [70]. In Tanzania for instance, the competitiveness on the open market for Global System communication (GSM) for mobile phone companies has increased coverage in rural areas. Mobile technology is now familiar to communities in developing countries; phones are cheap and simple to use, which is an important incentive for uptake and use. In contrast, rural communities rarely have the knowledge to use advanced technology such as computers and Internet, as many residents have not completed primary or secondary education and are engaged in agricultural activities, whereas those who went to school and acquired university degrees often do not return because prospects are better in urban areas.

The rapid expansion of mobile applications services in developing countries brings with it potential benefits for public heath surveillance that deserve specific attention. Despite initiatives made to improve health surveillance, on the ground primary data are typically collected using pen and paper, where inaccuracy and high levels of underreporting are unavoidable [93]. Paper-based surveillance for health systems requires considerable investment of time and money and often results in information that is hard to process and access by third parties (see 1.6). Research scientists and clinicians need to work in remote areas, where power is unreliable and infrastructure is poor. In these circumstances mobile phones can link with outsourced technology and backup facilities. Mobile phones with long life batteries and large storage capacity can be used to collect data and provide real time remote updates for managing and monitoring large-scale interventions [109].

In southern Tanzania, I developed a mobile phone-based application to integrate disease surveillance between human and animal health sectors to improve rabies control. This study demonstrates the capacity to use mobile phones in developing countries lacking in infrastructure to increase the quality of data collected across large spatial scales as part of public health programmes.

1.7 Conclusion

This chapter has discussed the potential of mobile phones as surveillance tools in health information systems to support disease surveillance in resource-limited settings. We introduce the concept of surveillance, which is a means of collecting information and monitoring a situation using that information. In the context of health, routine surveillance is used to collect, collate and disseminate data on disease incidence, treatment, prevention and control, including analysing and responding to outbreaks of disease. We explained the problem that exists in many resource-limited settings and challenges for infectious disease surveillance systems, which are mainly not well implemented and may be poorly designed providing little incentive for compliance by health or veterinary workers. However, moving into electronic surveillance in these settings is often difficult because of limited infrastructure and lack of facilities and trained people capable of using these technologies.

Alternatively, we propose and discuss the promise that mobile computing technologies show for improving health surveillance in developing countries. Mobile technology is now familiar to communities in developing countries; network coverage is widespread; and phones are cheap and simple to use, which is an important incentive for uptake and use. The main focus of this thesis is to explore and evaluate the potential of mobile phone-based surveillance systems for resource limited settings. There is every reason to consider mobile systems as an appropriate approach that can potentially lead to improvements in speed of acquisition, quality and consistency of data, as well as savings in the overall budget for research institutions and local and national governments. However, there are very few mobile phone-based systems that have been implemented across large spatial scales by public health and veterinary services in developing countries and more generally, surveillance systems are very rarely evaluated [46].

1.8 Thesis outline

The foundation of this thesis is a mobile phone-based system that I developed for the surveillance of infectious diseases in Tanzania. This system is being used in Tanzania for veterinary and medical surveillance during large-scale domestic dog vaccination campaigns to evaluate their impacts on reducing human rabies. This system enables mass data collection, improved quality by rapid validation of records and therefore potential for adaptive management to reduce the impact of this infectious disease.

The primary objective of Chapter 2 is to evaluate the usability of this mobile phone-based surveillance system to determine the major obstacles to its widespread use and the potential ways in which such systems could be improved to facilitate uptake in the future. Quality and efficient healthcare delivery and vaccine distribution at both a national and regional level need to be guided by accurate and timely surveillance data. Some areas/populations need more attention than other regions where diseases are endemic. Reliable information could help policy makers to provide more appropriate levels of resources to such areas. The cost for mobile computing technologies may be offset by the cost savings from switching from traditional paper-based approaches, which are likely to be inaccurate and may not support timely detection and response to disease outbreaks. In Chapter 3, we assess the completeness, timeliness and costs of mobile phone versus paper-based surveillance systems for reporting infectious disease data.

An effective Integrated Surveillance and Response System could empower all the major stakeholders concerned with public health problems by providing them with appropriate real-time information on disease incidence. In Chapter 4, we use the system to gain a greater understanding of the dynamics of rabies across Southern Tanzania. We evaluate the public health impacts of rabies control measures, specifically focusing on dog vaccination campaigns and whether they affected animal bite injuries, which may reflect rabies incidence across the study area.

Integrated disease surveillance could extend the medium of mobile computing in a different context and has the potential to solve many of the problems with current surveillance infrastructure in developing countries. Non-attendance to clinics/hospitals and poor compliance with treatment regimens is a common problem in many countries, that results in higher incidence of preventable diseases and death [49]. We hypothesize that using short-text message (SMS) reminders for animal bite victims could result in significant improvements in compliance over the course of post-exposure vaccinations that are required to prevent rabies. In Chapter 5, we evaluate the effect of automated SMS reminders on patients' adherence to rabies post-exposure vaccination regimens.

In Chapter 6, we briefly summarize the results of the research and draw general conclusions about how mobile phone technology can be used most effectively to improve infectious disease surveillance systems. We share the challenges that arose whilst implementing the mobile phone based surveillance system in Southern Tanzania. We discuss the need for effective integration between human and animal surveillance, which has been repeatedly identified as key to successful surveillance for zoonoses. Overall we summarize the conclusions from applying and evaluating large-scale mobile phone-based surveillance in Southern Tanzania.

2 Design of a robust user-friendly mobile phone-based infectious disease surveillance system for resource-limited settings

2.1 Introduction

Policy makers and public health authorities need to be able to respond to infectious disease outbreaks. Epidemiological information collected through routine surveillance is therefore essential for effective disease control programs, but surveillance is typically very poor in developing countries [29,64]. Although technologies and models for surveillance systems exist, they are often not used in developing countries [44,63,131]. The reality is that many infectious disease surveillance systems were not designed with the user experience in the field (veterinary workers) or the clinic (health workers) as a priority. Many systems are either not easy to use, or do not address the challenges faced by users, and this has resulted in the target users not being incentivised to use the available systems [71,116,135]. Several studies have reported high levels of underreporting making the early detection of disease outbreaks very difficult [17,113,137]. As a consequence government authorities and stakeholders are not notified and cannot respond to outbreaks and emergency situations [8,29]. The overall outcome is that communities in developing countries are prone to uncontrolled transmission of infectious diseases.

In developing countries, most infectious disease surveillance systems use traditional paper-based methods [29,99]. These surveillance systems are generally centralized and controlled by ministries of health, with data typically collected by surveillance units and transported to central units for processing. Information needs to be collected from all the places where the surveillance is operating. This information then needs to be reported to a central system where it is readily accessible by government officials, and local and international stakeholders who are responsible for disease control. The scale at which surveillance systems are implemented may vary from a small well-defined geographical area to the global community. Data validation and dynamic changes or updates are required for all users operating the system, which necessitates enormous time and financial resources [71,74,116]. However, the traditional paper-based approach does not enable timely or regular data collection, which can often result in incomplete information and hinder prompt health interventions. Furthermore, this approach is not efficient or practical for remote areas; poor infrastructure compounded by weather make many areas in developing countries inaccessible during adverse conditions. Surveillance systems need to provide mechanisms for generating and sharing accurate and efficient routine reports, but paper-based surveillance lacks this capability.

Mobile phone subscriptions are rapidly growing in developing nations and continents worldwide. Africa has one of the fastest growth rates in voice, mobile Web and mobile commerce channels [70,114]. Compared to computers and Internet infrastructure, mobile phones have shown the strongest growth rate in resource-limited settings, due to their cheap availability and ease of use [87]. It is exactly this ease of use, network coverage and affordability that gives this technology the potential to improve infectious disease surveillance systems. Mobile phone technology offers the advantage of immediate data transmission and processing to enhance timely outbreak detection and responses [135].

Despite mobile phone-based systems being enormously promising for improving health systems, they have not yet been extensively used for disease surveillance in developing countries. In Tanzania for instance, authorities have massively invested in implementing computer-based disease surveillance systems, but numerous studies have reported difficulties due to poor digital infrastructure among primary healthcare facilities, which are the main sources of data for health surveillance [66,74]. These initiatives have suffered from unreliable power and Internet connections, particularly in rural and remote settings [116]. Moreover, there is a lack of competence in information technology, including the limited availability of software engineers and technical experts to advise policy makers on appropriate use of current technology within local and national government organizations [74].

Despite the ongoing increase in mobile phone-based applications in public health activities, few mobile phone-based systems have been fully explored or exploited [46]. Most currently available mobile phone applications rely on expensive smartphones, which are not yet widely available in resource-poor settings. In addition, large numbers of these systems lack the ability to adapt to local environments that include language specifications, varying education levels and digital technology literacy. Although, guidelines for the evaluation of surveillance systems are available, they have rarely been adopted in full [64]. The few evaluations of surveillance systems that have been made focused on laboratory capacity and technical epidemiological training, with relatively little attention given to the routine end users [65,109]. Haliday et al. [45] argue there is a need to design systems that make better use of the mobile phone technologies that are already widely distributed, thereby enabling rapid practical application. To improve the design quality and to meet user requirements, there is a need for user evaluation before implementing mobile surveillance systems that suffer from many of the same challenges as paper-based systems [114].

In this chapter, we discuss the practicality and user-friendliness of a nearly real-time mobile phone-based surveillance system. The system has been implemented as a case study integrating human and animal surveillance to monitor a large-scale rabies control program conducted in twenty-eight districts in Southern Tanzania. The primary objective of this chapter is to evaluate the usability of this mobile phone-based surveillance system to determine the major obstacles to its widespread use and the potential ways in which such systems could be improved to facilitate future uptake. We define usability as public health and veterinary workers' ability to collect and share data on disease incidence and control interventions effectively and efficiently and in a way that is both satisfying and incentivising. Additionally, we provide recommendations for the future development and application of mobile phone-based surveillance systems and, more generally, the use of mobile phone-based tools in health systems in developing countries.

2.2 Methods

2.2.1 Study area

The mobile phone-based surveillance system was implemented in southern Tanzania. The area consisted of seven regions and encompassed twenty-eight districts: four districts from Pemba Island and twenty-four districts from the mainland with communities in both rural and urban areas. Primary healthcare and veterinary facilities were the target units for this surveillance system (Figure 2.1).

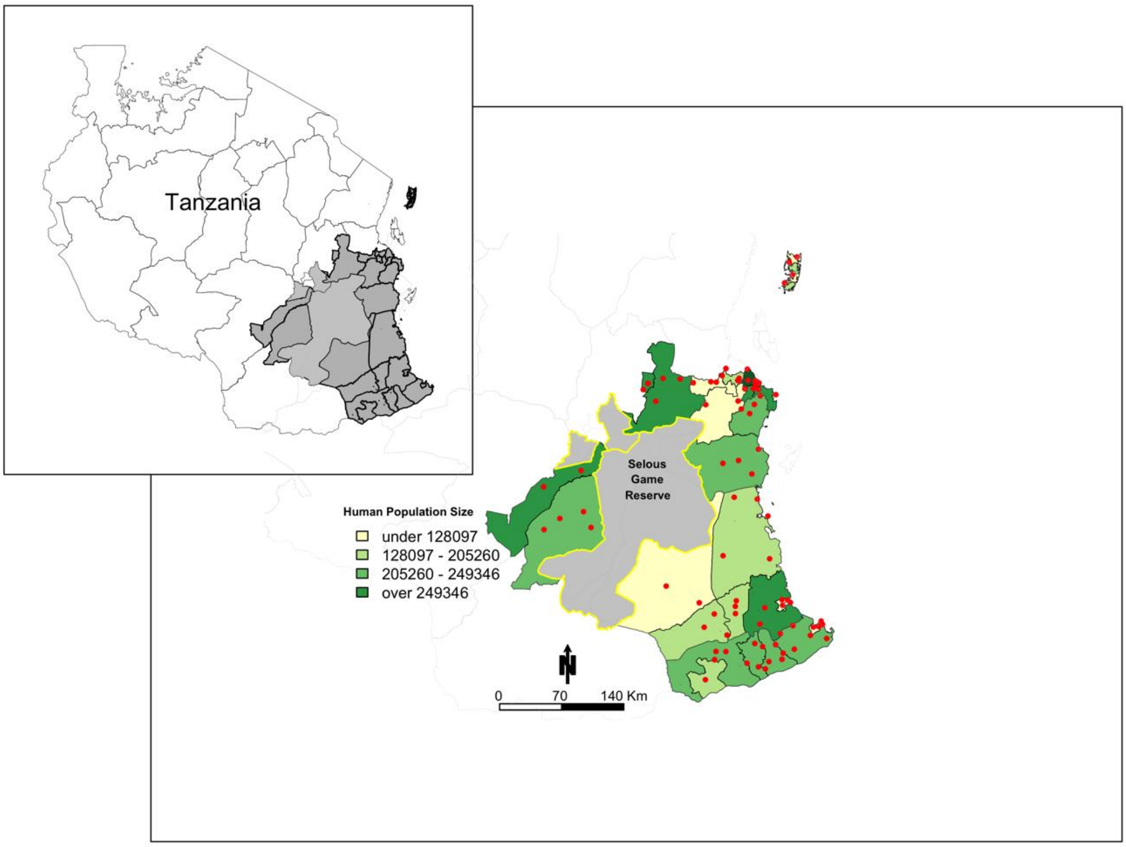


Figure 2.1. Map of Tanzania showing the study area where the mobile phone surveillance system is operating. Red dots represent health facilities that report directly to the surveillance system. The grey areas are protected areas: Mikumi National Park and Selous Game Reserve.

2.2.2 The design process

A focus group was formed to discuss issues associated with paper-based surveillance systems. These included poor reporting of outbreaks and the lack of ability to provide local and national authorities with up-to-date information from a large catchment area. The focus group included representatives from the: Ministry of Health and Social Welfare (MOHSW), Ministry of Livestock and Fisheries Development (MOLFD), WHO rabies control programme and other stakeholders in the public health sector such as health research institutions and universities. The focus group agreed to establish a reliable rabies surveillance system that could replicate and potentially replace traditional paper-based surveillance systems in Tanzania to enhance the ongoing monitoring of infectious diseases.

Mobile phones were used as the end user tool for the surveillance system instead of desktop computers, which would have required well-established infrastructure including Internet connections. We considered the ability to easily and cheaply replace system components, and mobile phones were the only option that satisfied the needs of the system compared to computer clients. Since users in rural and remote areas already had access to mobile phones (Figure 2.2), we investigated the use of mobile phones as a possible replacement to traditional paper-based surveillance systems. Moreover, the use of mobile phones for a disease surveillance system is an extension of previous studies conducted in Tanzania to address problems associated with monitoring a malaria control program in Dar es Salaam [105].

It should be noted the design process for rabies mobile phone-based surveillance have incorporated all the challenges that we encountered during the implementation of a dynamic arching system for tracking mosquito data, which was my MSc project [105]. The dynamic arching system described the development of a generic schema and database for collecting and managing ecological mosquito data. A web-driven database was developed using PHP scripting language; MySQL database and Java scripting languages were used. The use of a generic schema ensures that all essential information is collected by the researcher and also provides for controlled vocabulary and coding. The database allows the scientist to select which scientific observations will be recorded (e.g. household mosquito collections, ovary dissections, or CSP ELISA) and provides the template for data entry. Adapting the generic schema and database could have potentially benefited from automated data integration improve the quality of data archives, data validation, time management and provision for structural metadata. Because the database was web-based, it could have allowed researchers to share and monitor research projects from geographically remote locations. The archiving of samples and data could have allowed their use in future studies (i.e. new molecular analyses) or statistical analysis. Importantly, the database could have helped to drive entomology data synthesis and sharing across collaborative projects. The challenges encountered includes a lack of reliable computer infrastructure and Internet connections, therefore the use of computer-based clients and web-based systems were proved inefficient, particularly in resource-limited settings. However, the rabies mobile phone-based surveillance system seeks to improve and safeguard all the challenges that were encountered during the implementation of the malaria system.

Figure 2.2. A mobile phone network tower in a rural village of southern Tanzania within the catchment area of the surveillance system.

A mobile phone-based surveillance system was designed to use Global System for Mobile communication (GSM) and General Packet Radio Service (GPRS) network infrastructure, which is widely available commercially from mobile phone network providers in Tanzania. The coverage strength and quality of the GPRS network is largely determined by the proximity to a mobile phone network tower [30].

The surveillance system was designed to use three distinct components. First, the server-side is designed from a MySQL database responsible for storing different electronic forms for data collection, and authenticating the client-side (mobile phones) to store data collected through these devices. Second, the client-side consists of java-enabled phones with the ability to use the GPRS network to connect to the remote server. Third, the base transceiver station (BTS) is a network tower that facilitates the wireless communication between the client side (phones) and server side through the GPRS network. The client-side depends on the BTS to download and upload the data collection forms. In this study, we used Nokia phones for the clients due to their cheap availability in the study area and the reliability of their long life batteries (Figure 2.3).

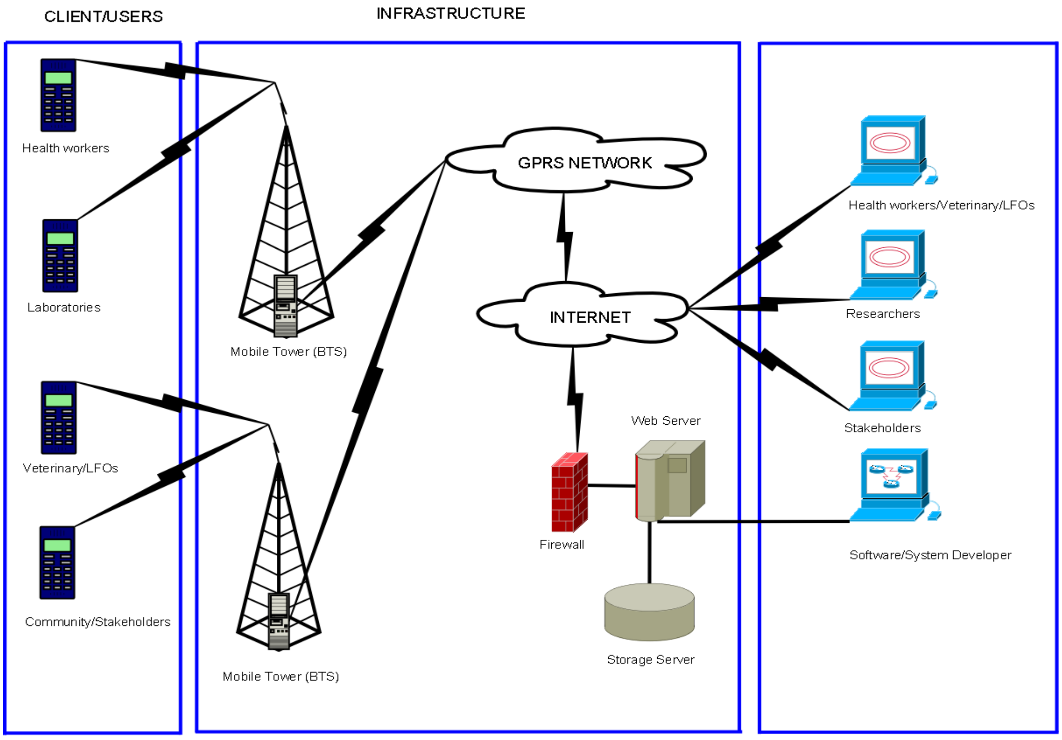


Figure 2.3. The system architecture for the mobile phone-based surveillance system as applied to rabies surveillance. Health workers and Livestock field officers (LFOs) from different locations used their mobile phones to connect to the system to download forms and upload data. Remote health facilities with no Internet access can immediately use this approach as well as areas that have good Internet connections.

2.2.3 System and user requirements

The system requirements were adapted from the focus group recommendations to build a system that would accommodate resource-limited settings. We considered the challenges posed by the lack of infrastructure and the educational background of potential users. The system needed to collect data for laboratory testing as well as from the clinic (patient records) and the field (vaccination campaigns, surveys and sample collection). The new system therefore had to collect the data required by the existing paper-based system being used by health workers, veterinarians and epidemiologists. It was important to ensure that all of the stakeholders from the focus group were satisfied with the data accuracy of the system and that the system enabled data sharing across sectors and among local and international stakeholders.

A formal definition of a sustainable surveillance system required by the limited-resource setting is a system that can accommodate unreliable power supplies with the poor Internet connections found in most developing countries, and enable users (clients) to work remotely to avoid travel on rough roads. The requirements also indicated that the sustainability, hardware (servers, phones) and software had to be easily and cheaply available. Open source software for the server's operating system and database were used to reduce costs and avoid licence expiration issues. To abide by Tanzania's ethical clearance for health information, outsourcing the servers to international companies was not allowed. The user requirements included accommodating different education levels, language barriers and user capabilities with mobile technology. The system was designed with the intention of not recruiting new (possibly more skilled) users, and needed to be accessible without extensive training. Users were generally based in rural areas with limited Internet access and had low digital technology literacy. The system therefore had to avoid the use of computers and Internet since many of the health and veterinary facilities had neither electricity nor Internet infrastructure.

2.2.4 System and user interfaces

Both system and user interfaces were designed to meet user requirements. User interfaces were designed to accommodate users with little knowledge or experience with digital technologies. From an early stage, when I decided to use mobile phones instead of computer-based clients, I sought to address the challenges discussed from the design process and requirement sections. Language barriers have obstructed the uptake of digital surveillance in resource-limited settings, particularly when some software solutions did not focus on the user experience. Hence, in this study language localization (specifically Swahili) was enabled to give users confidence while using these interfaces. Previous experience from a malaria management database designed to use a web-based interface highlighted the difficulties of poor and unreliable Internet, with users complaining that the system took more time than traditional paper-based database management [105]. Therefore, in this study network resources were given consideration as potentially limiting factors. Hence the use of the reliable mobile phone network infrastructure. Moreover, the mobile phone-based interface was designed to minimize resource consumption by avoiding unnecessary connections to the server-side, because frequent outages could cause delays and frustrate users. The application was only required to connect to the remote server for downloading and uploading data with both user authentication and data validation on the client side. The application was also designed to function independently of the server-side, allowing users to work offline and save data to the extended mobile device memory. These features were added to avoid the risk of unreliable reception that can be caused by towers being out of power or due to poor Internet connection on the server-side.

The electronic forms for data collection largely adopted the format of existing paper forms, but with more details added following discussions with stakeholders. The electronic forms were categorized into three groups. First, forms for use at clinics included those for animal bite injuries, human rabies suspect cases, and human post-exposure prophylaxis (PEP) stock control. The second group of forms was designed for veterinary use, including forms for an animal baseline census, animal vaccination campaigns, animal post-vaccination evaluations, animal vaccine stock management, and reporting suspect animal rabies cases and sample submissions. The third group was for laboratory use, including sample-processing forms designed to detail different tests in the laboratory and their results (Figure 2.4). To enhance the user interface, wherever we had long lists of answers such as list of districts or regions, drop down menus and dynamic selections were used to enable the user to narrow down the appropriate answers. To avoid users typing errors, radio buttons and pop-up menus for date data types were used. Moreover, to ensure accuracy these forms were designed with minimum questions by hiding unrelated questions after the user had answered the first questions. The forms did not ask for geographical reference as this information was recorded during the users' registration. Before the forms were used, pilot data collection to check if the forms and the system were functioning correctly was conducted. The pilot data was reviewed with the stakeholders for quality assurance and to evaluate if the system was capable of delivering the required information.

(a)

(b)

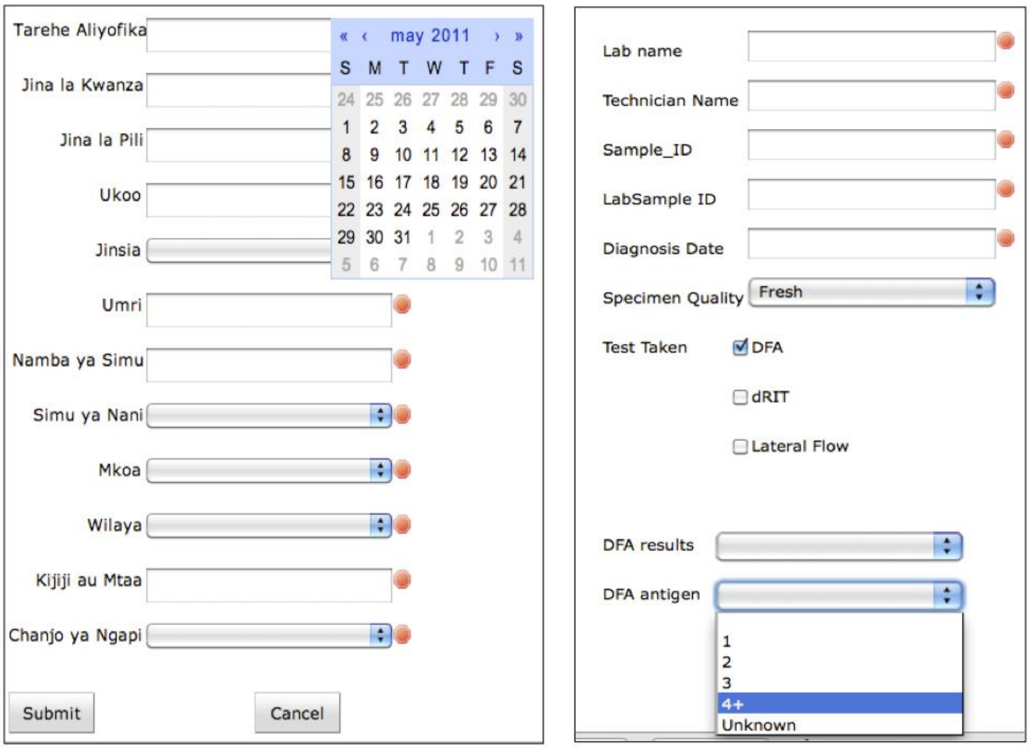


Figure 2.4. Typical example of a) paper-based versus b) mobile phone-based surveillance systems. Examples of paper forms and questionnaires used in Tanzania as well as some of the mobile phone-based electronic forms are shown.

2.2.5 User training

Before the new system was implemented, all users were trained. Training was intended to require minimal time, but still be effective, in order to allow users to carry on with their other activities. Users were informed two weeks before the training, with three users pre-selected from each health facility and five livestock field officers (LFOs) in each district. The training team included WHO Tanzania office personnel, MOHSW & MOLFD personnel responsible for introducing the team to the local authorities, district officers with responsibility for health or veterinary workers in his/her district and the surveillance system instructors. This team travelled from one district to another to train users at the four health facilities and the livestock office in each district for every district. The training goals were to train users to collect and submit data more quickly, accurately and efficiently than under the previous surveillance system.

Training materials were delivered by a “hands-on instructor” method, with users being assisted by the system instructors who demonstrated how the system works. Users were each given configured mobile phones, and were shown how to download the relevant electronic forms. Users were assisted whilst navigating throughout the system, and were shown all the system features such as system authentication using a dummy user name and password to login to the system, and how to download studies and forms for different purposes. Time spent training each user differed from ten minutes to a maximum of half an hour, as some users were already very familiar with mobile phones while others required more assistance.

During the training, each user was given a workbook lesson, which included a common task. Workbooks were designed to remind users how to: login into the system, download the forms, use the navigation tool and menus for digital forms and save and upload data. The system instructors helped users understand how to use the workbooks, which had illustrated diagrams showing the screen displays for users to familiarize themselves with the system. Lastly, each user was registered, with users required to provide their full name, address and contact information (personal phone number). Health facility registration included the health workers’ details and health facility information including a geo-reference (UTM coordinates), the facility name, address (region and district) and contact information (i.e. number of the phone configured to the system). Each health facility was given one mobile phone configured to the surveillance system with their username and password. Veterinary users were also registered with the same details except for the georeference, since their work was based in the field. Instead, veterinary workers were supplied with GPS devises and were asked to provide the geo-references for all events they reported to the system. Both health facility and veterinary client-sides (the mobile phones) were password secured to avoid non-users accessing the system and data or use of the device.

2.2.6 System and user evaluation

During the user training, after the users were trained and registered for the surveillance system, the instructors assisted users in doing pilot studies. Users were asked to download and use the electronic forms, while the instructors helped them whenever they encountered problems. As a part of this pilot, health workers from the human health sector were asked to fill in all the necessary information from patients and upload this dummy data. The same method was applied for the animal health and laboratory sectors. Thereafter, simple random selection of users from both sectors from twenty-eight districts for user questionnaires and focal observations were used to evaluate the user experience. At least one user from every district except from the urban districts was selected from the human health sector for user questionnaire and focal observation (n=39). In our study area, urban districts had more human population than rural districts (figure 2.1), therefore we chose to have more representatives in urban areas. However, urban clinics have more animal bite injuries reported; in chapter four we will look into more details of this factor. On the other hand, one user per district to represent the veterinary health sector was selected for user questionnaires and focal observation (n=28). Through questionnaires, users were asked to express their personal opinion about the system as a subjective measure. The following information about users was also recorded: gender, education level, sight problems (for example, if they wear glasses) and digital technology literacy such as whether users had mobile phones, computers, computer certificates, or Internet facilities, and the average number of texts they send per day as well as how much time they spend on their mobile phones. A focal observation was conducted, by giving users different tasks according to their tasks on the system such as attending to an animal bite injury victim. System user interactions were recorded from the time when users started to login into the system until they finished logging out. Events when users became stuck and needed prompting from the instructors were also recorded. Time spent on each task, the number of errors, successful task completion, and time taken to accomplish each task for individual users were recorded.

Later, system helpline logs were established to measure the frequency with which users sought help. The surveillance system helpline was provided through calls and texts by users to centralized personnel who detailed the issues that users encountered. Whenever users made a call or text to the facility, all of the information was recorded. Thereafter, both health workers and LFOs were evaluated based on their data collection. Follow-up visits were made to users who had appeared to be inactive to insist that reporting of all events was carried out on a real-time basis. Data collected from the helpline logs and data submitted to the server for reported events were analysed to evaluate different aspects of the surveillance system including how users interacted with the system. The system administrators were reminded to continuously monitor user activities and check for suspicious activities such as users who appeared not to be actively sending data or sending duplicate data (Table 2.1). If any suspicious or logical errors were found, follow up with the users who submitted these records was carried out to clarify the error.

Table 2.1. Summary of activities that were carried out during the implementation of the mobile phone based surveillance system. We detail the number of questionnaires conducted per sector, the number of timed observations of users, the number of data forms submitted by users in each sector and the number of times users accessed the helpline.

Sectors	Activities	Quantity
Human health	Questionnaires completed	39
	Timed observations	39
	Helpline accessed	216
	Data forms submitted	6139
	Users trained	336
Animal health	Questionnaires completed	28
	Timed observations	28
	Helpline accessed	129
	Data forms submitted	7078
	Users trained	140
Animal laboratory	Helpline accessed	1
	Data forms submitted	64
	Users trained	6

2.3 Analysis

Generalized linear models (GLM) were constructed to identify variables that explained variations in user performance in completing different tasks on the use of mobile phone-based surveillance systems. Two GLMs were carried out to explore user performance, one with users' error proneness as the response variable (or accuracy) and a second one with the time taken to complete tasks as the response variable (efficiency).

Different variables were hypothesized to be potentially limiting the widespread use of mobile phone-based surveillance systems. The explanatory variables were broadly classified into: digital literacy (age and education level, Table 2.1) and digital technology access (computer ownership, Internet access, phone ownership, SMS use, email use, Table 2.2). Prior to inclusion in the model, continuous variables were examined for collinearity using Pearson's correlation coefficient. All the explanatory variables were evaluated through the likelihood ratio test. Explanatory variables were eliminated using a backward stepwise elimination procedure until the simplest nested model was reached. The model was checked by examining residual plots. The analysis was carried out using the R software environment for statistical computing [112].

Table 2.2. Response and explanatory variables that were used to explore the factors that hinder the widespread use of digital technologies for disease surveillance in resource-limited settings. A poisson error structure was used in the models as the response variables were integers.

Type	Variable	Variable description	Data type
Response	Accuracy	Errors by user while completing task	Integer
	Efficiency	Minutes spent by user to accomplish task	Integer
Explanatory	Computer	User possession of computer	Binary (Y/N)
	Phone	User possession of mobile phone	Binary (Y/N)
	SMS access	Number of SMS sent or received daily	Integer
	Age	User age (y): <30, 31-40, 41-50, 51-60	Categorical
	Education	User education: primary, secondary, higher	Categorical
	Vision	Whether user requires glasses	Binary (Y/N)
	Computer ownership	Months of computer ownership	Integer
	Phone ownership	Months of phone ownership	Integer
	Internet access	Availability of internet infrastructure	Binary (Y/N)
	Phone reception	Availability of mobile network	Binary (Y/N)
	Email use	Whether emails sent or received: daily, weekly, monthly, yearly or never.	Categorical

2.4 Results

Between May 2011 and July 2012, a total of 482 individuals, both from the human and animal health sectors, were registered to use the mobile phone-based surveillance system. A total of 13,281 data forms were submitted from both sectors (Table 2.1). Over 40% of the data forms were submitted into the system from health facilities reporting animal-bite injuries and PEP stocks, while others are as characterized in Table 2.1. Sixty-seven questionnaires were conducted among users, where animal health sector (N=28) and human health sector (N=39). In response to mobile phone or computer ownership, all of the users that were trained for this surveillance already owned mobile phones, whereas only 4% of all the users owned computers (Figure 2.5). In terms of supportive infrastructure to access digital technologies, less than 29% of the users had access to computers, while all users had adequate mobile phone reception. Furthermore, ninety-four percent of users already sent and received SMS on a daily basis, while only 29% ever sent or received emails (Figure 2.5).

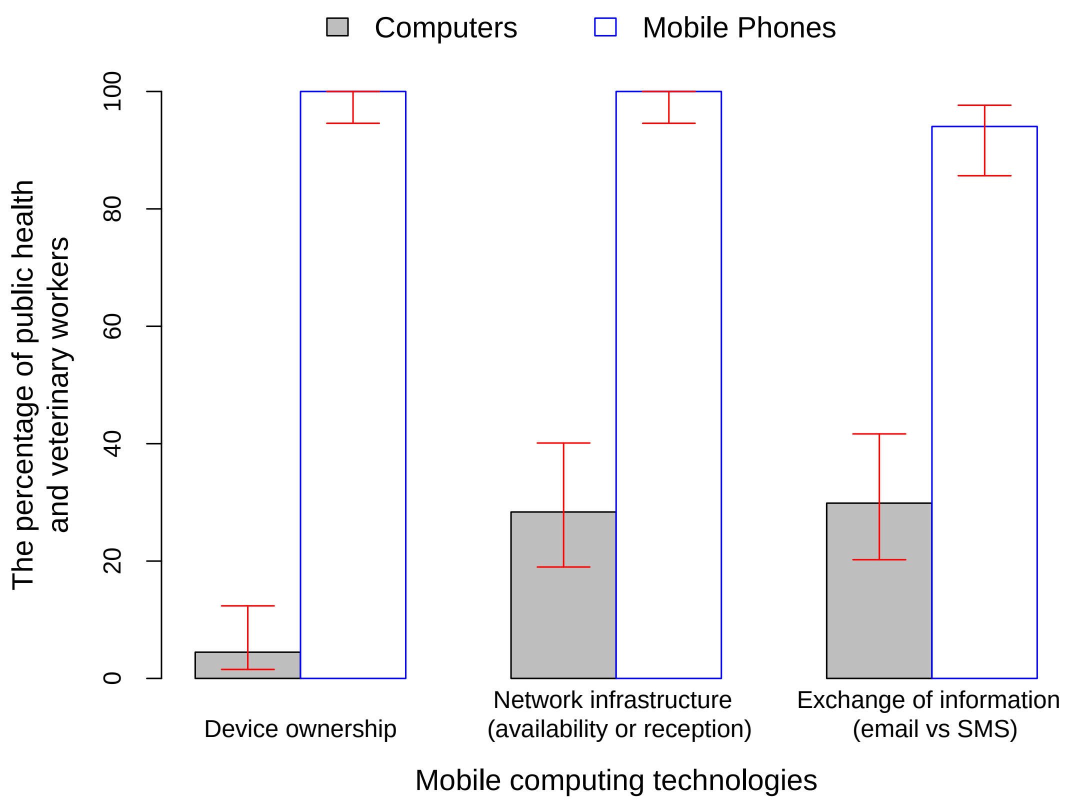


Figure 2.5. Digital technology devices ownership, the availability of digital infrastructure and ways of exchanging information among users through mobile phone versus computers in southern Tanzania. The 67 respondents comprised 28 animal health and 39 health workers.

2.4.1 Factors affecting the usability of mobile phones as surveillance tools

User-related factors that affect the usability of mobile phone devices as surveillance tools in health information systems are described in Table 2.3 and Figure 2.7. There was a significant relationship between users' accuracy and digital technology experience as well as digital literacy (Table 2.3). Users who had more time of device ownership, particularly mobile phones, had fewer errors in event reporting to the surveillance system compared to those who had less time of device ownership (Figure 2.6a). A number of variables were found to have significant effects on users' accuracy in reporting events to the surveillance system where users' number of errors is used as a response variable to measure users' accuracy and these effects were tested statistically significant for: mobile phone time of ownership ($p = 0.031$, Figure 2.6a), SMS access ($p = 0.018$, Figure 2.6b). In the final model, users' age groups were not tested with statistical significant effect, although this variable was tested as statistically significant for inclusion during the model selection (Figure 2.6c). Our analyses show a statistically significant relationship between users' efficiency and users' digital experience with an interaction between education level and users' age group ($p < 0.001$, Figure 2.6d). In a user experience measure, time of own mobile phones had effects with the users' efficiency in reporting to the surveillance system, where users who had owned a mobile phone for longer reported more quickly to the surveillance system. A similar interaction was found between users' age group and education level. Users aged between 20 and 50 years with higher than primary education were more efficient in reporting surveillance events; this grouping represents 87% of all users in our study.

Table 2.3. Explanatory variables that had statistically significant effects on the efficiency and accuracy of data reporting by users of the mobile phone-based surveillance system

Response	Explanatory variables	Coefficient	Standard Error	z-value	p-value
Accuracy	Mobile phone ownership	- 0.087	0.0402	-2.163	0.031*
	SMS access	- 0.046	0.0197	-2.357	0.018*
	Age (<30y)	Reference	-	-	-
	Age (31-40y)	- 0.743	0.4017	-0.343	0.664
	Age (41-50y)	0.545	0.3473	1.571	0.116
	Age (51-60y)	0.388	0.392	0.993	0.321
Efficiency	Mobile phone ownership	- 0.058	0.2123	-3.610	<0.001**
	Education (Higher)	Reference	-	-	-
	Education (Secondary)	0.182	0.212	0.858	0.391
	Education (Primary)	0.217	0.218	0.997	0.319
	Age (<30y)	Reference	-	-	-
	Age (31-40y)	<0.001	0.223	0.004	0.997
	Age (41-50y)	0.616	0.167	3.680	<0.001**
	Age (51-60y)	0.4281	0.217	1.971	0.048*
	Age (<30y) | Education (higher)	Reference	-	-	-
	Age (31-40y) | Education (Secondary)	0.283	0.294	0.964	0.335
	Age (31-40y) | Education (Primary)	0.295	0.378	0.779	0.436
	Age (41-50y) | Education (Secondary)	-0.621	0.304	-2.041	0.041*
	Age (41-50y) | Education (Primary)	- 0.379	0.239	-1.586	0.113
	Age (51-60y) | Education (Secondary)	0.153	0.314	0.487	0.626

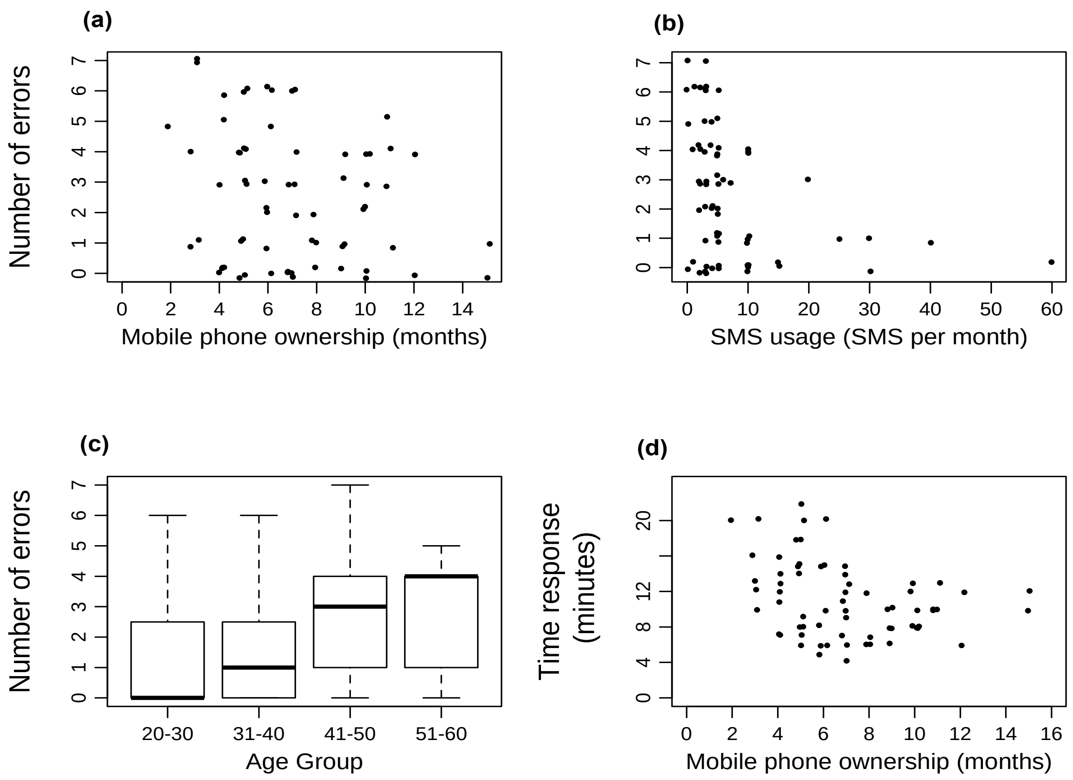


Figure 2.6. Factors affecting accuracy and efficiency in use of mobile phones as surveillance tools. Numbers of errors and time spent in completing data forms on mobile phones according to (a) duration of mobile phone ownership (b) Number of SMS usage (c) Users' different age-groups and (d) Duration of mobile phone ownership and time taken by the users to accomplish tasks.

2.4.2 System evaluation (success/failure) of reporting of infectious disease data

The variation in helpline access through time revealed that users were more likely to seek help shortly after training (Figure 2.7). Thereafter, helpline access decreased. In most cases, this behaviour ofusers seeking help on data submission shows gradual increases with the number of events that were reported to the surveillance system (Figure 2.7). Users had difficulties using the forms that were less frequently used in the surveillance system, and were more efficient in filling out forms that were frequently used to report activities (Figure 2.8). In general, users did not have problems in using the surveillance system to perform multiple tasks, the average error rate for completing the different tasks being 2.25 (range 0.08 – 6.69 based on 18,300 data forms that were submitted into the surveillance system) (Figure- 2.8). For all tasks, there was individual variation in accuracy, efficiency of user time spent on the task, and the number of instances users accessed the helpline in order to submit data (Figure 2.8). Users from the human health sector (health workers) had substantial delays in reporting events from the day when the patients presented to the clinic.

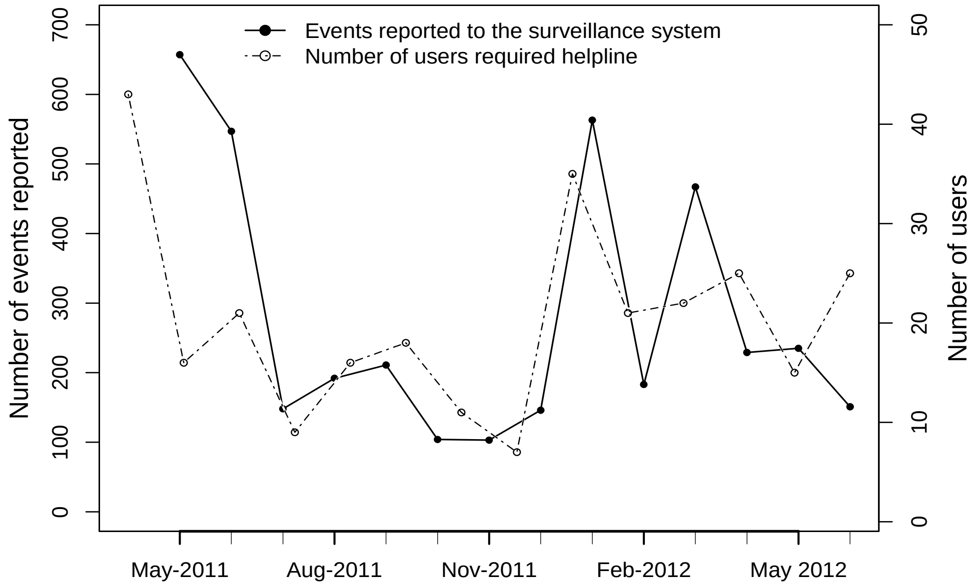


Figure 2.7. The number of events that were reported each month on the surveillance system, and the amount of assistance that was required by the users. Users who had problems were assisted with data submission through the helpline facility.

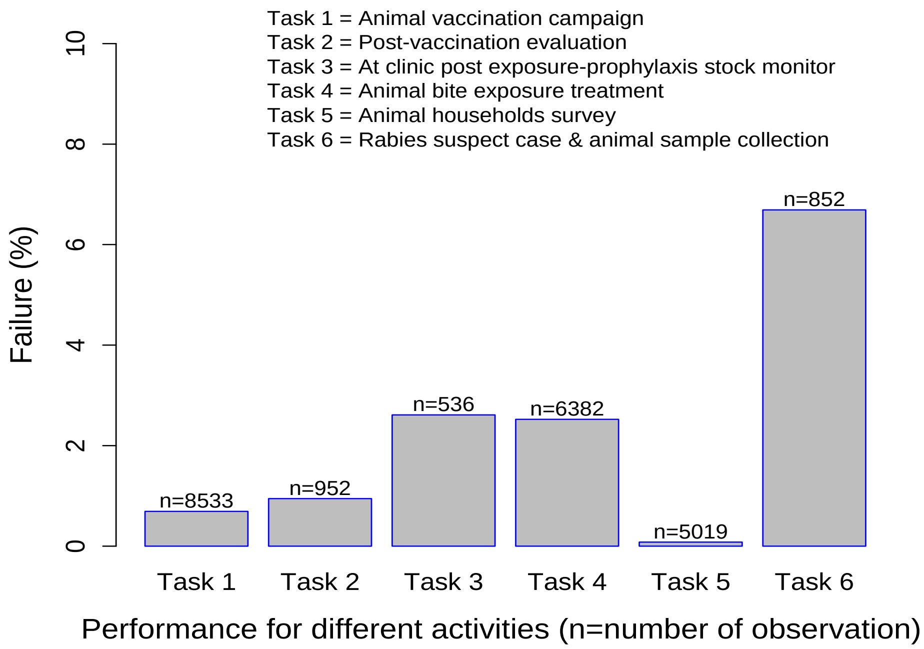


Figure 2.8. The number of tasks that were reported in the surveillance system as successfully completed based on 18,300 data forms submitted in the surveillance system as distributed in different tasks (n) and percentage failure on the first attempt to submit data and required helpline access per task to accomplish successful entry into surveillance system.

2.5 Discussion

In this chapter, we examined different factors that affected the usability of a mobile phone-based surveillance system to determine the major obstacles for digital disease surveillance systems in Tanzania. We analysed these constraints and looked for potential ways to strengthen infectious disease surveillance systems in resource-limited settings. The results presented in this study indicate that usability of mobile phone devices as surveillance tools in health information systems, particularly in resource-limited settings, is largely affected by the users' digital experience through digital literacy and ownership.

The analyses show that there was more ownership of mobile phone devices compared to computers (Figure 2.6a). Moreover, users who had better access were less likely to make errors and took less time to submit data to the surveillance system. Therefore, this result highlights the potential bridge that exists to reduce underreporting of infectious diseases in resource-limited settings. Similarly, the results highlight the key aspects of digital device ownership that could be targeted to improve infectious disease surveillance systems. For instance, in this study 100% of users had mobile phones while only 4.48% had owned a computer. These results suggest that despite the limitations and challenges of digital infrastructure, such as those required by computers and the Internet, systems based on mobile phones are more likely to be well received in limited resource settings, particularly in rural areas. Thus, the mobile phone-based system appears to be the best potential alternative for a digital disease surveillance system to eliminate the high rate of underreporting in many resource-limited settings.

We examined the use of digital technology for a disease surveillance system. In Tanzania for instance, despite the initiatives made to establish computer and Internet-based surveillance systems, many of these systems have suffered challenges including lack of computational skills to support and to administer them [116]. Our results showed that users who had experience using mobile phones for SMS were more literate and accurate when using the mobile phone-based surveillance system (Figure 2.6b). The analysis implied that the majority of surveillance system users had more experience in using mobile phones than computers. User experience and familiarity with mobile phones needs to be targeted to strengthen health information systems in resource-limited settings. As suggested by the growth in device ownership and availability, this finding may be an effective solution for digital divides that exist for health surveillance systems in many developing countries [34] due to poverty and lack of supportive infrastructure.

Analysis revealed that neither user education level or computer ownership had any effect on users' accuracy in using the mobile phone based surveillance system. Thus, an added advantage for mobile phone-based surveillance systems is that they can be used more widely and with less training since a lower level of skill and less cost is required than computers and Internet based systems [70]. Previous studies by Mghamba et al. (2004) and Kimaro et al. (2005) both highlighted the challenges to computerizing health information systems in Tanzania, where lack of adequate staffing with computer and information technology skills to support the system were mentioned as hindrances that limit the uptake of digital surveillance systems [66,74]. However, our analyses have shown the efficiency of a digital surveillance system is much determined by the combination of user education level and users' age group.

Our results have revealed that appropriate training and follow-up appeared to positively affect the system's usability. The analysis highlights that users' age and education level had an interactive effect on efficient use of the surveillance system; users who had at least a secondary school education and age of less than fifty years were more efficient than the other combinations of less education and higher age. Although different age groups were significant during the variable evaluation, age group did not appear to be statistically significant in the final model for accuracy. These findings imply that this technology can accommodate the conditions that exist in many developing countries and that technology that requires relatively little skill to operate is an incentive for many users [10,34,88,109].

Similarly, many users proved to be accurate while using the mobile phone-based surveillance system, but there was variation in the time spent submitting data into the surveillance system. We have identified users from the human health sector that had substantial delays in reporting events from the day when the patients presented to the clinic. Unlike veterinary workers, who report occasional, scheduled events such as animal household surveys or vaccination campaigns, which were planned for particular dates or times, health workers reported unscheduled events such as animal bite-injuries, which needed to be reported when patients presented to the clinic. The delays in health workers reporting the patients' data are likely to be caused by several reasons including: network problems which are likely to be caused by unreliable power to mobile towers (minor), loss of project phones in some health facilities were reported (few); lack of time to report on time due to workload in the facility (major) and some health facilities reported that trained workers were transferred to other working stations (few). However, the detection of variation in efficiency of reporting can be used to improve system design by targeting more user-friendly design, comparable to the findings by Loo et al. (2012) [88].

In the user and system evaluation, we expected that more users would require help soon after the surveillance system was implemented and less often as they spent more time using the system. We found that users accessed the helpline facility more frequently after the initial training. However, access behaviour also cycled with time since the last training and with the amount of data that was submitted into the surveillance system (Figure 2.7). These patterns can be explained by the type of activities that users were supposed to report as we did not find users had difficulties with the activities that they reported frequently. Many of these users had problems caused by either forgetting how to use the phone to submit surveillance information or were new users who were trained by other users after the trained user had moved to another workstation.

Mobile phone devices as surveillance tools offer great potential for health information systems, particularly in resource-limited settings. Our research shows that users only need minimum education and experience to operate mobile phones compared to computers, which require skills and supportive infrastructure. The growth and wide use of mobile phones in most resource-limited settings have potential that can be applied to strengthen health information systems. The mobile phone-based surveillance that we have implemented in southern Tanzania demonstrates significant improvements in data collection that can be applied in other areas, and more generally for infectious disease surveillance. However, there is a need to explore major obstacles and knowledge gaps in resource-limited settings to intensify uptake of this potential tool in the future. As they are cheap, easy to use, and widely available, mobile phones are an excellent tool for public health authorities and policy makers to incorporate into disease surveillance systems.

3 Mobile phone- versus paper-based surveillance systems in Tanzania: a comparative study.

3.1 Introduction

Epidemiological surveillance systems for infectious diseases, particularly notifiable diseases, are essential for the public health sector. To date, no pathogens have been detected or predicted before their first appearance, although through effective surveillance strategies, new pathogens and origins have been noted [104]. Surveillance is defined as the on-going systematic collection, analysis, and interpretation of data, vital to plan, implement, and evaluate public health practices with timely dissemination of data to those who need to know [42,123]. The aim of infectious disease surveillance is to monitor and report disease occurrence and use the collected data to establish patterns of progression for future prediction and control to minimize the disease burden [58,130]. Authorities and professionals including research institutions and universities need effective and accurate surveillance systems that can integrate both human and animal health sectors to reduce the burden of endemic zoonoses [8]. Public health cannot progress without effective disease surveillance [67].

Recently, initiatives have been taken to restructure health information systems in many countries, although, their quality varies from one place to another and few include animal health sectors [104]. Unreliable surveillance systems that report only a small proportion of the actual burden of disease are most common in developing country settings, where infectious diseases are more of a problem [13,45]. In these areas, where people and animals interact on a day-to-day basis and live in close association, disease surveillance needs timely evaluation to ensure the early detection and response to emergence events [97]. Timeliness and completeness of reporting disease data are key indicators for the effectiveness of a disease surveillance system [63,136]. Early detection and reporting of infectious diseases are fundamental measures needed to initiate prevention measures and warnings before an epidemic occurs [13,40]. However, despite the existence of frameworks and flexible procedures that can be used to evaluate surveillance systems, only a very few studies have attempted to evaluate the performance of surveillance [45,63].

Adopting guidelines and practises for health surveillance into local areas is a particular challenge in resource limited-settings [66]. Governments and local authorities have much fewer resources to spend on prevention and control of infectious diseases in developing countries [2]. Limited budgets mean that priorities are targeted towards solving problems such as malaria, HIV and water borne diseases. Therefore, more general disease surveillance systems and practitioners involved in surveillance are often not prioritized and lack motivation [74]. In this context of poor and unreliable surveillance, whenever there is an outbreak of an infectious disease it is difficult to detect and share the relevant information within and across sectors [13]. Delays in detection resulting from using slow and inefficient surveillance systems can result in the rapid and uncontrolled transmission of infectious diseases and subsequent morbidity and mortality.

Lack of effective surveillance has lead to regions in Africa massively underreporting disease occurrence and to significant delays in the detection of infectious diseases compared to other regions such as the Americas and Europe [13]. Globally, the World Health Organization (WHO) has reported that there is a great improvement in health information systems that use Internet-based frameworks, which have resulted in more accurate and timely outbreak detection [36,46,58].

The growth of mobile phones in the developing world has presented an alternative approach for digital innovation that can be cost effective for disease surveillance systems. By 2010, in developing countries, mobile phone user rates were predicted to reach 68% compared to 21% Internet user rates[61]. In many remote and rural areas in developing countries, mobile phone companies have established global communications infrastructure that can be also used to strengthen disease surveillance and communication [62]. However, there are few studies that have looked into mobile phones as alternative tools and approaches that can be applied to empower disease surveillance systems [113]. Moreover, only a few studies evaluate the innovations that have been applied to surveillance systems to accommodate the challenges that exist in resource-limited settings [46,47,90].

In Southern Tanzania, we have established a mobile phone-based surveillance system for a rabies control program operating across twenty-eight administrative districts. The aim of this system was to improve the ease of access to and management of data, and lead to better ways of sharing of information among sectors, which is still a major challenge in most developing countries [66,80,90,116]. This study aims to compare the case detection capacity, data completeness, timeliness and costs of mobile phone-based surveillance and traditional paper-based surveillance.

3.2 Materials and Methods

3.2.1 Study area and data collection

We conducted a retrospective study of surveillance systems for recording animal-bite injuries, comparing traditional paper-based and mobile phone-based surveillance systems. The study area comprises of seven regions of southern Tanzania: Coast, Dar es Salaam, Lindi, Morogoro, Mtwara, North Pemba and South Pemba (Figure 3.1). The study area is located at the coast of the Indian Ocean, which is bordered by wildlife-protected areas to the west and north (Mikumi National Park and Selous Game reserve) and by Mozambique to the south. Data was collected from hospitals and clinics within the study area that provide PEP. These regions are inhabited by multi-ethnic, agro-pastoralist communities, and include both rural and urban settings.

CDC guidelines [40] for describing the operation of surveillance systems and for evaluating key performance attributes were adapted for the surveillance system comparison described in this chapter. Timeliness and completeness are defined as a key performance attributes that can be used to evaluate a public health surveillance system in terms of availability of information for control of a health-related event, including immediate control efforts, prevention of continued exposure, or program planning [27,40]. Timeliness can vary by disease, intended use of the data and system level [63]. In this chapter, data were compiled and compared from two surveillance systems, summarized in Table 1. These systems comprised traditional paper–based surveillance and a mobile phone-based surveillance system that I developed. Recorded variables that were used to compare the performance of the two systems include demographic information for all patients with animal bite injuries (age and gender), geographical location information (regions, district and village/street) and, lastly, details of the timing of events (date of exposure, date of clinic presentation and date that the surveillance information was reported) (Figure 3.2, Table 3.1).

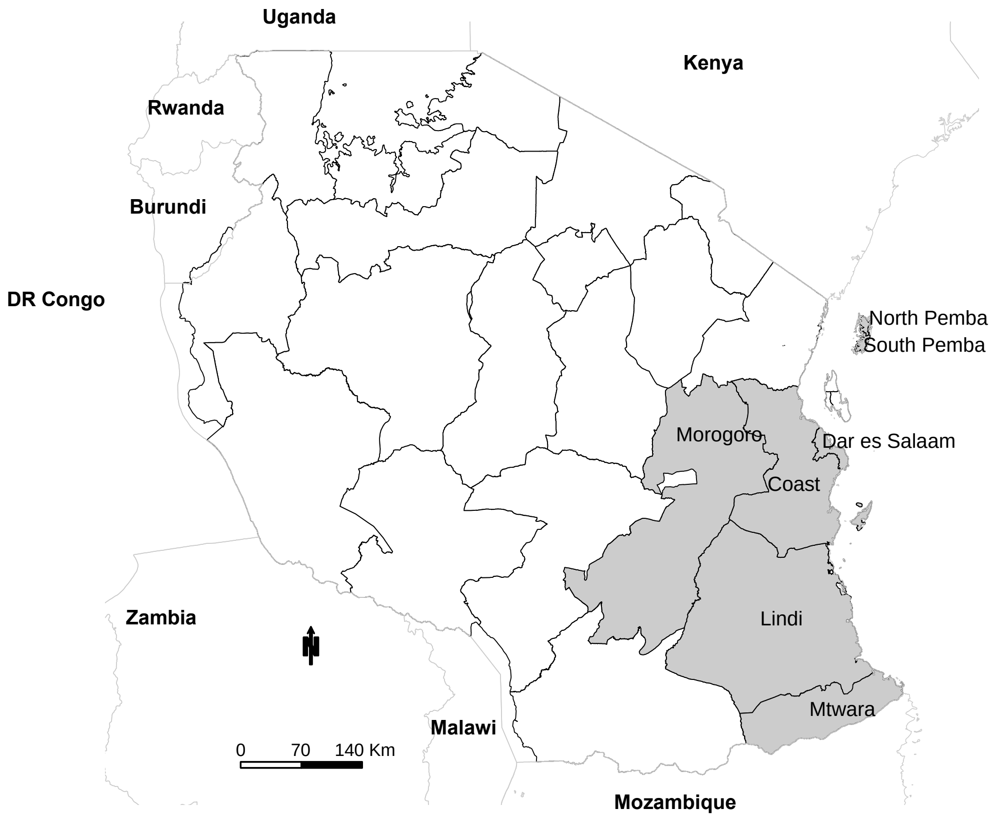


Figure 3.1. Map of Tanzania, the grey colour show seven regions of the study area where both mobile phone and paper–based surveillance systems operated to collect animal-bite injuries reported at primary healthcare facilities.

3.2.2 Surveillance system summaries

The structure and main features of the mobile phone-based and paper-based systems that are compared in this chapter are summarised in Table 3.1. The flowcharts given in Figure 3.2 illustrate the data collection and processing steps involved for the two systems.

Table 3.1. System summaries for both the traditional paper-based and mobile phone-based surveillance systems.

System components	Mobile phone-based	Traditional paper-based
Regions	Coast, Dar es Salaam, Lindi, Morogoro, Mtwara, North Pemba and South Pemba	
Period of data collection	June, 2011to January 2013. (N=20 months)	January 2005 to December 2010. (N=72 months)
Number of observations	Total of 3273 records	Total of 3620 records
Data sources	Four health facilities per districts, which provide PEP across the study area (Figure 1), more details can be found in Chapter 2.	
Data collection	Patient location: districts; villages for rural areas and street for urban areas Patient age (years) Date of exposure, day when the patients encounter animal-bite injury Date of clinic presentation, day when victim went to clinic or hospitals. Date of report, day when data on animal-bite injury were reported to the authorities.	
Data submission and management	Health workers (users) uploads animal-bite injuries data to the central server, therefore system administrators monitor user access and ensure timely follow-up of user activities and check for any suspicious or logical errors. Data validation is carried-out by rabies focal person and research scientists before these data are compiled for national surveillance (Figure 2), also see Chapter 2.	Paper-based records are collected from clinics and hospitals for the district medical officer then physically transported to Ministry of Health and Social Welfare (MoHSW) via regional offices. Data entry teams enter the collated paper data into a computer system and thereafter the data is compiled for national surveillance (Figure 2)
Data analysis and dissemination	Weekly data analysis is conducted and results are shared across all sectors and stakeholders through a website, which is password enabled (http://rabies.esurveillance.o.tz). SMS notification is used for timely dissemination of laboratory results (Figure 2).	Annual compilation of data at the MoHSW (Figure 2).

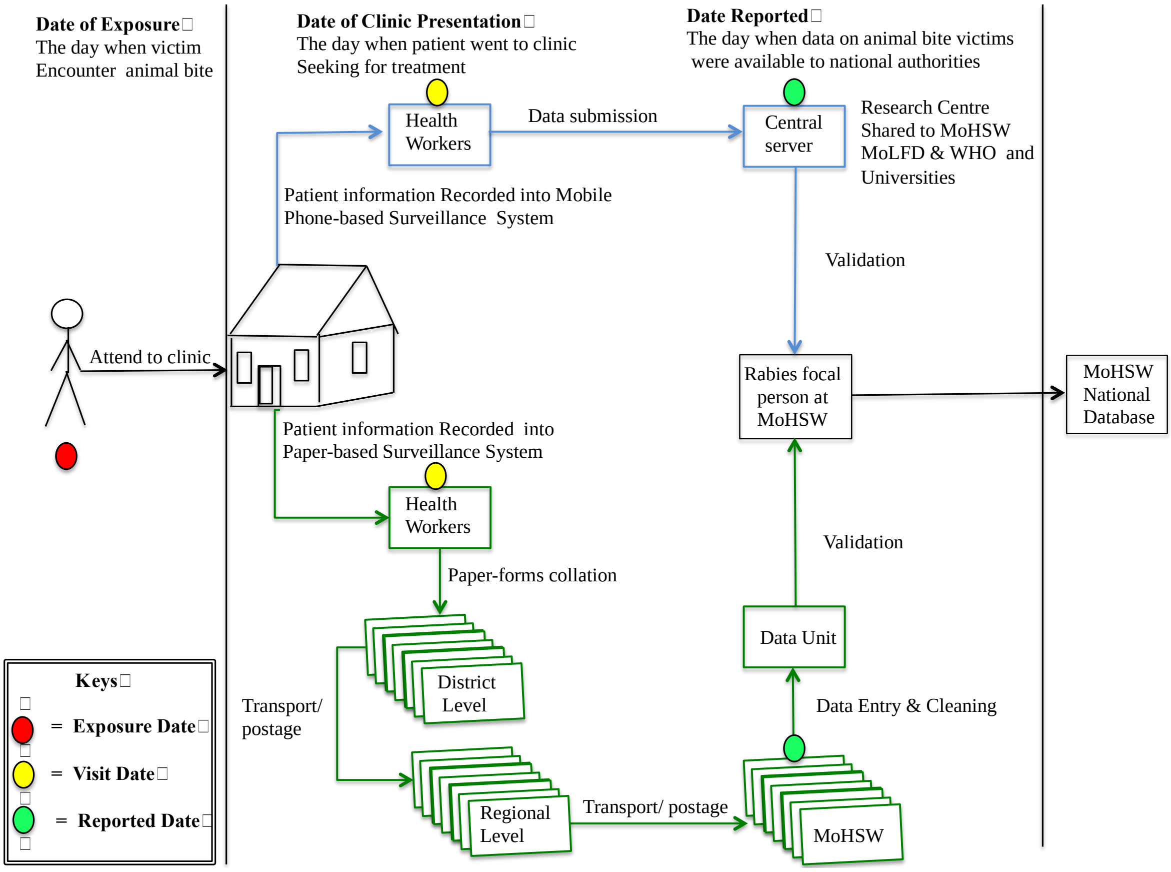


Figure 3.2. Description of typical data collection and reporting stages for both mobile phone-based and paper-based surveillance systems

3.2.3 Case detection capacity

We calculated the mean number of animal-bite injuries reported quarterly in each study region to examine the capacity of the two surveillance systems to detect and record dog bites that occurred in the study area. Data collected from January 2005 to December 2010 were summarised to calculate the quarterly bite numbers for the paper-based system and data from June 2011 to January 2012 were summarised for the mobile phone-based system. Case detection capacity was evaluated by comparing the number of cases detected per surveillance system used through time in the study area through. We summarized the number of cases detected quarterly (Table 3.2).

3.2.4 Data completeness

We evaluated the surveillance systems reporting data completeness by comparing patient's information recorded that was collected whilst attending clinics for PEP, such as demographic and geographical information (Table 3.1). Individual records were coded in order to calculate the percentage of missing values (NA) between 0 percent and 100 percent for both the surveillance systems.

3.2.5 Timeliness

We evaluated the surveillance system timeliness in reporting patient information by examining and comparing the time intervals between date of clinic presentation and reported date. These intervals were calculated to allow comparison of the speed of reporting across the different regions within the study area through the two systems (Figure 3.2). Timeliness refers to the time taken by the primary healthcare facilities to report the animal-bite injuries to the authorities, here described in figure 3.2 as the time between the date of clinic presentation and the date reported. Exposure date is defined as the date when animal-bite injury victim(s) encounter the animal-bite exposure, while we define visit date as the date when victim(s) attend the healthcare facilities seeking PEP. Reporting date is defined as the date when the data on animal bite-injuries were notified to the authorities.

Traditional paper-based surveillance normally reports summaries of numbers of events at the end of the week; later individual paper forms are collated and processed annually. Therefore, to establish a comparison of individual records reporting between the surveillance systems, we assigned an annual event date for the paper-based surveillance system as the date reported and for those events that were reported by the mobile phone surveillance, the date of reporting was used. The annual reporting date was assigned for the paper-based surveillance system with all the events that were recorded in a clinic on the same year assigned to the same reporting date corresponding to the end of the year. We assume all the events that were recorded at the hospitals and clinics since 2005–2010 were collected and processed annually [116].

3.2.6 System costs and Stakeholders' perceptions

To assess and compare the costs of the surveillance systems, we conducted stakeholder questionnaires to collect data on the costs and budgets that were used to build and run the surveillance systems. The questionnaires were designed for people who coordinate and supervise the public health surveillance activities including data collection for reports and planning disease control activities. The questionnaires were administered only for those stakeholders and sectors already using both paper-based and mobile phone-based surveillance systems. The questionnaires gathered key information such as the scales over which these surveillance systems were implemented (households, village/street, district and regions). Specifically we focused on: what was the surveillance unit per population, whether training of personnel was required for the surveillance and what supervision if any was necessary and how often it was provided, what was the size of the collected data/reports, how frequently data were collected and how data were collected and processed. Using the information from these questionnaires we aimed to gather an accurate picture of the annual costs of both paper and mobile phone based surveillance systems including capital costs, annual personnel costs, and annual running costs. We compiled these data and estimated the reported annual cost for each surveillance system. The cost was converted to US dollars values based on conversion at exchange rate of 1.00 USD = 1,638.62 TZS.

3.3 Results

3.3.1 Case detection capacity

In evaluating the capacity of the surveillance systems to detect animal-bite injuries, the mobile phone-based surveillance system had more reported animal bite injuries than those reported by the paper-based surveillance system (Table 3.1). Fewer cases were reported from January 2005 up to June 2006 and again during 2010 (Figure 3.2). Between June 2011 and January 2013, the mobile phone-based surveillance system was in operation and more animal bite injuries were reported, with the results characterized in Table 3.2 and Figure 3.3.

Table 3.2. Mean quarterly numbers of animal-bite injuries detected in each study region captured by the two surveillance systems. Numbers in brackets are the minimum and maximum number of bites reported quarterly. Data from January 2005 to December 2010 are included from the traditional paper-based surveillance system versus data from June 2011 to January 2013 for the mobile phone based surveillance system.

Regions	Tradition paper-based surveillance system	Mobile phone-based surveillance system
Coast	30 (0-107)	61 (39-90)
Dar es Salaam	22 (0-243)	125 (81-185)
Lindi	2 (0-21)	54 (36-84)
Morogoro	56 (0-187)	191 (146-230)
Mtwara	1(0-1)	79(25-85)
North Pemba	0	3 (0-6)
South Pemba	0	3 (0-6)

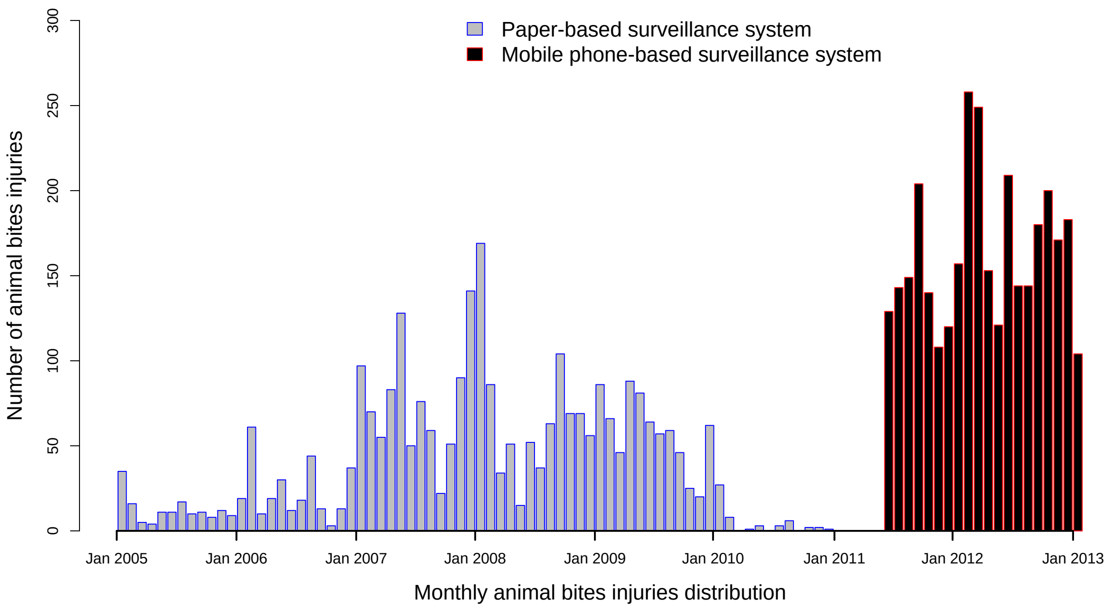


Figure 3.3. Numbers of animal bites injuries reported by paper-based versus mobile phone-based surveillance systems from Jan 2005-Jan 2010 and June 2011-Jan 2013 respectively. These timeseries illustrate inconsistencies of reporting by the two systems. Fewer injuries were reported by paper-based surveillance, compared to those reported by the mobile phone based surveillance.

3.3.2 Data completeness

A total of 3,620 and 3,273 individual records of animal-bite injuries were collected between January 2005 and December 2010 for the paper-based surveillance system, and between June 2011 and January 2013 for the mobile surveillance system and were included in this analysis. The traditional paper-based surveillance system reported less patient information compared to the mobile phone-based surveillance system. The reporting completeness of the traditional paper-based surveillance system ranged from 70% to 96%, (n = 3620) compared to the mobile phone surveillance (97% to 100%, n = 3314) (Figure 3.4). The worst reporting completeness was identified in the following variables: age, gender, location, date of exposure and date of clinic presentation (Figure 3.4).

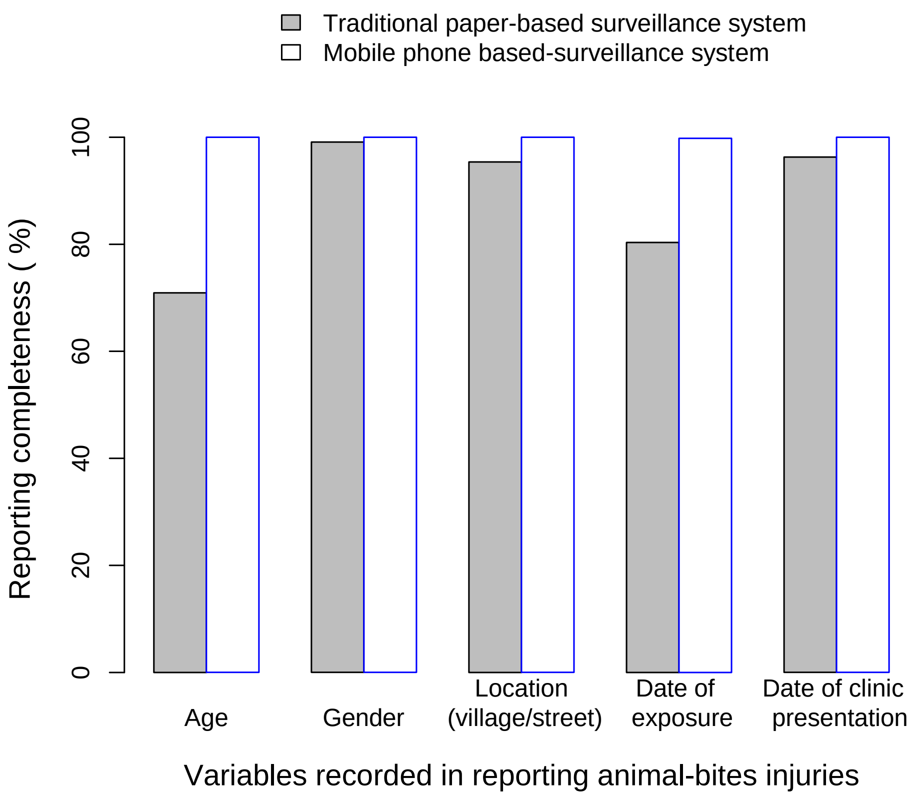


Figure 3.4. Comparison of data completeness for animal-bite injuries recorded through the mobile phone-based and traditional paper-based surveillance systems. The completeness of individual variables (patient's age, gender, location, exposure date and date of clinic presentation) were summarised (% missing values) to measure the data completeness of the two systems.

3.3.3 Timeliness

The majority of data collected through the mobile phone-based surveillance system were reported to the authorities within a month of patients presenting to primary healthcare facilities. Our analysis revealed a significant difference in reporting of animal bite injuries between the two surveillance system; 61% of injuries (n=2010) were reported the same month that the events occurred through mobile phone-based surveillance, while was only 14% (n=499) were reported on the same month when paper based surveillance was used (Figure 3.5a). For the paper-based surveillance, data were annually collated at districts and regional offices and later processed at MoHSW (Figure 3.5b) and this is reflected in the longer intervals between the date of patient clinic visits and data reporting as compared to the mobile-based system.

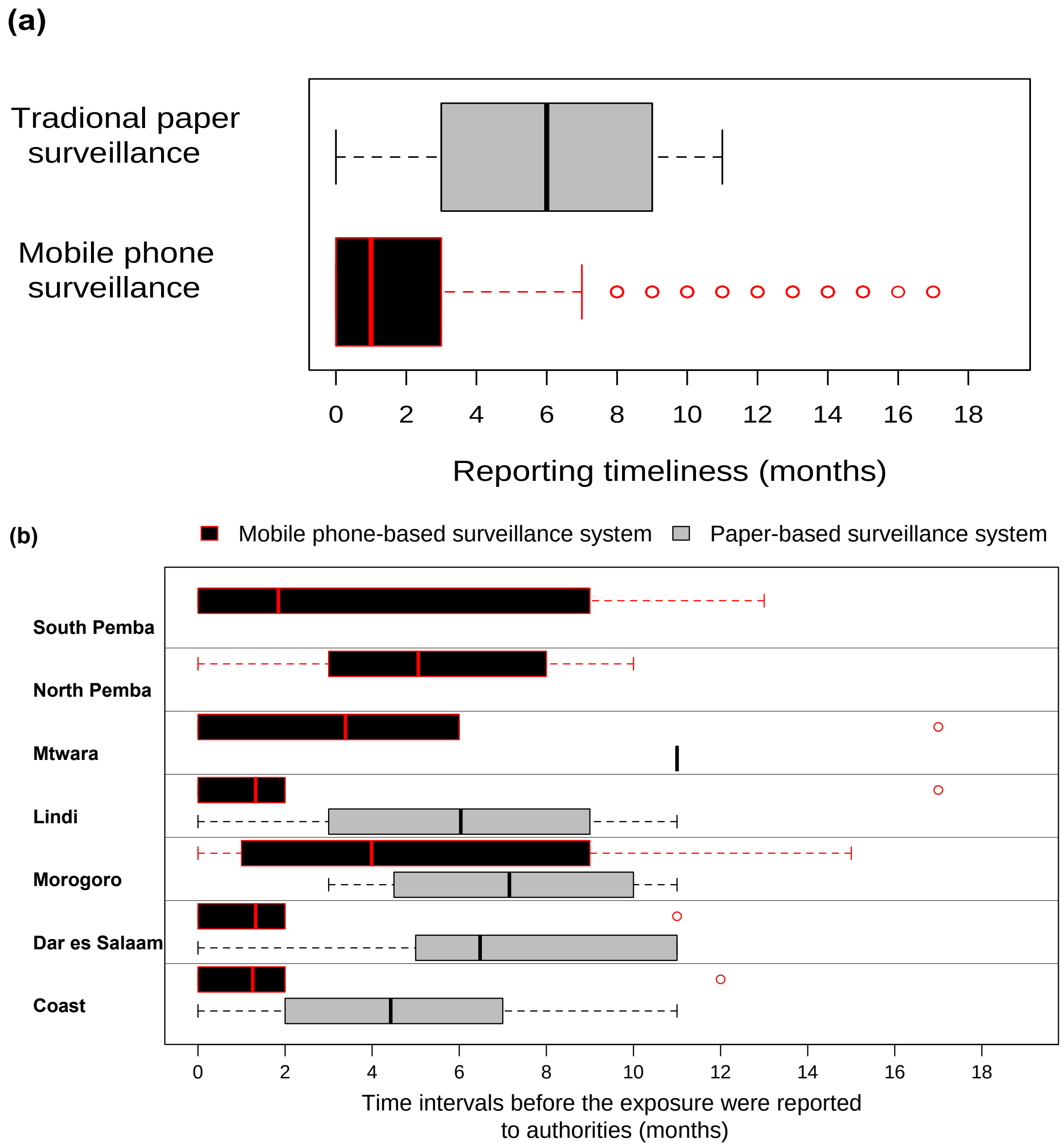


Figure 3.5. The summary of the time intervals between clinic visits and reporting of animal-bite injuries from primary healthcare facilities to the authorities from the surveillance systems. (a) Timeliness, the intervals extracted from patient's date of clinic presentation and date when these events were reported to the authorities (reported date). (b) Data are summarised to show the intervals for each region within the study area using both the surveillance systems. The whisker box shows the minimum interval in delays, the 1st quartile, the median, the 3rd quartile and maximum delays in intervals before the events were reported to the authorities. There were no data collected by paper based surveillance for Mtwara and Pemba regions.

3.3.4 Surveillance costs

According to the qualitative analysis, capital and personnel costs to establish a paper-based surveillance system were less than those required by the mobile phone-based surveillance system (Table 3.3). However, there were more expenses required for maintenance/running of the paper-based surveillance than the amount required for the operation of the mobile phone-based surveillance. Overall, mobile phone-based surveillance cost less annually compared to paper-based surveillance. The cost characteristics for both the surveillance systems are summarized in Table 3.3.

Table 3.3. **Mobile phone-based versus paper-based surveillance cost description for different particulars that were used to comprise the total budgets for both surveillance (capital, personnel and running costs). The annual personnel and running costs detailed in this table are relative to a study area of six regions, which encompasses twenty-eight districts of average 300,000 people and 4 health facilities in each. The costs are subject to change depending upon the number of health facilities and size of the area, which a surveillance system serves. The overall gross total here includes the start-up costs plus running costs for one year.**

Particulars			Mobile phone-based surveillance					Paper-based surveillance				
Infrastructure	**Items**	**Description**	**Unit/cost (TZS)**	**Quantity**	**Frequency per year**	**Sub Total (USD)**	**Total cost (USD)**	**Unit/cost (TZS)**	**Quantity**	**Frequency per year**	**Sub Total (USD)**	**Total cost (USD)**
Capital costs	Servers	Cost to purchase central storage for the collected data	6,250,000.00	2	start up only		8,064.52	6,250,000.00	1	start up only		4,032.26
	Computer	Cost to purchase computers for data entry/managers	1,147,500.00	3	start up only		2,220.97	1,147,500.00	2	start up only		1,480.65
	Phones	Cost to purchase phones for data collection	150,000.00	192	start up only		18,580.65	NA	NA	NA		0.00
	SIM cards	Cost to register into mobile phones networks	1,500.00	192	start up only		185.81	NA	NA	NA		0.00
	Sub total					**29,051.94**					**5,512.90**	
Personnel (Annual)	Data Clerk	Salary for data entry	NA	NA	NA		NA	700,000.00	1	12		5,419.35
	Data manager	Salary for person responsible for daily data collection actvities	1,200,000.00	2	12		18,580.65	900,000.00	1	12		6,967.74
	System administrator	Salary for person who develop and manage the system integrity	1,200,000.00	1	12		9,290.32	NA	NA	NA		0.00
	Sub total					**27,870.97**					**12,387.10**	
Running costs (Annual)	Airtime	Charges required to pay for sending data on use of phones' network	500.00	192	12		743.23	NA	NA	NA		0.00
	Papers	Cost of papers forms and printed books	NA	NA	NA		NA	100.00	6545	1		422.26
	Transport	Travel cost required to travel to health facilities during user training	1,500,000.00	6	2		11,612.90	1,500,000.00	6	2		11,612.90
	Per diem	Cost of accomodation and meal allowance for the training team	50,000.00	126	2		8,129.03	50,000.00	126	2		8,129.03
	Printing fee	Cost required to print the official forms and books for data recording	NA	NA	NA		NA	50.00	6545	1		211.13
	Distribution of forms and books	Cost required to distribute paper-forms and books for data recodring	NA	NA	NA		NA	1,500,000.00	6	4		23,225.81
	Collating of paper-forms	Charges required to (post, call, email) the paper forms and books from health facilities	NA	NA	NA		NA	10,000.00	192	52		64,412.90
	Sub total					**20,485.16**					**108,014.03**	
Annual Total costs						**48,356.13**					**120,401.13**	
Gross Total							**77,408.06**					**125,914.03**

3.3.5 Stakeholders' perceptions

In Tanzania, surveillance systems are mainly designed and carried out by government personnel and local research institutions. Many of these surveillance systems are focused on specific projects. All the stakeholders responded that they were focused on one infectious disease only. For example the initiatives have been made to establish computer-based surveillance to report Human Immunodeficiency Virus (HIV) and Tuberculosis (TB) patient data. These surveillance systems report directly from health facilities to the national level and notably achieve good completeness and timeliness. However, this surveillance operates for only a few health facilities (n = 250 out of 1,400 hospitals and health facilities in Tanzania) and there remain a number of challenges to be solved. The majority of stakeholders responded that user training was required before the implementation of the surveillance system, although most training was on-the-job training and no special skills were required before recruitment.

The primary unit and source of data for the disease surveillance systems were mainly implemented in health facilities under villages-settings and hospitals in districts. As for resolution, data were reported weekly or were reported to be collecting data on an events basis. The majority of stakeholders responded using postage as way of exchanging information from the local units to the central units where data is processed for national statistics. None of the stakeholders were satisfied with the paper based-surveillance systems and reported that data was rarely received on time. Most of the data being reported required only one page of text, but some data was quite extensive, with up to 15 pages in a single submitted report.

Generally, through traditional paper-based surveillance systems, data collection, storage, and access of information from one sector to another have underperformed. The health management due to the delays in reporting mean that health authorities cannot make use of the data, while difficulties of sharing the findings from one sector to another remain. Apart from donor driven projects such as HIV and TB, data collection and flow of information are conducted on summary information only. The reports from various health facilities are collated at district level, and later these reports are aggregated into an overall district report and not kept in individual records from various health facilities.

Typical examples of the surveillance systems responsible for collecting data from various health facilities in Tanzania include: Heath Management Information System (HMIS), Districts Health Information Software (DHIS) and Infectious Disease Week Ending report (IDWE). The HMIS system was established to facilitate the monitoring of all indicators from routine data collection from all the health facilities within the districts and later this information is collated into the district level where DHIS system is used to process the collected data into national surveillance though regional surveillance.

3.4 Discussion

In this comparative study, traditional paper-based and mobile phone-based surveillance systems were evaluated in terms of case detection capacity, data completeness, timeliness and costs. Prompt detection is crucial to effective surveillance, which may lead to timely disease control and prevention of future disease outbreaks [113]. Our findings show that there was a major increase in the number of animal bite injuries reported through the mobile phone-based surveillance system compared to the traditional paper-based approach (Table 3.2 and Figure 3.5).

The mobile phone-based surveillance detected more animal bite injuries than those detected by the traditional paper based surveillance. Moreover, there were cases detected by the mobile phone-based surveillance in areas where traditional surveillance did not report any records. Although both the surveillance systems were supposed to collect data from all the regions in the study areas as shown in Figure 3.1 and Table 3.1, the paper-based surveillance system did not manage to collect data for the entire area. North and South Pemba were entirely not represented due to lack of data from the paper-based surveillance during the time of this study. These two regions are typical examples of the considerable underreporting challenges that exist when using a paper-based surveillance system. It is unlikely that there were no animal bite injuries for the period of 72 months in these health facilities. Personal communication with health workers from these regions indicates that rabies was present at this time. Therefore data likely existed in health facilities but this information was not communicated (Figure 3.2).

There was a lack of data reported using the paper-based surveillance system from areas that were more rural areas and far from urban areas, where districts and regional offices responsible for collating paper forms require more resources compared to urban areas. These results demonstrate the relative efficiency of mobile phone based surveillance, where easier reporting supported the users to report more cases in areas where paper-based surveillance failed. It is likely that this approach can accommodate the challenges that exist in resource limited-settings, which hinder disease reporting.

It is unlikely that the few cases detected and reported by the traditional paper based surveillance represent the actual number of animal bite problems despite the time differences between when the two surveillance systems were implemented. Previous studies on rabies control in Tanzania and elsewhere in resource-limited settings have shown there is considerable underreporting of rabies incidence and bite exposures [22,23,49,51,52,69,100]. We do not expect that the fewer injuries detected by paper-based surveillance from the same regions where mobile phone-based surveillance detected more animal bite injuries, to be the true number of injuries that occurred (Table 3.2).

Our analysis revealed inconsistencies in case detection between the two surveillance systems using paper-based versus mobile phone-based reporting. The fewer cases reported under the paper-based surveillance are likely a result of difficulties in reporting. Increased awareness about rabies and availability of PEP may have increased the likelihood that victim's visit health facilities, increasing numbers of cases reported, whilst mass vaccination campaigns would be expected to reduce incidence. Nonetheless, it is surprising that the number of cases detected over five years using the paper-based system is comparable to the cases detected in less than two years by the mobile phone-based surveillance system. In some regions not even a single case was reported when paper-based surveillance was used, even though healthworkers that were interviewed claimed that rabies was present. Furthermore, several studies have highlighted the systematic underreporting of infectious diseases due weak surveillance in many developing countries [13,22,66].

Although paper data exists, the majority of these forms remain unprocessed due to various challenges, which include collating and transcribing the information from the paper forms. Several studies have highlighted how such misleading case detection is mainly caused by unreliable surveillance systems [13,113]. This sort of misleading representation of the key indicators of disease can result in morbidity and mortality, due to the delays or lack of responses to the prevention and control of diseases. Examples include the supply of drugs to health facilities, including PEP for rabies, where severe stock shortages result from a lack of up to date information from surveillance systems [25,49]. In contrast, the mobile phone-based surveillance had higher case detection, but this might have been influenced by other factors including levels of disease awareness among communities. However, previous studies conducted elsewhere in Tanzania [22,23,49], together with our personal communication with health workers from these regions, indicates that rabies was present but underreported. Case detection is important for identifying clusters of infection, which may be indicative of outbreaks. Thus high levels of case detection are essential for the rapid control and prevention of infectious diseases, particularly of notifiable ones (Figure 3.5).

This analysis revealed poorer reporting completeness by the traditional paper-based surveillance system (range from 70% to 96%, n = 3620) compared to the mobile phone surveillance (97% to 100%, n = 3314) (Figure 3). The worst data completeness was shown in reporting patient's age and date of exposure (Figure 3.3). The incompleteness of data reporting by the paper-based surveillance system was likely caused by the delays in updating of the paper forms for patient records. Several studies have identified inconsistent data recording caused by poor surveillance [66]. Rumisha et al. (2007) reported less than 2% of health facilities in Tanzania had all the working tools including the recording books and forms for attending patients. Instead local health facilities had to prepare their forms and books [74,116]. It is unlikely the local-made books and paper forms include all the variables required by the national surveillance. This result suggests that it is hard to maintain data quality using traditional surveillance systems.

Once the patient's information is recorded in paper forms across health facilities, forms are collated in districts offices where they are aggregated and summaries of data reports for districts are prepared. This allows room for transcription mistakes including error proneness, loss and damage to data sources and later results in incomplete data [35,44,77]. The overall results show reporting data completeness was more accurate through mobile phone-based surveillance than traditional paper-based surveillance systems (Figure 3). Data recording using mobile phone surveillance was validated on entry, with prompts of error messages, which help the nurses and physicians to maintain completeness before data submission. The controls that can be implemented on digital surveillance cannot be applied to paper based surveillance, where the majority of data processing and sharing requires manual work and involves a large number of steps before the information is ready for analysis (Figure 3.2).

Our analysis revealed significant differences in reporting animal bite cases by both surveillance systems whereby 61% (n=3273) of cases were reported in less than a months interval through mobile phone-based surveillance, while only 14% (n=3620) were reported in the same intervals through paper-based surveillance (Figure 3.4a). The majority of data collected through the mobile phone based surveillance system reached the authorities in less than a month interval after the patient presented to the primary healthcare facility. Reporting events through the mobile phone based surveillance system are far more likely to be timely due to the ease and low cost of reporting. Although the mobile phone-based surveillance system demonstrated timeliness in reporting the events, still there were some events that were reported very late (Figure 3.4b). These sorts of delays are likely to be caused by various reasons including the health facilities having lost their phones and reports when they were sorted out. Due to limited number of staff and high numbers of patients at clinics, few health facility staff reported that when they finish attending to patients they enter the data. This is likely to cause the delays in reporting. However, overall, these delays were minimal compared to the same delays that were experienced through traditional paper-based surveillance (Figure 3.4b).

For some regions, particularly those located in rural and remote areas, the collation of paper-forms across health facilities is problematic. Notably the geographical settings and transport infrastructure in many developing countries are unreliable and this is likely to limit paper-based surveillance to abide with timely reporting. Unlike the mobile phone surveillance system, which takes less than a minute for data submission once the patient's information is recorded into mobile phones (Figure 3.2 and Figure 3.4b). Even for a well-designed and organized paper-based surveillance, circumstances such as the rainy season can hinder reporting and storage. For traditional paper-based surveillance, data were annually collated at districts and regional offices and later processed at MoHSW (Figure 3.4) and this is reflected in longer intervals between the date of patient clinic visits and data reporting as compared to the mobile phone-based system.

The analysis revealed the initial cost for mobile phone based surveillance system was higher than the cost required to establish the paper-based surveillance system. The higher capital investments of the mobile phone surveillance are due to the cost required to buy phones for data collection and servers. These costs are likely to go down once the system is implemented. The results show that the mobile phone system had less operational costs than the paper based system that required a higher annual cost, almost twice those required to established mobile phone surveillance.

It should be noted that these systems were implemented across a large-scale area of twenty-eight districts, each of which serves an average of 300,000 people per district. The size of the study area is likely to affect other costs such as the travel costs that were required for user training. The expenses of the traditional paper based surveillance in maintenance/running are likely to be higher if the system manages to collect all the data from health facilities. Personnel costs such as more data clerks, and more computers to process data on time and transport cost for distribution and collation of paper forms from health facilities are more likely to increase for a reliable paper-based surveillance system. However, the mobile phone based surveillance system was demonstrated to be affordable and able accommodate the challenges in resource limited settings including very limited budgets.

4 Evaluating public health and veterinary metrics using a real-time surveillance system: rabies in southern Tanzania as a case study

4.1 Introduction

Infectious diseases are now the world's biggest killer of children and young adults, with heavy morbidity and mortality in developing countries [50,103]. Despite the availability of effective control interventions for many infectious diseases, the impacts of these interventions on morbidity and mortality has been difficult to monitor [25,92]. This is in large part due to poorly designed or poorly used surveillance systems. In Africa for instance, despite the evidence that laboratory diagnosis is critical for detection of rabies outbreaks, very little effort has been made to improve the submission of samples, making it difficult to evaluate the impacts of control interventions [84]. Poor quality health information systems and their inconsistent implementation have resulted in difficulties in evaluating biomedical interventions. In many resource-limited settings, epidemiological surveillance is not prioritized [42,74,99]. Therefore it is hard for authorities to respond to outbreaks, as they are not reported, and to ensure health and veterinary facilities have sufficient resources to meet their demands.

Most developed countries have eliminated canine rabies through mass dog vaccinations [22]. However, in developing countries rabies remains endemic and kills thousands of people each year despite being vaccine preventable [49]. Monitoring and evaluating large-scale rabies control programmes presents considerable challenges that are typical of zoonotic diseases that involve both the medical and the veterinary sectors [47].

In order to increase the capacity to detect rabies outbreaks and then notify the relevant authorities, rabies surveillance and communication needs to bridge all sectors. Specifically, information sharing between animal and human health professionals needs to be improved. One way to accomplish this is to intensify and modernize the data collection tools and surveillance systems. This will improve timeliness and efficiency of access to information on rabies outbreaks [25,137].

To accomplish this sort of modernization, in southern Tanzania we have developed a mobile phone-based surveillance system for rabies. The system promises to be effective for data collection and sharing among stakeholders who are involved in a large-scale rabies control program. The control program involves mass animal vaccination campaigns across twenty-eight districts. Our aim was to establish a sustainable integrated disease surveillance and response system for collecting nearly real-time data essential for monitoring the control program. The system was designed to collect data on the vaccination campaigns, from households surveys to assess the size of dog populations; sample collection and laboratory results for rabies diagnosis as well as human rabies post exposure prophylaxis (PEP) administration and records all victims with animal-bite injuries.

This chapter aims to evaluate the impact of the rabies control programme using the surveillance system across the twenty-eight districts in southern Tanzania. Since human rabies cases are rare because most bite victims receive pep, and samples from rabid animals are rarely obtained, we use animal-bite injuries as a measure of rabies incidence. Previous studies in Tanzania have shown bite injuries to be a good proxy for rabies incidence (Hampson et al. 2008, Beyer et al. 2010). However, variation in animal bite injuries through time and across districts is also likely to be affected by a number of different epidemiological, geographical and social factors. For example, the costs and availability of PEP as well as awareness about the need to seek treatment may affect whether bite victims report to hospital, which may also depend on socioeconomic conditions. We hypothesize that geography, vaccination interventions and prior incidence of rabies in the focal area and its surrounding populations will all affect the spatiotemporal patterns of bite-injuries. We therefore explore how a range of epidemiological and geographical variables relates to bite incidence in addition to the effects of the control programme.

4.2 Material and methods

4.2.1 Study area

This study took place in Southern Tanzania, the area located at the coast of the Indian Ocean, which is bordered by wildlife-protected areas to the west and north (Mikumi National Park and Selous Game reserve) and with Mozambique to the south. The study area encompasses four regions from the Tanzanian mainland and two regions from Pemba Island, which are divided into twenty-eight administrative districts for human health and veterinary sectors (Figure 4.1). The study area was categorized into rural and urban settings; with twenty-two rural districts. Rural settings were mainly inhabited by agro-pastoralist and pastoralist communities of multiple ethnicities and religions. The majority of rural inhabitants depend on livestock production and crop cultivation as their main source of income. The study area included four districts that were classified as urban settings predominantly inhabited by working classes. There may be differences in PEP accessibility and residents awareness about the need for PEP in rural versus urban areas as well as across different districts.

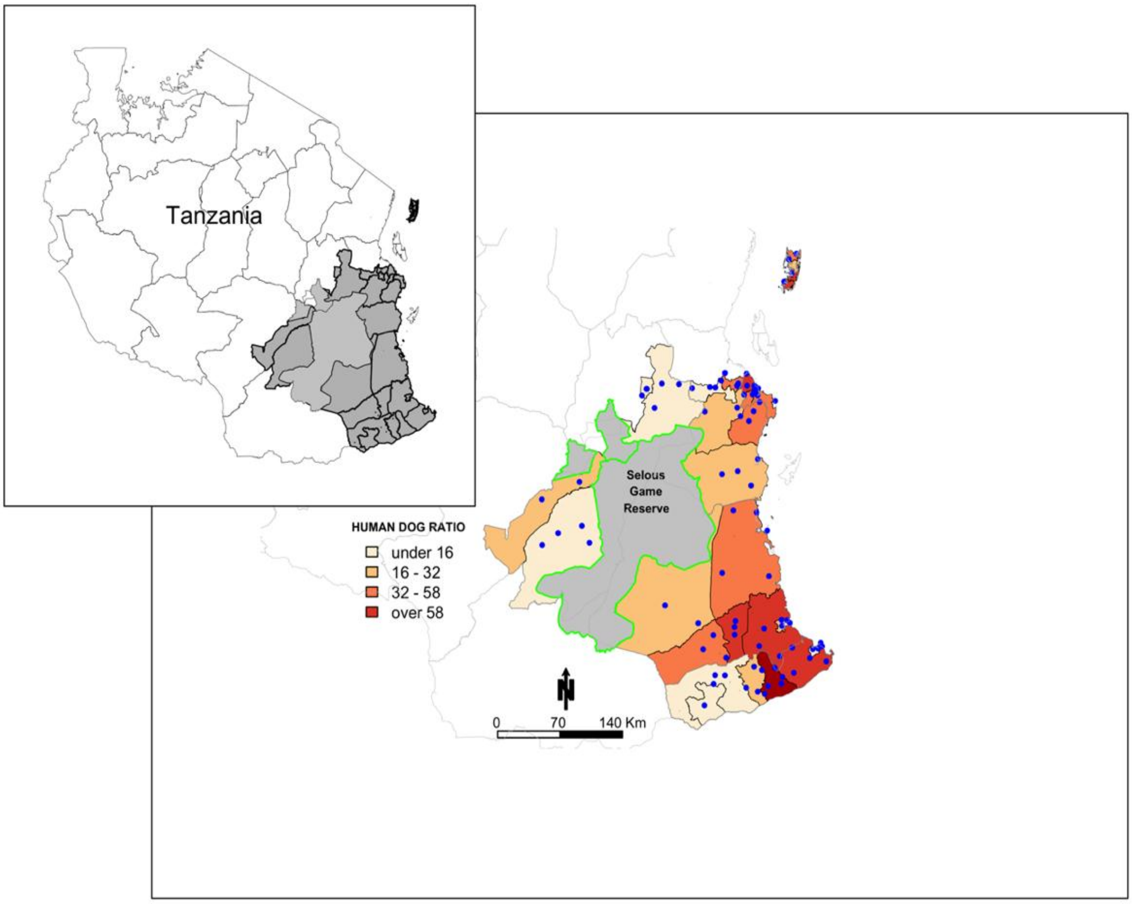


Figure 4.1. Location of study districts in southern Tanzania where a mobile phone-based surveillance system was operating to monitor a large-scale intervention to control rabies. All 28 districts conducted mass animal vaccination campaigns between 2010 and 2013. Colours highlight human: dog ratios across the districts. The locations of all the primary healthcare facilities from which animal-bite injury data were collected are shown by blue dots.

4.2.2 Data collection

A mobile phone-based surveillance system was developed and implemented in all the districts within the study area. The surveillance system was mainly used for data collection at clinics and hospitals that provide PEP as well as veterinary activities such as mass animal vaccination campaigns, household surveys to assess animal populations and vaccination coverage, and recording of rabies suspect cases and animal sample collection for laboratory diagnosis. The system enables sharing of these data between sectors and stakeholders involved in rabies control. For more details on how this system was designed and operates refer to chapter 2. Here we analyse data that were collected by users of this system. In brief, the system was designed to use mobile phones for data collection (Table 4.1). All forms on the phones were in the local language, Kiswahili. One-on-one training was provided to livestock field officers (LFOs) and health workers who used the phones, with routine follow up every 4 months. Printed manuals with diagrams were also initially supplied to users and a remote help desk was set up so that users could text or call whenever they faced obstacles.

4.2.3 Incidence of animal-bite injuries

PEP was supplied to the ministry of health by the WHO coordinated rabies control programme to enable PEP to be administered free of charge in facilities across the study area. Centralised hospitals provide PEP as well as three additional primary healthcare facilities that were relatively easily accessed by communities (Figure 4.1). PEP stocks within these facilities were monitored through time by the surveillance system. Health workers reported animal-bite injury data as patients attended facilities seeking PEP. All the data variables that were recorded from the health facilities on animal bite injuries are characterized in Table 4.1.

4.2.4 Animal vaccination campaigns

The district veterinary officers organized the administration of vaccination campaigns within their districts in the study areas. A central point vaccination strategy was adopted both in rural and urban areas, whereby villages and streets and other common places such as schools, markets, churches and mosques were used as the central point for vaccinations. LFOs within the districts communicated with local authorities to inform the communities' in advance of the campaigns. The communities were informed at least one week before, and reminders were given a day before. Different methods were used to distribute this information including reports on television and local FM radios as well as announcements at schools, churches and mosques by the local authorities. On the vaccination day, a team of at least three people registered the animals that were brought, vaccinated the animals and gave animal owners vaccination certificates. Vaccination campaign data were recorded into logbooks then data were submitted into the surveillance system after the campaign was finished including recording the geo reference for the central point.

Table 4.1. Summary of the data collection forms used by health workers and LFOs. Forms are downloaded onto mobile phones from the remote server.

Data form	Captured information	Details of data
Animal bite incidence	Health facility	Facility name (phone number and clinic location)
	Patient's demographics	Full name, gender, age, address, phone contact
	Exposure	Patient visit date, date of bite, site of bite, severity of bite, biting animal species, whether animal was suspect for rabies, and immediate action taken.
	Treatments	Use of immunoglobulin, vaccine availability, route of vaccine administration, vial batch number, vaccination certificate ID, other treatments and comments
Vaccination campaigns	Campaigns	Supervisor name, campaign date, phone contact, location (region, district, village or street), head of village or street and georeference of the village or CP
	Outcomes	Start time and end time, number of vials used and batch number and total number of animal vaccinated per CP

4.2.5 Data compilation

We summarized animal bite injuries in monthly intervals in each district for all the twenty-eight districts for the period of twenty-four months (January 2011–December 2012). One-month intervals were used on the basis of rabies transmission dynamics, with an average incubation period of 22.3 days. Therefore most animals become infectious the month after they are bitten [5,51]. Numbers of bite injuries in each district each month were converted to incidence by dividing by the total human population in the district. Animal bites in neighbouring districts refers to the summation of bites across all districts that border the focal district. The initial dog population size in each district was estimated from the human:dog ratio derived from household surveys that were conducted in selected villages within the study area. We compared the human:dog ratio with the 2011 human population size projected with the regional growth rate of 2.9% per annum from the Tanzania national bureau of statistics [121]. Projected vaccination coverage in each district was modelled through time as a function of dog birth and death rates (0.42 and 0.38 per year, respectively) and the rate at which vaccination immunity wanes (the average duration of vaccine induced immunity is assumed to be 2.5 years, corresponding to a waning rate of 0.4 per year) [5]. Pulsed vaccination campaigns were implemented within this deterministic model. Coverage in each district was instantaneously set at the level of coverage achieved when each campaign took place coverage and thereafter declined due to demographic processes and waning of immunity.

4.3 Analysis

We examined different factors that we hypothesised may have had an impact on the incidence of animal-bite injuries in the study area. These factors were broadly classified according to geography, vaccination interventions and the force of infection in terms of rabies incidence through time and in neighbouring districts. Candidate variables related to geography that were considered in the model included the following fixed effects: whether the district was situated on the Tanzanian mainland or the island of Pemba (γ) and whether the district was considered urban or rural (α), and random effects for district (δ) and month (μ). Candidate variables considered related to vaccination interventions included vaccination coverage in the month when bites occurred and each of the previous three months ($V_{t,i,}$ $V_{t-1,i,}$ $V_{t-2,i,}$ V_{t-3}). Candidate variables considered that related to the force of infection included bite incidence the previous month in the focal district ($B_{t-1,i}$) and bites in neighbouring districts that month and the previous month ($B_{t,N}$, $B_{t,N}$ respectively). Collinearity between variables were examined. Univariate relationships were initially examined for each of these variables in relation to the response variable incidence of bites per 100,000 people in each district (i) every month (time = t).

A Generalized Linear Mixed Model (GLMM) was constructed to identify which of these variables explained variation in the incidence of animal-bite injuries, using logged population size as an offset. We first built a ‘beyond optimal’ model including all independent explanatory variables [118]. We used AIC to determine the best fitting most parsimonious model. We compared models with poisson error structure, with negative binomial error structure and with zero inflation negative binomial error structure. We sequentially added district and month as random effects, and removed interactions and variables according to the AIC. Vaccination coverages at different time lags were highly correlated; therefore models were compared that included only one coverage variable. Model suitability was checked by visual inspection of residual plots. The model was fitted using the R language for statistical computing [112] using the package glmmADMB.

4.4 Results

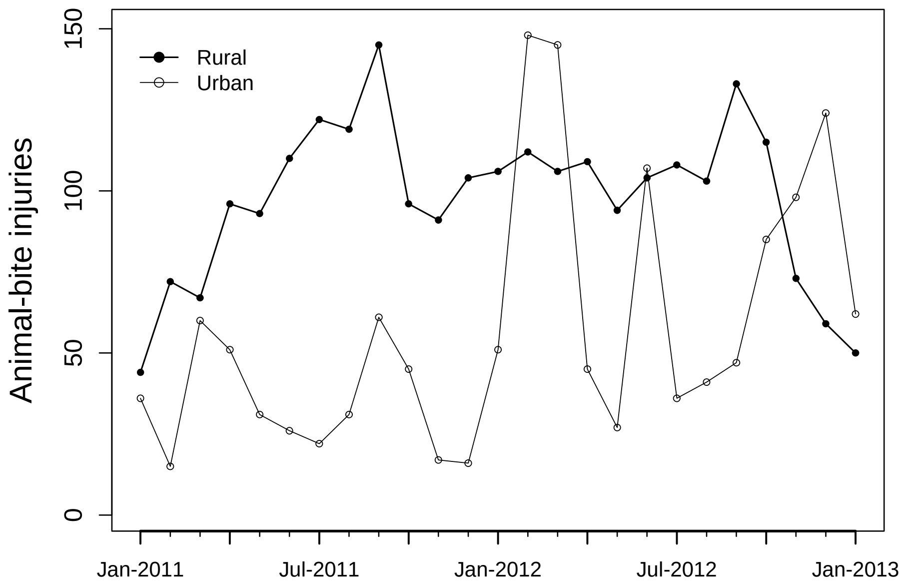
4.4.1 Incidence of animal bite injuries

From January 2011 to December 2012 a total of 3567 animal bites were recorded from all the primary healthcare facilities across southern Tanzania that provide PEP (Figure 4.2a and 4.2b and appendix I). Reported animal bite injuries varied from 0 to 61 in urban districts and 0 to 51 in rural districts (15 to 148 per month across all urban areas, versus 44 to 145 across all rural areas, Figure 4.2a). Morogoro rural and Morogoro urban districts had most injuries, accounting for 17% and 8% of all bites respectively, while Pemba Island had the fewest bite injuries. There were more bites per person in rural areas than in urban areas (Figure 4.2b), with the highest incidence occurring in Kisarawe, Morogoro rural, Nachingwea, Nanyumbu and Ulanga districts (> 76 bites/100,000 persons in Sept 2011, Feb 2012, Sept 2012 and Nov 2012).

4.4.2 Mass animal vaccination campaigns

In the three annual vaccination campaigns that were conducted in 2010, 2011 and 2012 a total of 21776, 70274 and 34763 animals were vaccinated (appendix II). The aim of the intervention was to conduct annual vaccination campaigns in each district achieving at least 70% vaccination coverage in each district. However, campaigns did not start effectively until 2011 (Figure 4.3a) and the coverage achieved both in 2011 and 2012 campaigns was quite low. Among districts the minimum coverage recorded was 0% (i.e. when campaigns were not carried out in districts) and the maximum coverage recorded was 90% and the average coverage achieved was 22% (Figure 4.3a). The average coverage across the entire area varied from 0.4% to 50% corresponding to when campaigns were conducted (Figure 4.3b).

(a)



(b)

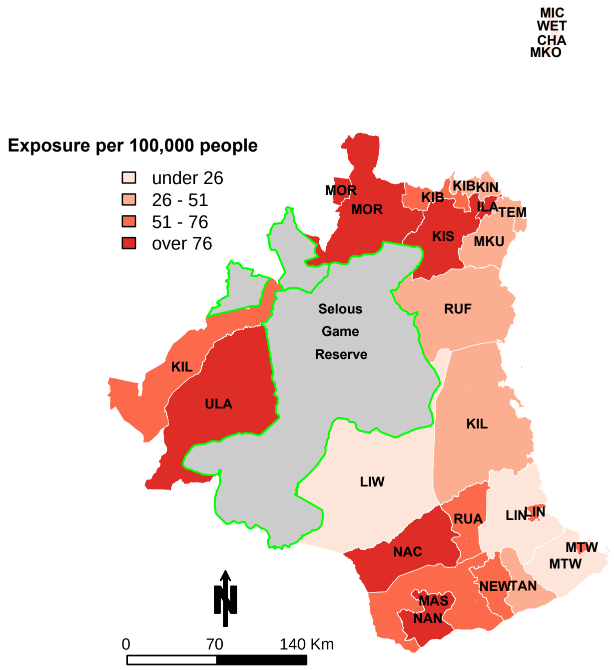


Figure 4.2. Geographic distribution of animal bite injuries in southern Tanzania that were recorded between January 2011 and December 2012. (a) Animal-bite injuries reported from rural and urban settings each month (b) annual incidence in each district per 100,000 persons.

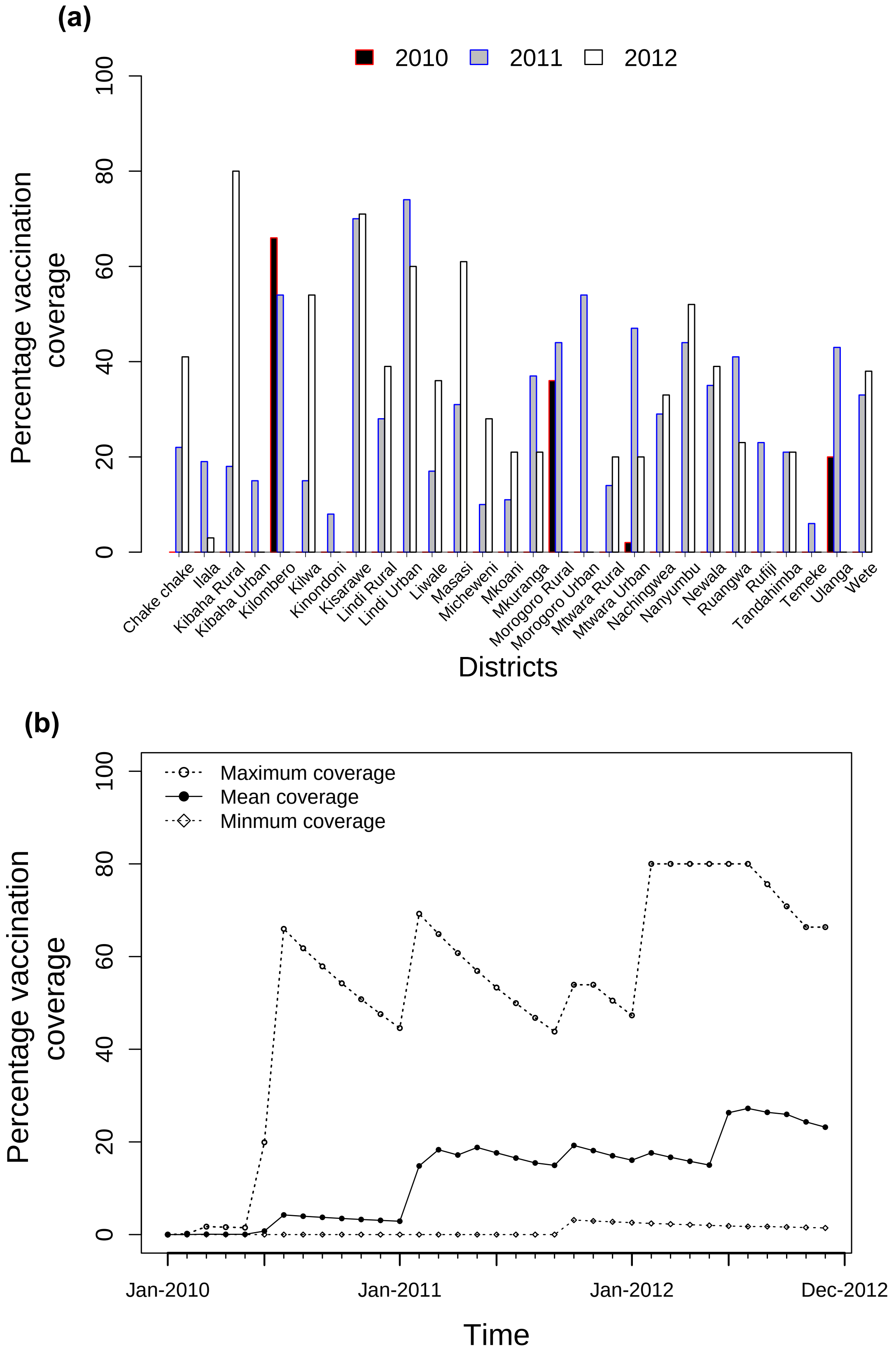


Figure 4.3. Levels of vaccination coverage achieved between 2010 and 2013 in southern Tanzania. (a) Vaccination coverage achieved during annual campaigns in each district during 2010, 2011 and 2012; (b) Projected vaccination coverage based on turnover of the dog population and waning of immunity. Peaks correspond to when campaigns were conducted. Mean coverage was calculated across all districts (solid line), and the maximum and minimum coverage across all districts are shown (dashed lines).

4.4.3 Predictors of animal bite injuries

The final best fitting model had a negative binomial error structure, had district as a random effect and was described by the following equation:

$$\mathbf{B_{t,i} \sim \beta_1 B_{t-1,\,i} + \beta_2 B_{t-1,\,n} + \gamma_k + \beta_3 V_{t,i} + \beta_4 V_{t,\,i} B_{t-1,\,i} + c}$$

Where:

$\mathbf{B_{t,i}}$ = Animal bite incidence per 100,000 people in month t in the focal district i (offset by the human population in the district)

$\mathbf{B_{t-1,i}}$ = Animal bite incidence per 100,000 people in month t in the focal district i (offset by the human population in the district)

$\mathbf{B_{t-1,n}}$ = Number of animal bites in month t-1 in neighbouring districts

$\mathbf{V_{t,i}}$ = Percentage vaccination coverage in month t in district i

$\boldsymbol{\gamma_k}$ = Influence of mainland versus islands location

The variables that had significant effects on monthly animal bite injuries reported from each district are detailed in Table 4.2. Specifically, bite injuries in the focal district and in neighbouring districts during the previous month at time t-1 (Figure 4.4a & b) were positively related with animal bite injuries in the focal district (i) at time t. There was significantly higher bite incidence in districts on the Tanzanian mainland than on the island of Pemba (Figure 4.4d). Although there were more bites per month in urban compared to rural settings; bite incidence was lower in urban districts than rural districts, and there was no significant effect of setting in the best fitting model (Figure 4.4e). Vaccination coverage was positively related with animal bites (Figure 4.4c), and there was a significant negative interaction between vaccination coverage and animal-bite injuries from neighbouring districts the previous month (interaction not visualized).

Table 4.2. Variables that had statistically significant relationships with monthly animal bite injuries across 28 districts in southern Tanzania over a 2-year period.

Predictors		coefficient	Std.Error	z-value	p-value
β_1	Bites /100,000 people in month t-1 in district i	13700	2100	6.51	<0.001 ***
β_2	Number of animal bites in month t-1 in neighbouring districts	0.0087	0.0043	2.03	0.043 *
γ	Mainland	1.17	0.298	3.93	<0.001 ***
β_3	Percentage vaccination coverage in month t in district i	1.19	0.487	2.44	0.015 *
β_4	Percentage vaccination coverage | Animal bites in month t-1 in neighbouring districts	-0.0397	0.0164	2.41	0.016 *

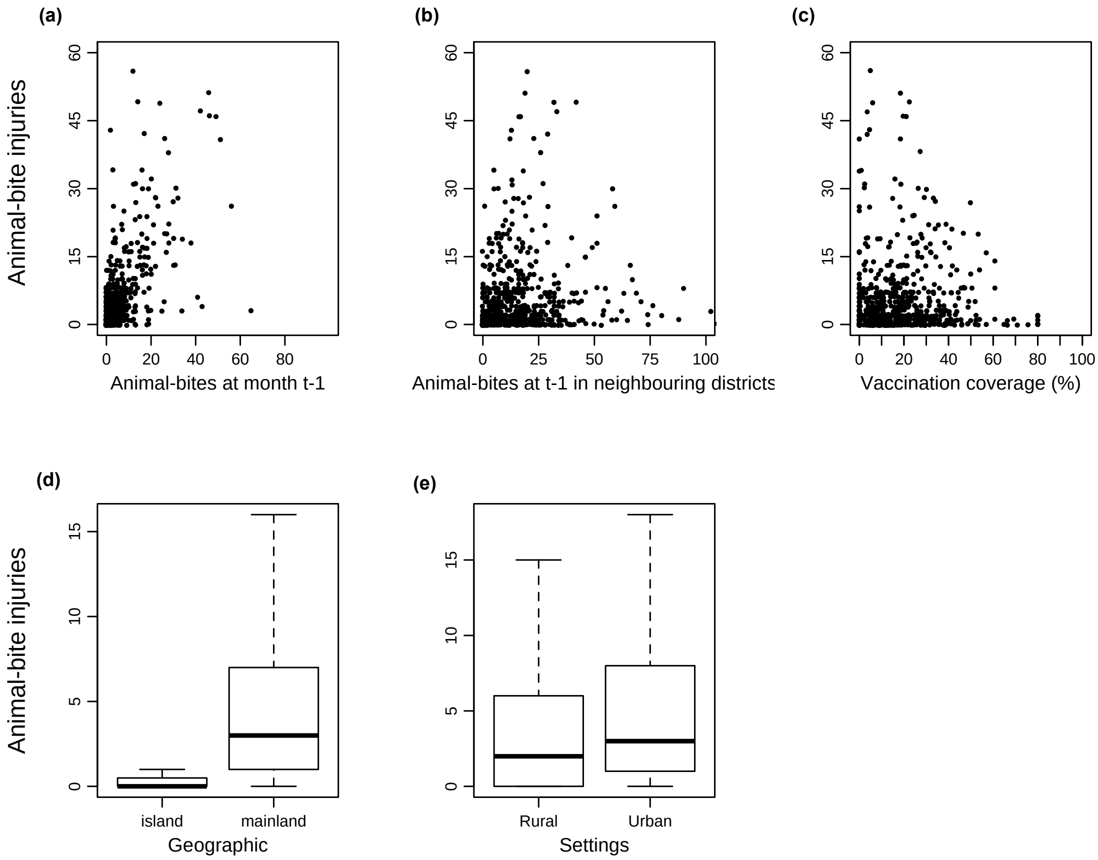


Figure 4.4. Significant univariate relationships between animal bite injuries and geographical, and epidemiological predictors and control interventions: numbers of animal bite injuries compared to a) bite injuries the previous month (at t-1); b) bite injuries from neighbouring districts in the previous month (at t-1); c) vaccination coverage; d) geographical location (mainland versus island) and e) geographical settings (rural versus urban).

4.5 Discussion

This analysis of more than 3000 animal bites injuries across southern Tanzania demonstrates that there is considerable variation in the spatiotemporal patterns of bite-injuries. The strong temporal and spatial correlation in bite injuries suggests that these patterns are indicative of a contagious process, i.e. rabies transmission within and across districts over the two years period. In a study conducted in northern Tanzania, Cleaveland et al. (2002) suggested that bite injuries provide a useful source of epidemiological information that can be used to estimate human rabies burden [22]. Other studies also have suggested that patterns of animal bite injuries can be used to elucidate spatial transmission dynamics and identify drivers of disease [5]. However, this is the first study to use animal bite injuries to assess the effectiveness of a large-scale rabies control program.

Our results have shown there were variations in animal bite injuries across districts and through time both in rural and urban settings. The majority of bite injuries were caused by animal’s whose history was unknown, but the correlations in patterns of bites, suggests that many of these were likely to have been mainly caused by rabid animals. Awareness about the dangers of rabies, socioeconomic status and location of living (rural/urban) among districts could also explain some of the variation in animal bite injuries, as these factors may affect how people bitten by dogs (healthy or rabid) seek PEP [49].

The significant positive relationships between animal bite injuries and incidence from the previous month in the focal and neighbouring districts. This may be indicative of ongoing rabies transmission and point to the persistence of uncontrolled rabies outbreaks across districts with transmissions from one month to another. Therefore, infected animals such as domestic dogs maintain and transmit the disease through bite inflictions, where areas with higher number of dogs are at more risk if there is no immediate control interventions [26,52,83]. These relationships also suggest the existence of animal movement across district boundaries. These surveillance data could be used to identify areas with persistent rabies transmission, where further mass dog vaccinations are required. These results are comparable to the findings of a study conducted in north Tanzania in the Serengeti ecosystem based on laboratory sample diagnosis. Their findings shows that although rabies circulates among a range of species, domestic dogs maintain transmission; therefore mass vaccination campaigns need to target dogs to interrupt transmission and ultimately eliminate rabies [83].

Another potential explanation for the variation in animal bite injuries is the geographical setting, specifically mainland versus island. The analysis revealed more animal bites in mainland settings than in island settings. These patterns suggest that the majority of these injuries were likely to be associated with rabies outbreaks that spread among districts. The more animal injuries on the mainland are probably due to the greater numbers of dogs maintaining disease on the mainland, whereas there dog population is only small on Pemba, and are isolated from other populations by the ocean. Other studies have shown rabies persistence depends on high-density dog populations and is absent in very low-density dog populations [50,83].

There were more bite injuries in urban settings than in rural settings, but the incidence of bite injuries (per 100,000 people) in rural areas was higher than in urban areas. This was likely because there is much more dog ownership in rural areas than in urban areas. i.e. areas with higher human: dog ratios had a lower incidence of animal bite injuries. However, rabies control programmes, which are likely to suppress these outbreaks, are more challenging in rural areas than in urban areas. Moreover, rabies awareness is likely to be much higher in urban areas than in rural areas due to better access of education [21,32,76,120].

Studies show that to eliminate the source of infection and to reduce rabies outbreaks, vaccination campaigns need to achieve between 60-70% coverage annually [5,25,52,69,82,85]. However, achieving the required vaccination coverage is a major challenge as shown by these data. This may be due to several factors, including financial constraints and geographical location. For example, the areas that were most rural and remote or isolated may have greater difficulty in reaching the required coverage and vaccination campaigns were not completed annually (across all three years) in any of the districts.

Our results have shown that the majority of rural districts were less successful in achieving high vaccination coverage and conducted fewer campaigns compared to urban districts (Figure 4.3a). Some of these districts did not conduct vaccination campaigns at all in some years. The poor performances in vaccination campaigns demonstrate the typical financial limitations in developing countries. Vaccination campaigns are more likely to happen in areas which are easy to access and where it is relatively cheap to conduct campaigns. Moreover, in areas inhabited by pastoralists, it is possible for entire communities to miss vaccination campaigns due to their tendency to seasonally migrate in search of better grazing. Another major obstacle for effective rabies control is the difficulty in estimating dog population size. This is particularly difficult because of the large and localized variation between communities in human: dog ratios. This makes it difficult to evaluate coverage. Moreover inaccuracies in these estimates may affect the predicted relationship between estimated coverage and the incidence of bite injuries. Ensuring sufficient veterinary resources to target areas most in-need or with high dog densities is still a challenge.

Surprisingly, we detected a significant increase in animal bite injuries with vaccination coverage i.e. districts with higher vaccination coverage had more animal bites than districts with lower coverage (figure 4.3c). Examination of this result indicates a complex relationship (figure 4.3c) that may not be very well captured by this model, despite our attempts to develop a formally appropriate model. The interaction between vaccination coverage and bites from neighbouring districts in the previous month is negative and the effect size (once the interaction is accounted for) is larger than the main effect of vaccination coverage, indicating that vaccination coverage likely helped rather than hindered the control of rabies. A better model that more effectively captures the contagious process as well as variation in bites by healthy animals (that people have sought PEP for) is needed in the future. Our understanding of these dynamics may be further improved as more surveillance data becomes available. Nonetheless, this research suggests that large-scale rabies surveillance programmes that capture bite injuries have potential to identify rabies outbreaks and monitor the impacts of control measures.

We have shown that fluctuations in animal bite injuries are a useful indicator of rabies outbreaks. These data provide several clear messages for rabies control programmes: major improvements in vaccination campaigns are required to improve the vaccination coverage in many districts. Our results have highlighted the spread of rabies from neighbouring districts. Areas that are missed from campaigns may become the source of infection that can sustain outbreaks between campaigns and re-infect neighbouring areas. Timely evaluation of rabies control is needed. Follow up of vaccination campaigns using data such as those presented here, could be used to identify districts where campaigns need to be improved or repeated if initial attempts were particularly poor (as they were in many districts here). These data can also aid the proper planning of campaigns; for example, ensuring consistent time intervals between the vaccination campaigns to reduce the dangerous waning of population immunity. Critically, the dog population needs to be accurately estimated and updated following coverage calculations during consecutive campaigns, to ensure that sufficient dogs are vaccinated.

Several studies have highlighted the potential use of surveillance system data to control diseases, from the early sixties when surveillance and vaccination campaigns were used successfully to eradicate smallpox [39,58,59]. There is a need for innovative tools to strengthen and integrate human and animal surveillance in order to monitor infectious diseases and evaluate the impacts of control programmes. This study demonstrates that a mobile phone-based surveillance system for rabies provides useful information that can be used to evaluate control interventions. This is the first time a mobile phone surveillance system has been used for the real-time evaluation of rabies control in Africa, and demonstrates the value of sharing both human and animal health data.

5 Evaluating the effect of automated SMS reminders on patient adherence to rabies post-exposure vaccination regimens in southern Tanzania.

5.1 Introduction

In developing countries, despite unreliable digital infrastructure, mobile phone subscriptions have been rapidly increasing [72,95,114,135]. Mobile phone text messaging is a potentially powerful tool due to its widespread use and cheap availability, even in rural communities, in sub-Saharan Africa. Use of such technology in health information systems for infectious diseases may provide an alternative approach for monitoring and evaluation and improvement in service delivery [14,28,70].

Poor attendance to healthcare facilities and compliance with treatment regimens is a common problem in many countries that can increase the incidence of preventable diseases and death [16,72]. Non-adherence is one of the primary obstacles to medical treatments that require multiple clinic visits worldwide, and improving individual compliance is a major challenge. Mobile computing applications can potentially be used to monitor and evaluate adherence [16,28,43].

Rabies is a fatal disease that is endemic in developing countries and spread by bites from infectious animals, predominantly domestic dogs [23,54]. Post-exposure prophylaxis (PEP) for rabies generally consists of a course of injections that should be started immediately by animal bite victims following an exposure to prevent the onset of this fatal disease [49]. Delays in obtaining PEP and lack of compliance with PEP regimens increase the risk of developing rabies [48,56]. Such delays may be caused by scheduling errors by health workers, and forgetfulness and confusion over dates by patients.

SMS is a short message service also known as text messaging which is standardized by the Global System for Mobile communications (GSM), allowing a maximum of 160 characters of data to be transferred from one mobile phone or computer to another simultaneously [55,87]. SMS can be sent in near-real time to thousands of people as recipients of standardized, bulk messages or even as personalized or tailored messages. SMS can therefore be used to provide health care information directly to patients and appropriately timed and targeted SMSs could be automatically generated through an effective surveillance system. In developing countries SMS may be an effective healthcare intervention to increase effectiveness and efficiency of public health care delivery and administration [28,87,95]. The direct and two-way communication between patients and health care providers is convenient and allows greater privacy compared to paper-based communication. SMS may therefore be used as an intervention to provide key information such as when and where patients need to go to obtain treatments.

In Tanzania where demands on health workers are high, and few health facilities provide PEP, information on where and when patients can obtain PEP can potentially improve patient adherence [28,95]. With the rapid development of innovative uses of mobile phones, SMS interventions can possibly improve health service delivery. Moreover, this innovation can potentially facilitate resource management in developing countries, particularly stock management and distribution across remote areas [86,113]. In this study we hypothesize that using SMS reminders for animal bite victims could result in significant improvements in PEP compliance.

5.2 Methods

5.2.1 Study area

A mobile phone-based surveillance system was designed for monitoring rabies incidence and the accessibility and use of PEP. The system was designed to operate across twenty-eight districts in southern Tanzania. Four primary health facilities from each district were chosen to provide PEP (Figure 2.1), with a total of 112 health facilities registered within the surveillance system.

5.2.2 The surveillance system architecture and procedures

The surveillance system was designed to use the mobile phone network to connect to a remote server, which is accessible from the Internet (Figure 2.3). Mobile phones were configured to use GPRS-Internet architecture and installed with a java application to connect to the server that hosted a MySQL database so that users could download forms to capture data and upload data that they collected. These settings enable data exchange in remote areas where there is otherwise no access to Internet infrastructure.

Users of the system (health workers or veterinary workers) submit surveillance information using mobile phones. This chapter focuses on health workers, who collect information on animal bite victims, and the treatment they are provided with, including details of PEP. This information is collated on the central server and can be used for subsequent interventions such as SMS reminders. Details of data collected by health workers on animals bite injuries and treatment are described in Table 5.1. To overcome reception and connectivity issues, users can choose to save the data on their local device and upload the data whenever a good connection becomes available.

Table 5.1. Details of the data collection forms used by health workers showing the different information collected when animal bite injury patients attend clinics. Forms are downloaded onto mobile phones from the remote server.

Captured information	Description
Health facility information	Facility name (phone number and clinic location)*
Patients' personal information	Full name, gender, age, address, phone contact
Details of exposure	Patient visit date, date of bite, site of bite, severity of bite, biting animal species, whether animal was suspect for rabies, and immediate action taken.
Treatment provided	Use of immunoglobulin, Vaccine availability, route of vaccine administration, vial batch number, vaccination certificate ID, other treatments and comments

***Hidden information captured when users log in, therefore reducing the amount of information entered directly by users.**

5.2.3 User training and system implementation

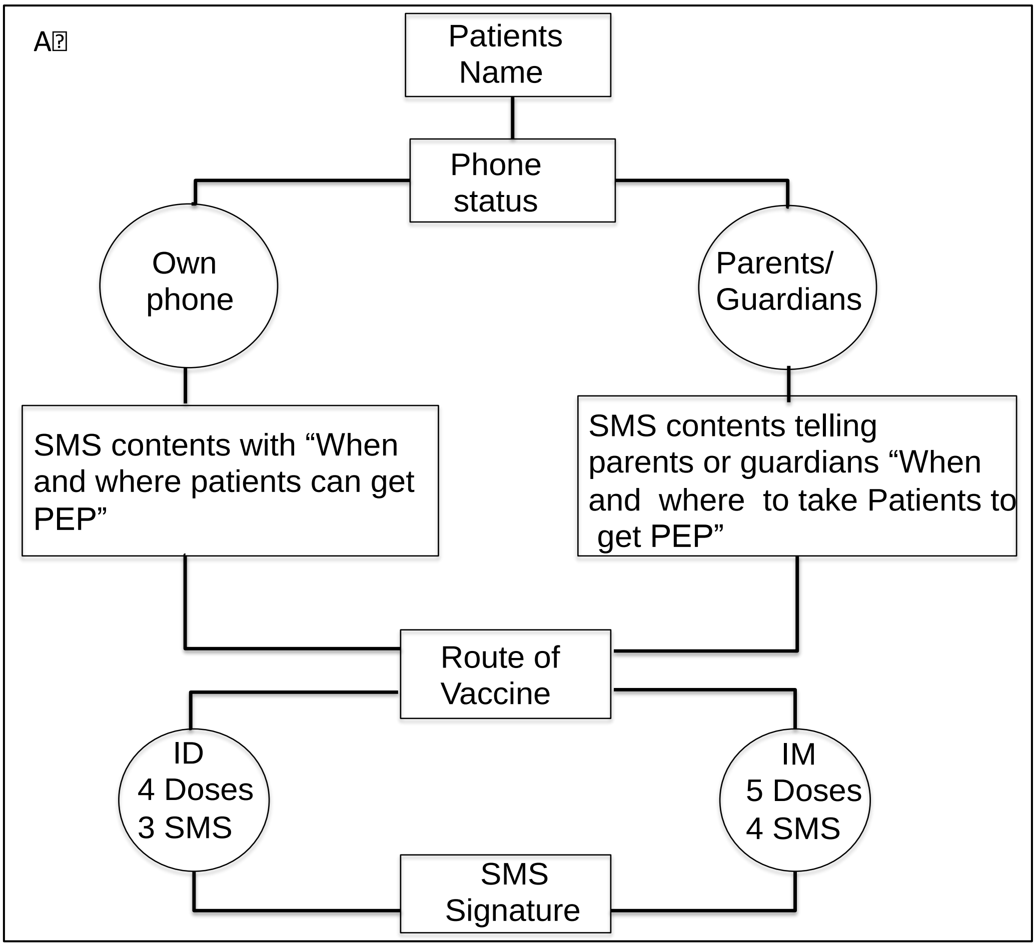
Briefly, the system was designed to use mobile phones for initial data collection and all forms on the phones were designed to use the local language, Kiswahili. One-on-one initial training was provided to health-workers who used the phones with routine follow up provided every 4 months. Printed manuals with diagrams were also initially supplied to health workers, and a remote help desk was set up so users could text or call whenever they faced obstacles. Four users from each health facility were trained before the clinics were registered into the surveillance system by a trainer who demonstrated how the system works. Users were given the mobile phones configured for the system and shown how to download forms with questions for animal bite victims. During their training, users were given test cases and practiced sending dummy data. Thereafter animal bite patients' attendance and PEP supplies from public health authorities were recorded by health workers and submitted into this surveillance system using the phones. A full description of the system design and user training is described in Chapter 2 of this thesis.

5.2.4 Automated SMS design and SMS intervention procedure

Health workers entered data on patients with animal bite injuries into the mobile phone-based surveillance system when they attended clinics. Patient information that was uploaded was stored in a MySQL database (Table 5.1).

WHO recommends different schedules of PEP administered either intradermally (ID) or intramuscularly (IM). We developed PHP script algorithms, based on patients' attendance dates recorded in the MySQL database and their schedules (ID or IM), to determine the SMS content of reminders to patients (figure 5.3A). Patients with PEP delivered through the ID route were scheduled to return to clinics on day 3, 7 and 28, while patients with IM PEP were scheduled to return to clinics on day 3, 7, 14 and 28. The algorithms were automated to assign patients an SMS one day before their clinic visits as a reminder to complete their vaccination schedule.

The SMS content was tailored to patients who owned their own mobile phone (Figure 5.3B) and for those who only received the SMS through the phone of a neighbour or other family member (Figure 5.3C). To keep track of processed patient information we used another algorithm to monitor the status of the reminders implemented within PHP MySQL. This algorithm recorded when patients were assigned SMSs depending on ID and IM regimens and the status of the SMS: sent but pending delivery, sent and delivered successfully or sent but failed. All SMS reminders were assigned into a queue for sending, and 33 attempts to send the SMSs were made before abandoning further attempts and updating the records accordingly.



B

Please [**patient_name**] go to [**clinic_name**] for you [**visit_status + 1**] PEP vaccination tomorrow [**date**]. [**signature**]

C

Please bring/tell [**patient_name**] go/ to go [**clinic_name**] for their [**visit_status + 1**] PEP vaccination tomorrow [**date**]. [**signature**]

Figure 5.1. Automated SMS reminders for animal bite injury patients. A) The algorithm for compiling SMSs and B) the resulting automated SMS structure to be delivered one day before the PEP due date for patients who own their own phone and C) for patients who receive SMSs via the phone of a friend, neighbour or relative. The algorithm takes the animal bites patients’ information including visit status and route of vaccination to construct the patient reminders. SMS’s were written in Kiswahili.

To evaluate the impact of SMS reminders on patient compliance with PEP regimens, patients were enrolled into a study. Patients were recorded in the surveillance system as they attended clinics for PEP and all patients who had access to a mobile phone, either their own phone or that of a family member or a neighbour, were enrolled into the study. Patients who attended clinics for their first PEP dose between May 2011 and October 2011 were not sent any SMS reminders prior to their subsequent PEP visits (Figure 5.4). Patients who were recorded in the surveillance system during their first visit for PEP between November 2011 and June 2012 were assigned SMS reminders (intervention), which sent to them the day before their PEP due date requesting them to go to the clinic (Figure 5.3). Here we regard the patients who attended clinics for PEP between November 2011 and June 2012 as the intervention group as they were assigned SMS alerts. Those who attended clinics from May 2011 to October 2011 did not receive reminders and were regarded as the control group. The compliance of patients in both groups was monitored by the surveillance system, with health workers recording patients as they returned to clinics for subsequent PEP vaccination doses. It should be noted; patient compliance in this study is determined by whether patients returned for their second dose of PEP either through ID or IM administration. We did not examine the compliance for subsequent doses, although this information was recorded.

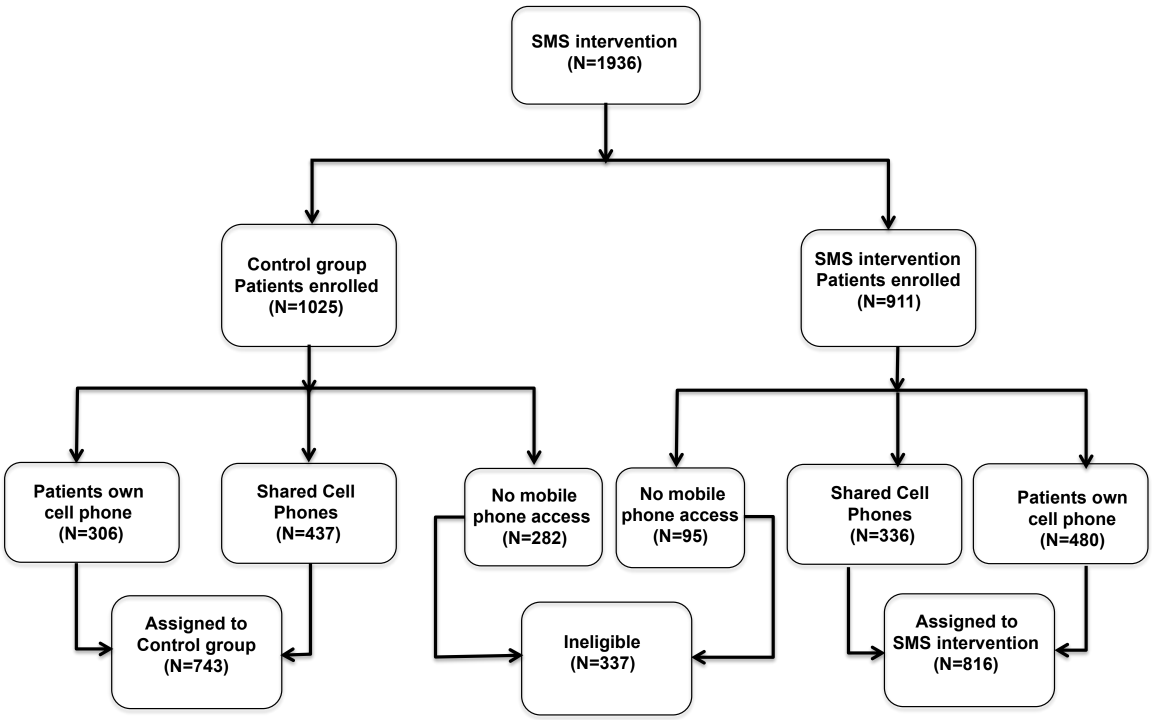


Figure 5.2. Patient's compliance study schematic describing the total number of patients who were enrolled into the study and assigned to the intervention, and those dropped from the study due to lack of mobile phone access.

5.3 Statistical Analysis

We estimated that a sample size of 487 individuals would be required to detect at least a 10% improvement in patient compliance with PEP, with 80% power at the significance level of 0.05. We used a generalized linear model (GLM) with binomial error structure to test for differences in compliance with second PEP doses according to whether patients attended clinics prior to the intervention (no SMS reminders), or during the intervention when patients were assigned SMS reminders, and according to different categories of the enrolled population, including age, gender, residence (urban or rural), route of vaccine administration (ID or IM), and mobile phone access. We carried out univariate analysis on all covariates that we hypothesized could affect patient's compliance to PEP to explore their individual effects. Later, all the variables and their combinations were included into a multivariate analysis and we used the likelihood ratio test to remove those which appeared not to have effects in our full model. Our final model is characterized in Table 5.3. We calculated the odds ratios for factors affecting compliance. All statistical analyses were carried out using the R statistical package [112].

5.4 Results

Between May 2011, and July 2012, a total of 1936 animal bite patients attended clinics in the study area for their first dose of PEP and were enrolled in the study. 19% of patients (N=377) had no access to mobile phones and were excluded from the study (figure 5.4). The characteristics of all remaining patients enrolled in the study are described in Table 5.2. Initially we carried out univariate analysis of all covariates that we hypothesized may have affected adherence to PEP regimens. The following variables had significant effects on patients' adherence: SMS (SMS intervention group versus control); patients' residence (urban versus rural) and route of vaccine administration (ID versus IM). Patients in the intervention group who has been assigned SMS reminders had much better compliance with PEP regimens than those who had not been assigned SMS reminders (51% versus 41%). Except for compliance of those receiving PEP via the ID route, overall PEP compliance for the control group ranged from 31 – 44%, (N = 743), while in the SMS intervention compliance ranged from 42 – 60% (N = 816, Figure 5.5).

Table 5.2. Characteristics of patients (N=1599) who were enrolled into the PEP compliance study

Characteristic		Patients in the control group N (%)	Patients who received SMS reminders N (%)
Age	Child (below 18)	356 (48)	377 (46.20)
	Adult (above 18)	387 (52)	439 (53.80)
Gender	Female	286 (38.50)	315 (38.60)
	Male	457 (61.50)	501 (61.40)
Residence status	Rural clinics (42 clinics)	464 (62.45)	356 (43.63)
	Urban clinics (17 clinics)	279 (37.55)	460 (56.37)
Phone access	Own phones	306 (41.18)	480 (58.82)
	Shared phones	437 (58.82)	336 (41.18)
Regimen type	Intradermal (ID)	317 (42.66)	384 (47.06)
	Intramuscular (IM)	426 (57.34)	432 (52.94)
Total participants		743	816

Patients who were assigned SMS reminders (n = 816) had significantly better compliance with PEP regimens than those who did not (n = 743, 95% OR = 1.58, CI: 1.2 – 1.95, p < 0.001). Patients from rural areas were more compliant with their PEP regimens than those who were from urban areas (n= 356, 95% OR = 1.52, CI: 1.22 – 1.90, p = 0.0002). Patient's who were administered PEP via the IM route were less complaint compared to those who received PEP via the ID route (n=384, 95%, OR= 0.51, CI: 0.41 – 0.63, p < 0.001) (Table 5.3). We did not find any significant difference in PEP adherence between age groups (adult/ child), or phone access (own/ friend or family phone) (Figure 5.5).

Table 5.3. Comparison of adherence between groups, control versus SMS intervention. *indicates statistical significance

Patient categories (test variable)	Coefficient	OR (2.5% - 97% CI)	P-value
SMS	0.455	1.58 (1.28 – 1.95)	< 0.001 ***
Residence (rural)	0.421	1.52 (1.22 – 1.90)	0.0002 ***
Route of vaccines administration (IM)	- 0.673	0.51 (0.41 – 0.63)	< 0.001 ***

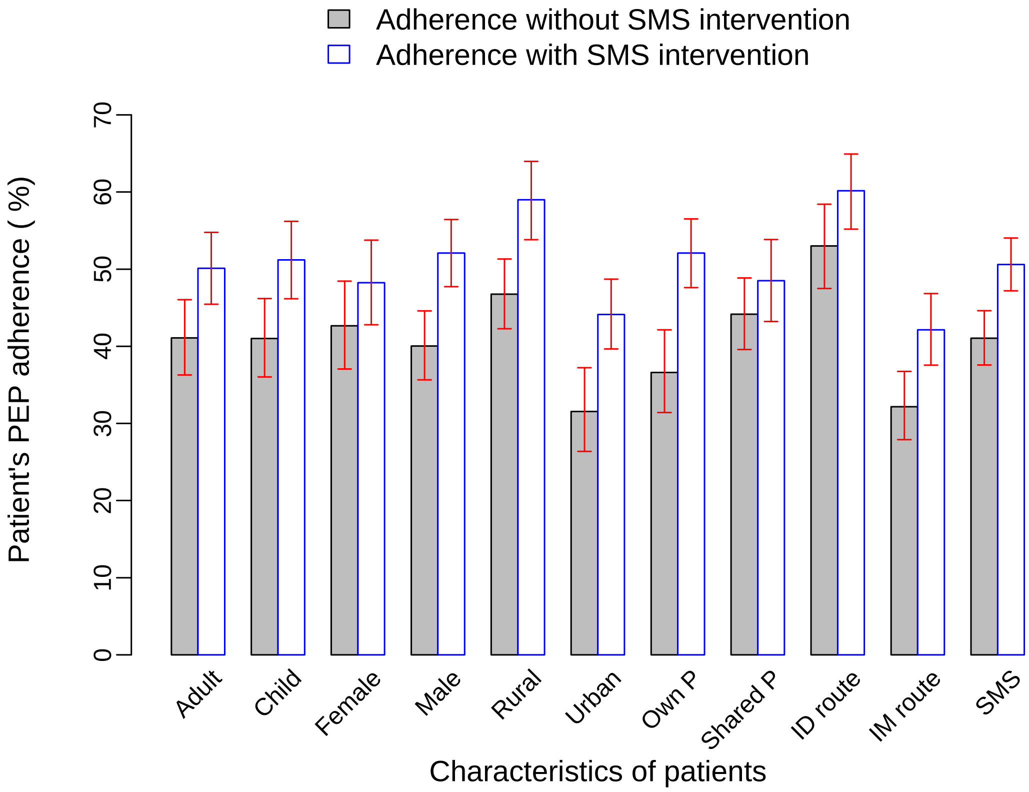


Figure 5.3.The effect of SMS reminders on patient compliance, broken down by: age, gender, residence, mobile phone access, route of vaccine administration and overall according to the SMS intervention.

5.5 Discussion

This study shows that short message service (SMS) reminders for animal bite victims may be able to improve their compliance with post-exposure prophylaxis (PEP). Patients who were assigned SMS reminders in this study had much better compliance with PEP regimens than those who did not (51% versus 41%). Except for the compliance of those receiving ID vaccinations, overall PEP compliance for the control group ranged from 31 – 44% (N = 743) while for those in the SMS intervention group compliance ranged from 42 – 60% (N = 816). These results demonstrated an overall improvement in PEP compliance of 10% (Figure 5.5).

For logistical reasons, it was not possible to run this study as a randomized controlled trial. The study design employed was practical for the situation, but had several limitations. It was not possible to determine the attributable effect of the SMS intervention, and seasonal effects could be confounding, for example changes in occupation and routines during different periods of the year affect a patient's ability to adhere to the PEP schedule. Nonetheless, this pilot study suggests that the use of SMS reminders to alert patients could be a useful tool for improving compliance and merits further investigation through a more robust and comprehensive study. Moreover, the poor overall compliance suggests that there is need to further study patients' reasons for abandoning treatment regimens, for example to know if patients have learned that the biting animal was healthy or has been certified by veterinary authorities. The poor compliance reported here might have been caused by a lack of awareness or forgetfulness. However, this study suggests that an SMS intervention that reminds patients and gives them information on where and when to attend has potential to greatly influence compliance.

The observed effect of higher compliance among the SMS intervention group was consistently positive across categories of patients irrespective of age, residence, gender, or route of vaccine administration (Figure 5.5). This result suggests that SMS reminders were well received by patients. It should be noted that although all patients in the intervention group were assigned SMS's, not all of these patients received the assigned SMS. This may have been a result of poor network connectivity in the area or at the time of the scheduled SMS, however the vast majority of SMS's were delivered on the first attempt (>90%). Another problem may have been that healthworkers did not enter data until after the SMS reminder was due, in which case no SMS would have been sent. Nonetheless, the observed increase in compliance across demographic categories suggests that overall the SMS intervention helped to improve adherence in the population. This may have been because patients received the SMS, but the intervention may have also increased rabies awareness and the need for prompt PEP among both the healthworkers who provide advice to patients and more generally among the community by providing information on where and when patients could obtain PEP free of charge.

Patients in rural areas were more complaint in PEP regimens than those from urban areas (Figure 5). The poorer compliance in urban areas suggests that patients in urban areas are more likely to abandon treatment regimens after their first clinic visit. This may indicate that animal bite victims in urban areas were more likely to access the veterinary authorities and check if the biting animal was healthy. Several studies have reported domestic dogs are the main cause of animal bite injuries [81,83], and that vaccination coverage is typically higher in urban areas than in rural areas (Chapter 4) [24,25]; therefore, there are many potential reasons why patients from urban areas may be more likely to abandon the PEP regimen. Further studies are needed to identify whether this poor compliance in urban areas was due to the success of animal vaccination campaigns and was certified from vets.

Our results shows the adherence rate reported among patients whose vaccines were administered through the IM route was lower compared to those who were administered PEP through ID (Table 5.3). In this study patient’s compliance were only determined by the ability of patients to return for the second dose, which is common for both ID’s and IM’s. But the SMS intervention may have also had an impact on adherence in terms of the timeliness with which patients attended hospital. This will be further investigated in future. It should also be noted that PEP administered through the ID route requires fewer clinic visits compared to the IM route. The greater compliance detected with the ID route suggests that the fewer visits required by the ID route may be a further incentive that increases compliance. WHO recommends ID because it is not only cost effective but it also requires less vaccine compared to the intramuscular (IM) route [128], therefore improved clinic attendance has an added advantage.

Previous studies have demonstrated that children < 15 years of age are at a higher risk of developing rabies compared to adults [49,101,122,134]. Our results however revealed that adults > 18 years of age were more vulnerable to animal bites compared to children < 18 years (Table 5.2). However, not all of these bites were due to rabid animals and only a small proportion of bites by rabid animals result in human rabies cases and this depends on whether or not PEP was administered. Our study may not reflect vulnerability to rabies, as those who do not obtain PEP or die from rabies without attending hospital are not recorded into our surveillance system. Indeed our study may reflect the greater likelihood that adults seek PEP in comparison to children.

Poor infrastructure and a lack of operational surveillance systems have resulted in insufficient healthcare, particularly in rural areas. Studies have identified substantial shortages of PEP where clinics/hospitals frequently experienced a lack of PEP and patients had to travel to multiple health facilities seeking PEP [48,49]. PEP shortages have a major effect on patient adherence with PEP regimens, which could further explain the poor compliance in our study, as shortages were still reported in some of the study clinics. Moreover, animal bite victims still had to pay relatively large sums for travel to a clinic with available rabies PEP, and many victims may have had the perception that they needed to pay for PEP. Thus, receiving an SMS that assured them when and at which facility they could obtain PEP regimens could have resulted in patients' better compliance.

The SMS intervention was well received by both patients and health workers since it involved less manual work and provided assurances of free-of-charge rabies PEP across all the study areas. The cost of PEP for a single dose is estimated at $7-14/per visit; therefore completing a full PEP course is beyond the average family in Tanzania [48]. Therefore, having free PEP had positive benefits for communities.

Unlike other studies, all the activities within this study including patients' enrolment, patients' PEP schedule assignments, and SMS management were automated. The intervention was centrally controlled, extending the capacity of the mobile phone-based surveillance system. Therefore, health workers were only involved in patients' registration for normal clinic attendance. The timing of the SMS intervention could have introduced potential biases. For example change in rabies awareness through time including awareness about the cost/availability of PEP may have influenced adherence. It is not clear if or why awareness might have changed over time, over the course of this study. However the pilot data collected strongly suggests that a more robust randomized controlled trial of an SMS intervention could provide valuable evidence as to the potential future value of SMS reminders to improve healthcare service delivery and uptake..

To our knowledge, this study is the first to test the use of automated computer-based SMS reminders for rabies PEP compliance. SMS trials have been tested for improved compliance in other health-related contexts [87,95]. Our results are comparable to other studies that found SMS interventions positively affected adherence rates [3,28,87] Elsewhere, SMS systems are being used in biomedical interventions; for example, in Tanzania an SMS-based voucher system is used as a maternal health intervention to control counterfeited vouchers targeting pregnant women in the distribution of long-lasting insecticide-impregnated nets [91]. Through SMS interventions in Nigeria, HIV and malaria programs have managed to reach 350,000 young people, providing them with protective and preventive education [108]. In Indonesia, SMS-based interventions for avian influenza encourage travellers to be careful and to test their knowledge of disease [53]. In Australia, SMS alerts were used to notify communities if they were within the danger zone of Avian Flu transmission, e.g. within 1 km of a potentially infectious region [102]. In South Africa SMS voting systems have been used to ask communities to share what they have done to advance an HIV-free generation [31].

We have shown that automated SMS reminders have potential to significantly improve patient adherence to rabies PEP regimens. This study would not have been possible without reliable surveillance to monitor patient’s compliance through time. Mobile computing technologies therefore have the potential to improve health information systems, notably, in the developing world, where weak surveillance systems relying largely on paper-based approaches are used. This study provides further evidence of how quality and efficiency in healthcare delivery can be achieved through effective disease surveillance.

6 General Discussion

The threat posed by emerging and re-emerging of zoonoses have prompted the needs to integrate human and animal health surveillance, so far none of the emerging infectious disease have been predicted before the first hit, despite most of them are originating in animals [45,104]. Effective diseases surveillance is essential to understand diseases pathogen epidemiology, which can be used for disease control programmes and future prediction to minimize the disease burden caused by epidemics [45]. The need for effective integration between human and animal surveillance has been repeatedly identified as key to the successful surveillance, explicitly for zoonoses [46]. However, disease surveillance systems should be designed to assure accurate and timely data across-geographic boundaries and to encompass human and animal health, where appropriate because "pathogens do not respect geographic or species differences"[37].

Developing countries are more susceptible to infectious disease outbreaks, have less capacity to detect or report them, and are also least able to monitor and evaluate biomedical interventions in a timely manner [9,13,64,89,113]. A revolution in mobile computing applications and systems have brought greatly potential that can be applied to strengthen health information systems. This potential have proven largely growth and wide use of mobile phones in most of resource-limited settings, which hold great potential value for infectious disease surveillance, but have yet to be widely applied. There is a need to explore use of mobile phones as tools for surveillance in field trials to address current knowledge gaps and to see how they can be applied in resource-limited settings. This innovation should be targeted towards the development of mobile phone-based surveillance for animal and human health, data collection and handling systems that prioritise timeliness and two-way communication [93].

This thesis documented the use of mobile phone devices for health surveillance systems, as an alternative approach that can be potentially used to replicate traditional approach for health surveillance in resource-limited settings. We have demonstrated how mobile phone-based surveillance system can be applied into health systems as well as constructive challenges that arose whilst implementing a mobile phone-based surveillance system into large-scale infectious disease control interventions in southern Tanzania.

The case studies described here include lessons learnt in a large-scale rabies elimination project in twenty-eight districts in the southeast of the country. This is the first time a mobile phone surveillance system has been used for the real-time evaluation of rabies control in Africa, and demonstrates the value of sharing both human and animal health data.

In many resource-limited settings, infrastructure is generally very poor, power may be unreliable and much of the population may be based in remote areas with little access to modern computing technology. Infectious disease surveillance systems, though available, are often not well implemented and may be poorly designed providing little incentive for compliance by health or veterinary workers. Nsubuga et al. (2010) reported numerous challenges that existed for diseases surveillance systems in Africa, including: lack of awareness of standardised surveillance case definitions; delayed, incomplete disease reporting; and delayed investigation of case reports or suspected outbreaks [106]. Moreover, most current surveillance operates under a paper-based approach, which is error prone and time consuming to access and evaluate information. Several studies have looked into positive impacts that exist from adopting digital health information systems and how these systems can be introduced in developing countries to offer quality, effectiveness and efficiency [14,40,41,74,110]. However, these initiatives have mainly been computer-based surveillance systems, which do not function well when there are unreliable power and Internet connections, poor infrastructure and lack of facilities and trained people capable of using them.

On the other hand, developing countries have the fastest growing mobile markets in the world [7]. For people with no computer access, a mobile phone will be their first computing device. Mobile phone coverage can be found even in remote villages in Africa where local inhabitants have never seen computers. Mobile technologies offer a significant alternative approach to strengthen health information systems in resource limited settings, with respect to community based engagement in health interventions, reporting and sharing of immediate information with two-way communication.

Their ease-of-use makes these devices well accepted in the developing world, as only basic knowledge is required to operate them. They are also inexpensive, making them available in limited-resource settings, driving the exceptional growth in ownership compared to computers or other digital technologies [93]. Our findings have shown, despite the existence of digital illiteracy and poor infrastructure in our study area, that mobile phones had successfully emerged and promise to be a quick fix for digital communication in developing countries, we identified fewer computer and internet users compared to those who had access to mobile phones and SMS as the way of daily communication [117]. In chapter 2, we examined constraints and looked for possible ways to strengthen this potential; we designed and implemented a robust user-friendly mobile phone-based infectious disease surveillance system in a resource-limited setting, and through this case study we demonstrated various key challenges that can be used to build effective and sustainable systems under resource-limited settings.

Our results indicated that the uptake of mobile phone-based surveillance systems is largely determined by the users' digital experience through digital literacy and ownership. Therefore, to avoid unreliable data capture, user experience has to be given priority from early in the design stage. Incorporating the local language that will reduce the challenges of language barrier particular when the studies involves different education levels, nevertheless collecting minimum data necessary, none exhaustive user interface such as multiple questions with dynamic selection that can properly fit into the small screen are the key to success. Our findings identified different types of users who had different abilities and experience with technology. Users who had the most trouble using the system and required more assistance were those over 50 years old and those with only primary school-level education. Our findings also suggested that users who were familiar with digital technology, i.e. who owned and regularly used mobile phones, were able to more rapidly use the system and were less error prone. Therefore, we strongly recommend appropriate user training, which includes in-person user training and evaluation to understand what are the user limitations in digital technology, when necessary diagram and other pictorial instruction needs to be prepared as summary leaflet to remind user how to tackle some task, on the other hand we recommends regular supervision to evaluate the user experience.

In many of developing countries number of health information system have been implemented, but most these system have proven completely or partial unsustainable due to different limitations [74]. Some failed due to inadequate infrastructure and human resource capacity to drive these systems, while others suffered improper policy and approaches to adopt these systems. It should noted, the majority of the systems that are being shipped and implemented in developing countries, the top-down approach have largely lack local-integration [74]. The designed system has to reflect the challenges that exist in developing countries; for example roads and Internet connections often are limited. The distance between the head office and health facilities where mobile phone-based surveillance operates varies and the roads to drive from one to another are frequently not reliable. Sometimes it takes a day or more for system administrators to get physical access to a device or user. To accommodate large-scale implementation, the system needs to allow remote deployment and management of the end user application on the device for data validation. The application has to be able to carry on data collection even out of network reception to accommodate unpredictable power cuts and to later upload this information when the power supply or reception returns. Data ethics for health surveillance differ from one country to another, medical surveillance data are subjected to data ethics in different areas to maintain security and confidentiality of information; therefore surveillance systems design has to ensure privacy concerns. For example, in dealing with HIV or animal bite injury data, it is a risk for patients if their communities discover their HIV status or other sensitive medical information. The surveillance system has to maintain data encryptions and be password secured.

In many places, particularly in developing countries, adopting WHO guidelines for public health surveillance systems is a challenge [66]. Surveillance systems in developing countries lack priorities and motivation, lead to high underreporting and significant delays in detecting infectious diseases compared to other regions such as the Americas and Europe [13,74]. Additionally, paper-based surveillance information was not reported in a timely manner, which makes it difficult for control programs to immediately respond and appropriately allocate resources.

Despite mandatory reporting rules for notifiable infectious diseases[9,132] such as rabies, paper-based systems only report on an annual basis, which is not sufficient. Furthermore, paper-based records are often incomplete, lacking geographical information about outbreaks and demographic information about patients and timing of events, e.g. exposures and presentation to hospital. Summary records lack individual data that may be important for initiating responses or to evaluate interventions. In a comparison study that was conducted to reveal case detection capacity between paper-based versus mobile phone-based surveillance, findings shows records reported by paper-based methods are much fewer compared to those reported by the mobile phone based systems. Further study to asses directly disease surveillance sensitivity in reporting is needed, most likely our results is that mobile surveillance is more sensitive than paper based surveillance, but might be other possible explanations such as a change in true prevalence, or a change in awareness of disease. However, less case detection suggests that underreporting is more of a problem for paper-based than mobile-based systems. Paper-based systems also require high maintenance costs for collecting information. More manpower is required for data entry and data cleaning of paper-based records. Mobile phone based systems require more capital investment initially, but may be more sustainable in the long-term. Traditional paper-based surveillance is difficult to share amongst diverse stakeholders. Processing and accessing paper records are always difficult and time consuming to create and share timely reports across sectors, storage and keeping records for the required time can be also challenge into adhesive whether. To conclude, data completeness is more easily controlled through digital technology, while timeliness reporting for infectious disease is difficult to achieve through paper-based methods as the operational costs are higher and transcription is particularly time-consuming.

In Chapter 4, we evaluated the impact of a rabies control programme using a mobile phone-based surveillance system across twenty-eight districts in southern Tanzania. We examined a range of epidemiological and geographical variables related to bite incidence in addition to the effects of the control programme. There was considerable variation in animal bite injuries across districts. There were more animal bite injuries observed on the Tanzanian mainland than on the island of Pemba. While overall there were more bite injuries in urban settings than in rural settings, the incidence of bite injuries (per 100,000 people) in rural areas was higher than in urban areas. This was likely due to higher levels of dog ownership in rural areas than in urban areas, i.e. areas with higher human-dog ratios had fewer animal bite injuries.

More bite injuries were observed in districts that already had high incidence of injuries, and in districts with large numbers of bites in neighbouring districts. Incidence of bite injuries was also higher in districts where the incidence of bite injuries in neighbouring districts is already high. These results suggest that rabies outbreaks are the cause of many of these bites injuries, because an underlying infectious process is observed. In different studies conducted in northern Tanzania, Hampson et al. (2009) and Lembo et al. (2008) heighted the evidence of transmission dynamics, between species and the movements of reservoirs from one place to another [51,83]. However, the only solution that we fount in our results is vaccination coverage have the potential to reduced numbers of animal bite injuries, above all the mentioned risks.

Overall, vaccination coverage has increased with the implementation of vaccination campaigns across districts. However, some districts have achieved higher coverage than others. Given the WHO target vaccination coverage is 70% in all areas, there is room for improvement in most districts. Mobile phone-based surveillance systems have proven to be a potential tool that can deliver significant improvements in disease surveillance. Our surveillance system has managed to strengthen and integrate human and animal surveillance; valuable data and reports were shared among stakeholders in order to monitor and evaluate the impacts of the control programme. Note, however, due to the detailed nature of the mobile phone-based surveillance data, it has been possible to conduct statistical analyses of the impact of the project intervention on rabies incidence: vaccination coverage has reduced the number of animal bite injuries reported to hospitals in the project area, an effect which has been found to be highly significant. Through this surveillance we have highlighted areas with higher incidence of dog bite injuries, so that vaccination efforts can be improved. In particular, the system potentially can show in a timely manner when vaccination efforts have been very poor and need to be improved.

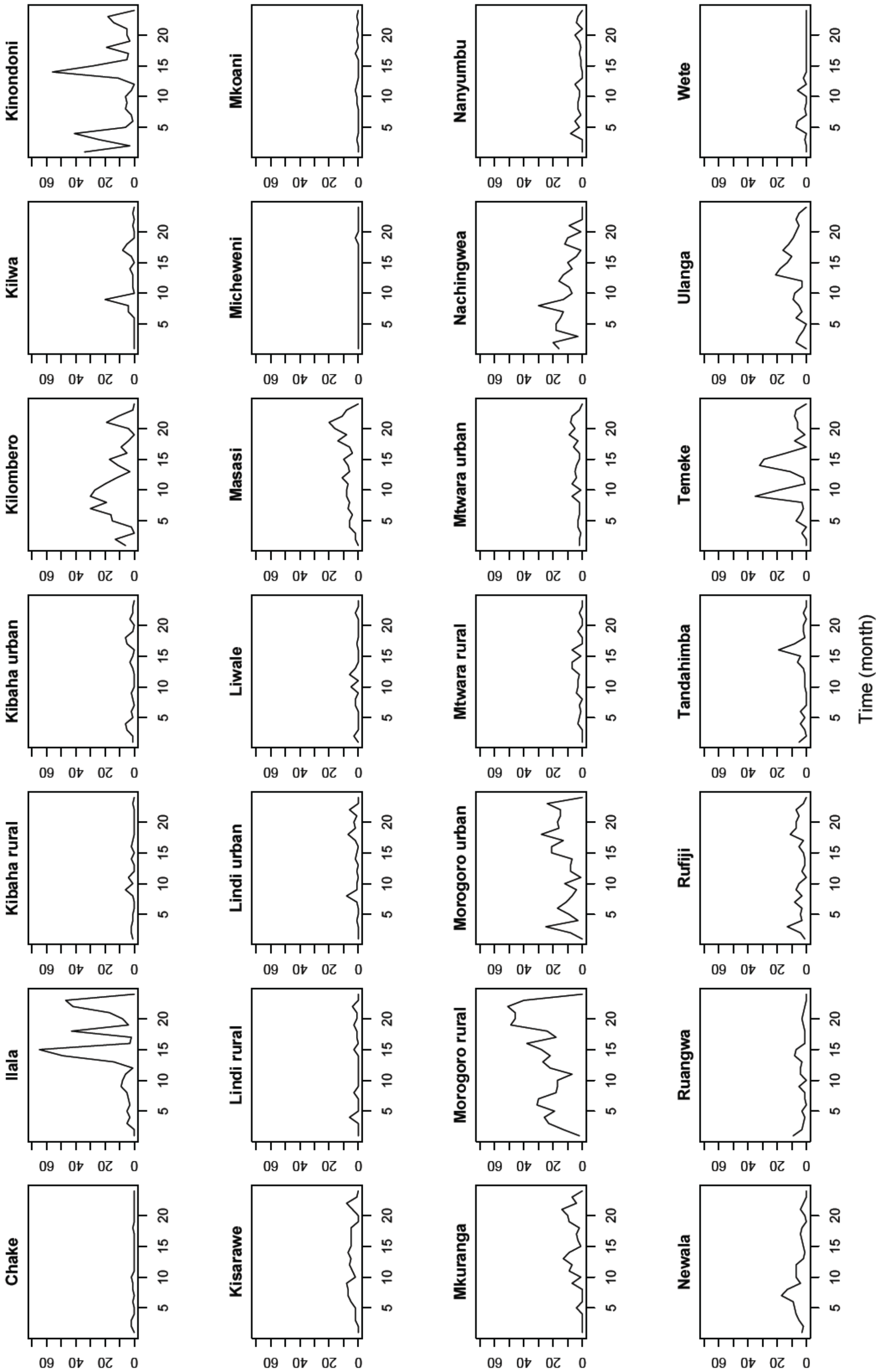
Finally, in Chapter 5, the mobile phone based surveillance system was used to collects detailed information on animal bite injuries at clinics attendance for PEP. Poor compliance with treatment regimens is a common problem in many countries, but that can be avoided through effective surveillance system that can monitor the patient’s compliance. Having detected the poor adherence on PEP regimens, short message service (SMS) was developed as an intervention to reminds animal bites injuries patient’s prior their PEP regimen. We found that patients who received SMS reminders had better compliance with PEP regimens than those who did not. This suggests that much of the incompliance in regimens is due to be caused by lack of information on where and when patients can get PEP, although that can also be linked with forgetful and lack of disease awareness. Similarly, SMS intervention not only improved the compliance but also has helped to build the disease awareness.

Our analysis reviled SMS intervention had consistently increased positive outcomes across categories of patients irrespective of age groups, residence, gender, or route of vaccine administration. We identified patient's compliance was also affected by route of vaccine administration and patient residence. Further, we did not find any significant difference in PEP adherence between age group (adult/child) or phone access (own/ friend or family phone). There may be more reason to explain why SMS intervention was successful to boost PEP compliance, and although some of non-compliances might have been caused by lack of awareness or forgetfulness but the PEP shortages have a major effect on patient adherence with PEP regimens, which could further explain the poor compliance in our study. Therefore having SMS intervention which assure you where and when you can obtain the PEP could the better answer for our success.

7 Appendixes

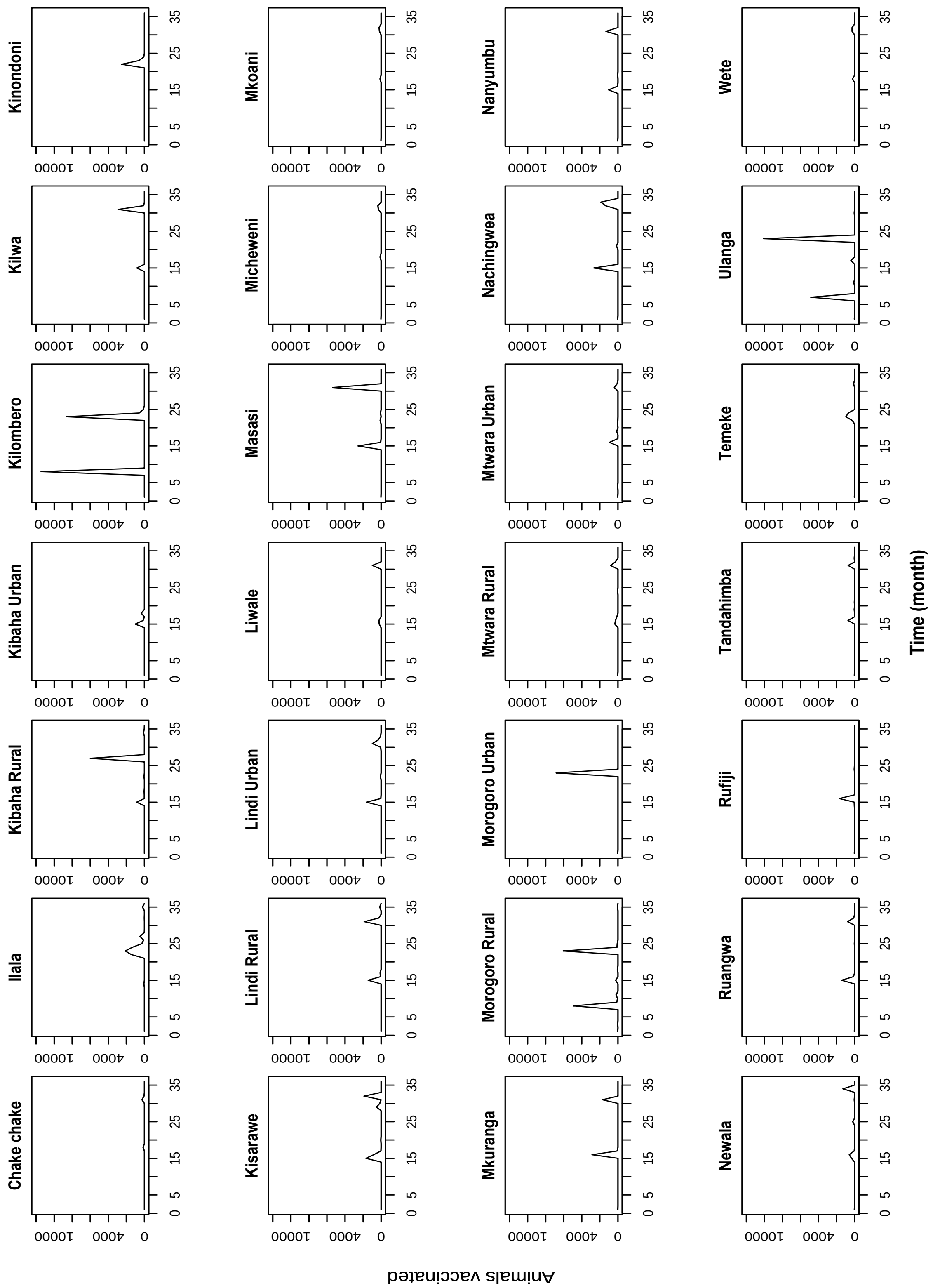
7.1 Appendix I

Figure 7.1. Animal bite injuries per month in every district in the study area from January 2011 until December 2012.



7.2 Appendix II

Figure 7.2. Dogs vaccinated each month in every district in the study area from January 2010 until December 2012.



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