Title

Understanding reservoirs of multi-host pathogens: A One Health approach to rabies in Tanzania

Summary/Abstract

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In this case study we report on a One Health approach to rabies in Tanzania. We highlight the importance of multi-sectoral collaboration in understanding the local epidemiology of rabies and show that domestic dog vaccination plays a vital role in disease control in two areas with very different disease ecology.

Abstract

Rabies virus is a multi-host zoonotic pathogen that is endemic across large parts of sub-Saharan Africa. This case study reports a One Health approach to rabies in Tanzania which highlights the value of multi-sectoral collaboration and illustrates the importance of understanding the reservoir dynamics of multi-host pathogens when targeting interventions.

As part of our research we have established contact tracing for rabies in Tanzania. This involves identifying patients presenting with animal-bite injuries and investigating the animals responsible for the bites. Through contact tracing we identify the owners of biting animals, ascertain the rabies status of these animals, and identify additional bite victims who have not presented to healthcare centres.

Domestic dog vaccination is a key component of current rabies control programmes as domestic dogs are responsible for most human rabies exposures across Africa. However, in some areas rabies transmission also occurs within wildlife populations. For example, in the Lindi and Mtwara regions of southern Tanzania, jackals represent an unusually high proportion of animal rabies cases. Maintenance of rabies virus within wildlife populations can have implications for control strategies centred around domestic dog vaccination.

Throughout this case study we illustrate the use of multiple data sources to identify the role of domestic dogs and wildlife in rabies transmission in the Lindi and Mtwara regions of southern Tanzania and compare this to the island of Pemba where domestic dog cases dominate. We highlight how domestic dog vaccination plays a vital role in controlling rabies in these two areas with very different disease ecology.

What is the incremental value that makes this a One Health case?

Rabies is a fatal viral disease that is most commonly transmitted to humans by bites from infected animals. Whilst prompt administration of post-exposure prophylaxis (PEP) (which comprises of wound washing, a series of post-exposure rabies vaccinations and, if indicated, administration of rabies immunoglobulin) to people exposed to rabies can prevent the disease developing, it does not tackle the source of the disease. The One Health approach recognising the link between human, animal and ecosystem health is highlighted in this case study by illustrating, with the help of two distinct examples from different sites in Tanzania, how preventing rabies in domestic animals can have wide-reaching benefits.

As a multi-host pathogen capable of infecting any mammal, rabies virus is particularly suited to a One Health approach to its control. Controlling rabies within animal populations benefits not only those animals, but also benefits human health and the health of other animal populations through a reduction in onward transmission. Interruption of rabies transmission can also have positive conservation impacts as previous rabies outbreaks in endangered species such as Ethiopian wolves and African wild dogs have been devastating (Johnson et al., 2010; Kat et al., 1997; Randall et al., 2006; Sillero-Zubiri et al., 1996).

This case study also highlights how cooperation between the human healthcare and veterinary sectors can lead to enhanced disease surveillance, improved evaluation of disease control interventions and greater understanding of the transmission dynamics amongst animal host species. By understanding which species are responsible for maintaining circulation of rabies virus (domestic dogs in Tanzania) and targeting interventions at those species, we increase the likelihood of rabies elimination locally and therefore reduce the risk of future human rabies exposures. This particularly benefits poor and marginalised communities who may not be able to access the PEP that is required if they were bitten by a rabid animal.

Learning outcomes

1. Illustrate how collaboration between workers in the human healthcare and veterinary sectors can enhance surveillance and maximise the impact of control strategies for zoonotic diseases such as rabies.
2. Highlight how identification of the species essential to sustained circulation of multi-host pathogens aids in optimising interventions.

Background and context

Rabies is a deadly viral disease that claims tens of thousands of lives each year worldwide (Hampson et al., 2015). A large proportion of these deaths occur in children under 15 years of age (World Health Organization, 2024). These figures are especially shocking when we consider that rabies is a vaccine-preventable disease and that safe and effective rabies vaccines have been available for many decades.

Domestic dogs are responsible for approximately 99% of human rabies cases (World Health Organization, 2024) with transmission to humans commonly occurring via bites from infected animals. Once the symptoms of rabies develop, the disease is invariably fatal. Prompt administration of PEP can effectively prevent the disease, but barriers to access of PEP exist in many rabies-endemic countries.

Widespread domestic dog vaccination across Europe, North America, and more recently Latin America, has all but eliminated dog-mediated human rabies cases in these regions. In contrast, rabies is still endemic in large parts of Africa and Asia, predominantly affecting poor and marginalised communities. Africa has the highest estimated per capita rate of human rabies deaths globally at 2.09 deaths per 100,000 people (Hampson et al., 2015; Taylor and Nel, 2015). In 2015, the 'Zero by 30' target to achieve zero human dog-mediated rabies deaths by 2030 was set. Effective surveillance and widespread domestic dog rabies vaccination are vital components in achieving this target of Zero by 30. More information on the Zero by 30 strategy can be found on the World Health Organization (WHO) website linked below in Further Reading.

Whilst nearly all transmission of rabies to humans comes from domestic dogs, some wildlife populations can maintain circulation of rabies virus. Across Africa, there is evidence that some wildlife species such as jackals and bat-eared foxes may be capable of maintaining circulation of rabies virus independently of domestic dogs (Bingham et al., 1999; Meredith and Thomson, 1993; Swanepoel et al., 1993). This has led to concerns that domestic dog vaccination alone will not be effective in controlling rabies transmission and preventing human rabies deaths in an African context.

Understanding which species are maintaining circulation of the pathogen of interest is key when planning control strategies for multi-host pathogens. If there is a single species maintaining the virus (the maintenance host) and only limited ongoing transmission within other species following spillover events, interventions targeted at the maintenance host should, in time, eliminate the disease from all species (Haydon et al., 2002). This was seen with rinderpest, a pathogen capable of infecting more than 40 species, when vaccination of cattle alone was able to eradicate the disease (Youde, 2013). If a virus is maintained in two or more separate host species, either with each serving as an individual maintenance host or with multiple host species serving as a combined maintenance population, control strategies targeted at one of these host species may be less effective as the pathogen may continue to circulate in the other host(s). If we can determine which host species are responsible for maintaining a pathogen we can target interventions accordingly. However, this is often not straightforward and it may be necessary to combine multiple sources of information to determine the maintenance hosts. An example of this is seen in the wildlife-rich ecosystem of Serengeti in northern Tanzania where multiple data sources were used to determine that domestic dogs were the only population essential for maintenance of rabies, although other carnivores contributed to the continued circulation of rabies virus as non-maintenance populations (Lembo et al., 2008).

Rabies is endemic in Tanzania and is a legally notifiable disease of both humans and animals. The annual incidence of human exposure to rabies via bites from probable rabid animals varies across the country with estimates ranging from 11.3 to 75.6 per 100,000 people (Changalucha et al., 2019; Sambo et al., 2013). The incidence of human rabies deaths in Tanzania is estimated to be between 0.8 to 2.4 per 100,000 people per year (Sambo et al., 2013). Access to life-saving PEP across Tanzania is limited by cost and availability (Changalucha et al., 2019; Sambo et al., 2013). Whilst access to PEP clearly needs to be improved, a One Health approach to rabies control would reduce human rabies exposures and thereby reduce the reliance on emergency PEP.

In 2010, a rabies elimination demonstration project commenced throughout the southern Tanzanian regions of Lindi, Mtwara, Morogoro, Pwani, Dar es Salaam and Pemba Island. This large-scale government-led intervention project was coordinated by the WHO and funded by the Bill and Melinda Gates Foundation. The goals of the demonstration project were to demonstrate the feasibility of the control and eventual elimination of canine rabies through mass dog vaccination, improve access to PEP (which was provided free of charge throughout the project), and improve surveillance and diagnostics (Mpolya et al., 2017; Sambo et al., 2022). The project was initially planned as a five-year project but was extended, meaning that the final project-funded domestic dog vaccination campaigns occurred from late 2016 to early 2017.

In this case study, we report on how a One Health approach has been successfully implemented to reduce both human and animal rabies cases in areas with very different disease ecology and highlight the importance of transdisciplinary collaboration in this success. We focus on the regions of Lindi and Mtwara in southern Tanzania where wildlife comprise a large proportion of animal rabies cases and compare these regions to the island of Pemba where domestic dog rabies cases predominate (Figure 1).

Figure 1: Map of the study area with the regions of Lindi, Mtwara and the island of Pemba shaded in light blue.

Transdisciplinary Process

Contact Tracing

Surveillance is a vital part of disease control programmes. Without an accurate understanding of the disease burden, we cannot track progress in disease control programmes or assess the effectiveness of interventions. Under-reporting of rabies is common in countries in which rabies is endemic. Across Africa and Asia, it has been estimated that official reports of human rabies deaths represent less than 3% of the deaths that actually occur (Knobel et al., 2005). A study from Tanzania in 2002 estimated the annual number of human rabies deaths at 1,499 per year, whilst official estimates for the same period recorded the mean number of rabies deaths per year as 10.8, suggesting that fewer than 1 in 100 deaths were reported (Cleaveland, 2002). Given the degree of under-reporting of human rabies deaths, it seems likely that there will be substantial under-reporting of animal rabies cases also (Nel, 2013).

Contact tracing provides a way of enhancing disease surveillance and improving estimates of disease burden, and is more tractable where the number of infectious cases is low. Contact tracing to enhance rabies surveillance has been successfully used across multiple regions of Tanzania (Hampson et al., 2008; Lembo et al., 2008; Lushasi et al., 2023, 2021) and was implemented across Lindi, Mtwara and Pemba as part of the rabies elimination demonstration project. For success, it relies on collaboration between human healthcare workers, veterinary field officers and researchers. Data on patients presenting with bites from probable rabid animals are obtained from healthcare centres and case reports of sick or biting animals are obtained from livestock field officers (LFOs). All animal-bite victims and owners of biting animals are traced and interviewed by researchers from the rabies research team at the Ifakara Health Institute (IHI) in Tanzania who are supported by Wellcome Trust-funded projects. The researchers work in collaboration with LFOs and local guides from village offices to obtain details regarding the bite incident. Rabies virus causes an acute encephalitis which often manifests in animals as increased aggression and a tendency to bite. These characteristic clinical signs and distinct route of transmission mean that rabies exposure events are often memorable to both those affected and to their friends and family. Details regarding the animal's behaviour and the circumstances of the bite are used to assess whether the animal is considered likely to have been rabid. Probable rabid animals are defined in accordance with the WHO definitions to describe animal rabies cases (see WHO Expert Consultation on Rabies linked below in Further Reading). If additional animal-bite victims or owners of additional biting animals are identified during investigations, they are also traced and interviewed. By interviewing people bitten by probable rabid animals, data on the species of the rabid animal and other animals that it has bitten may be obtained, improving our understanding of inter-species transmission events.

If probable rabid animals (domestic or wildlife) are identified during investigations and the animal has died or been euthanised, brain samples are collected for rabies testing. Samples are collected by LFOs and preliminary testing undertaken on site using a rapid diagnostic test, with additional samples sent to the Tanzania Veterinary Laboratory Agency for confirmatory testing.

The contact tracing surveillance method implemented throughout the project utilises human animal-bites to identify probable rabid animals and was the same across all of the project areas. Efforts were thus focussed on human settlement areas, excluding wildlife protected areas such as national parks and game reserves.

Figure 2: Contact tracing being undertaken in a village in southern Tanzania. Researchers work with local guides and/or livestock field officers to identify animal-bite victims and interview them about their potential rabies exposure.

Vaccination Campaigns

As part of the rabies elimination demonstration project, five rounds of mass dog vaccination campaigns were undertaken in the project regions between 2010 and late 2016/early 2017 (Mpolya et al., 2017; Sambo et al., 2022). The exact timing of the vaccination rounds varied between districts. No widespread mass dog vaccination campaigns had been undertaken in Lindi and Mtwara regions or on Pemba prior to this project. Dog vaccination campaigns were managed and supervised by District Veterinary Officers or the Head of the Livestock department and undertaken by LFOs.

Discussions with local authorities and village leaders were undertaken prior to vaccination campaigns to ensure that communities were aware of the campaigns, which were advertised using loud speakers, fliers, announcements at schools, and community messengers. A central point vaccination strategy was used whereby owners bring their dogs to a central location. Vaccinations were administered free of charge. From 2013 onwards, transects were undertaken following vaccination campaigns to enable assessment of the level of domestic dog vaccination coverage achieved (Sambo et al., 2017). Transects were undertaken by two trained enumerators in the evening of the same day as the vaccination campaigns. Each enumerator would walk (or occasionally cycle) a separate route through a village recording all of the marked (vaccinated) and unmarked (unvaccinated) dogs that were observed during a one-hour period.

Capacity building

As part of the project, over 250 government-employed healthcare workers, LFOs, and veterinarians have been trained in rabies surveillance and data reporting. Healthcare workers received training on PEP administration protocols, conducting joint rabies risk assessments for animal-bite victims, and on the importance of One Health collaboration in rabies control. Similarly, LFOs and veterinarians were trained in animal investigations, conducting joint rabies risk assessments for suspected animal rabies cases, sample collection, and field testing using rapid diagnostic tests.

In addition, local researchers have benefited from capacity-building initiatives at various levels, including support for Master's (4 researchers) and PhD (4 researchers) programmes, as well as participation in specialized short training courses in areas such as bioinformatics and modelling. These researchers have presented the project’s findings at both local and international conferences, fostering knowledge exchange and collaboration.

Project Impact

Data collection based around contact tracing has enabled assessment of trends in both human and animal rabies cases and underpinned a better understanding of both the burden and the local epidemiology of disease in the areas being studied.

Pemba Island

Annual domestic dog vaccination campaigns were undertaken across Pemba from 2010 – 2014. Prior to this period, rabies was considered endemic on Pemba. All of the animal rabies cases identified on Pemba were from domestic dogs. Following implementation of mass dog vaccination, rabies was eliminated on Pemba by May 2014 and no human rabies exposures, human rabies deaths or animal rabies cases were detected between May 2014 and July 2016 (Lushasi et al., 2023). A rabies outbreak was identified in August 2016, which authorities were alerted to by an influx of animal-bite patients in the hospitals on Pemba. Phylogenetic analyses confirmed that the outbreak was due to imported cases in dogs, rather than continued circulation of lineages that circulated previously (Lushasi et al., 2023). Domestic dog vaccination was reinstated, initially locally, but then island-wide, with high vaccination coverage achieved. Following the reinstatement of annual domestic dog vaccination, cases have once again declined with the last rabies case on Pemba identified in October 2018 (Figure 3). Analyses showed that the combined One Health approach of widespread annual domestic dog vaccination combined with free PEP for animal-bite victims rapidly eliminated rabies across Pemba and was highly cost-effective. Projections over a ten-year period suggested that with this One Health approach, no deaths would be predicted to occur after year four and that 71 deaths would be prevented overall at a cost of $1,657 per death averted (Lushasi et al., 2023).

Figure 3: Animal rabies cases and human deaths across Pemba from 2010 to 2022. Bars represent cases in animals, all of which were in domestic dogs. Annual domestic dog vaccination occurred during 2010-2014 and was restarted in 2016. Mass dog vaccination campaigns are depicted by vertical dotted lines. Annual mass dog vaccination is ongoing since 2016 but details of timing of recent campaigns were unavailable at the time of writing. Dots represent human rabies deaths scaled by the number of deaths.

Lindi and Mtwara

Extensive analyses have been undertaken of the data from Lindi and Mtwara for the period January 2010 to July 2019, with further analyses ongoing to incorporate more recent data. The last widespread dog vaccination campaign in these regions was undertaken in 2016.

During the period of domestic dog vaccination, there was a marked reduction in the number of animal rabies cases, human rabies exposures and human rabies deaths. Regression models confirmed a statistically significant reduction in animal rabies cases from January 2010 until August 2017 (Lushasi et al., 2021). Following cessation of domestic dog vaccination campaigns, the number of both human and animal rabies cases has steadily increased to return to the levels seen at the start of the demonstration project (Figure 4).

Figure 4: Animal rabies cases and human rabies deaths by species in Lindi and Mtwara from 2011 to 2022. Bars represent cases in domestic dogs (red), jackals (blue), other domestic animals (cats) (pink) and other wildlife (pale blue). Dashed lines indicate vaccination campaigns from 2011 to 2016. Dots represent human rabies deaths scaled by the number of deaths.

Approximately 40% of animal rabies cases observed in Lindi and Mtwara during the first eight-and-a-half years of the study were in jackals (Lushasi et al., 2021). The wildlife cases were found across all districts within the regions and did not appear to be clustered around the wildlife protected area of the Selous game reserve (Figure 5). This raised questions about whether jackals could be contributing to maintenance of rabies virus within Lindi and Mtwara. Understanding the transmission dynamics and roles of different species in maintaining rabies virus within this area was thus considered a priority due to the potential impact of additional maintenance host species on the effectiveness of control programmes centred around domestic dog vaccination.

Figure 5: Locations of animal rabies cases across Lindi and Mtwara regions from 2011 to 2022. The Selous game reserve (a wildlife protected area) is shaded grey. Domestic dog cases are shown in red and wildlife cases in blue.

Reconstruction of transmission chains using the detailed spatial and temporal data from contact tracing showed that frequent inter-species transmission was occurring, suggesting that rabies virus was readily transmitted between species. Inter-species transmission occurred in both directions (from domestic animals to wildlife and from wildlife to domestic animals) suggesting that wildlife, especially jackals, were not 'dead-end' hosts and were contributing to ongoing transmission (Lushasi et al., 2021). This presence of rabies in wildlife and frequent inter-species transmission might have been a barrier to interventions centred around domestic dog vaccination. However, over the period of domestic dog vaccination, a decline was seen in rabies cases in both domestic dogs and wildlife. Our analyses allowed us to infer a causal association of the vaccination campaigns with the decrease in cases and show that increasing domestic dog vaccination coverage was associated with a decrease in rabies cases in jackals as well as domestic dogs. A 35% increase in vaccination coverage (35% was the median vaccination coverage achieved across districts) was associated with a reduction in the incidence of dog rabies cases of up to 86% and a reduction in the incidence of jackal rabies cases of up to 91% (Hayes et al., 2022). By combining results from different analyses, we demonstrated that dogs alone were responsible for maintaining rabies virus in the region and that domestic dog vaccination was effective in reducing rabies in dogs, humans and other species of animal, including jackals.

Combined impacts

Following implementation of domestic dog vaccination in Pemba, Lindi and Mtwara, the number of animal rabies cases, human exposures to rabies and the number of human rabies deaths were all substantially reduced. In Pemba, rabies was eliminated initially in 2014, but freedom from disease was short-lived. However, since the subsequent outbreak was eliminated in 2018, the island remains rabies-free (as of August 2024). Domestic dog vaccination effectively reduced the number of animal rabies cases across all species which led to fewer people being exposed to rabies. By reducing human rabies exposures, we reduce the need for PEP, which can be challenging for people to access due to long travel distances to healthcare facilities and limited availability and affordability.

Surveillance is essential for understanding disease burdens and for assessing the impact of interventions. Contact tracing in southern Tanzania has given us insight into both the level of infection and the local rabies transmission dynamics. Contact tracing also allows identification of people exposed to rabies that have not sought appropriate healthcare. These people can be encouraged to seek PEP and their reasons for not seeking or receiving PEP can be identified, which helps to avoid unnecessary rabies deaths and provides insight into why these preventable deaths may occur.

Understanding the role of the different species in maintaining rabies allows us to advocate for the most appropriate interventions. Across Africa, the diversity of wildlife species and presence of rabies within wildlife populations has been previously seen as a potential barrier to interventions centred around domestic dog vaccination. By showing that, even in the Lindi and Mtwara regions where jackals comprised around 40% of animal rabies cases, domestic dog vaccination was effective in controlling rabies across all species and reducing the number of human rabies exposures and deaths, we have provided evidence to policy makers that investment in domestic dog vaccination is worthwhile. Moreover, while rabies continues to circulate in dogs, contact tracing reveals the risk of spillover to wildlife remains high.

Under this project, three PhD candidates and three MSc students have been trained, leading to an increase in local research capacity. Additionally, over 250 government staff members, including healthcare workers and LFOs across Lindi and Mtwara, have benefited from rabies-related training programs.

Project Outlook

Despite the end of the rabies elimination demonstration project, contact tracing (supported by Wellcome Trust-funded projects) continues in Lindi and Mtwara and analysis of the data from recent years is ongoing. In 2018, following the rabies elimination demonstration project, an active One Health surveillance approach, known as integrated bite case management (IBCM), was introduced across the study regions. Under the IBCM system, veterinary and livestock officers investigate suspected animal rabies cases reported by healthcare workers treating animal-bite victims seeking PEP. IBCM has become an integral part of the daily responsibilities of both veterinary officers and healthcare workers. The IHI rabies research team use the data collected through IBCM to implement contact tracing across Lindi and Mtwara. Within the framework of IBCM, healthcare workers conduct risk assessments for animal-bite victims, while veterinarians handle animal investigations, sample collection, and testing. Together, they ensure that PEP is correctly administered to individuals who have been exposed to rabies. Epidemiological investigations under IBCM focus on confirming the rabies status of animals that have bitten someone and identifying other exposed individuals who need referral to health facilities for PEP. This targeted approach is less labour-intensive compared to contact tracing, which involves gathering extensive additional information about the animal (such as tracing the animal it was bitten by or identifying its other contacts). Because of its focused nature, IBCM is more sustainable and feasible to implement on a wider scale than contact tracing.

On Pemba Island, contact tracing was discontinued in 2018 following the local elimination of rabies. Instead, the Ministries of Health and Livestock Development, with support from the IHI rabies research team, established IBCM to monitor any suspected rabies cases. Fortunately, since the elimination of rabies in 2018, no cases have been reported to necessitate contact tracing.

Evidence has been presented to governments and local authorities to highlight the impacts and importance of domestic dog vaccination with a view to trying to securing ongoing commitment to, and investment in, mass dog vaccination. Data and lessons learned from the project contributed to the revision of the National Rabies Control Strategy in Tanzania in 2024.

An application has been made by the Tanzanian government to Gavi, the vaccine alliance, for the supply of human rabies vaccines. In 2018, Gavi approved investment in human rabies vaccines, but the roll-out has been delayed due to the COVID-19 pandemic and vaccines are likely to reach the first eligible countries in 2025. Regular supply of human rabies vaccines across Tanzania would help ensure equitable access to PEP and reduce unnecessary rabies deaths.

Even with improved access to PEP, controlling rabies across Tanzania remains a One Health challenge. The veterinary sector typically has more limited funding compared to the human healthcare sector making implementation of nationwide mass dog vaccination financially and logistically challenging. Nonetheless, this project has strengthened the relationship between the human healthcare and veterinary sectors. The data and findings from this project, along with the strengthened intersectoral collaboration have played a key role in assisting the government of Tanzania in preparing their application to the World Organisation for Animal Health for endorsement of rabies control efforts.

Conclusions

Rabies provides us with an excellent example of how adopting a One Health approach to disease control can bring extensive benefits to both human and animal communities. We have shown how understanding which species are necessary for sustained disease circulation and targeting interventions at those species can greatly reduce the burden of disease, even in areas with very different disease ecology. Across both of the areas that we have focussed on in this case study, we saw marked declines in rabies cases during periods of domestic dog vaccination and observed the interruption of rabies transmission on Pemba. The elimination of rabies from Pemba contrasts with the situation in Lindi and Mtwara where rabies cases continue to rise. Whether this continued rise is driven by resurgence from residual low levels of disease or by introductions from neighbouring areas is currently unclear, but incorporation of genetic data in future analyses may help to resolve this question. Regardless of which of these mechanisms is driving the increase in rabies cases, it is of the utmost importance that domestic dog vaccination is reinstated and that surveillance is maintained in these areas if we are to reach the 'Zero by 30' target.

Group Discussion Questions

What should the reader be aware of? What are the potential pitfalls? Imagine these may be used for a classroom discussion or short essay question.

1. What are the long-term risks in the regions discussed in this case study if domestic dog vaccination is not maintained?
2. Given the limited financial resources available to sustain mass dog vaccination, are there areas that should be prioritized for vaccination? Which factors might you need to consider when planning the timing and location of vaccination campaigns?
3. What approach to vaccination should be taken by a conservationist only interested in protecting wildlife species from rabies?

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Further reading

1) World Health Organization (2018) Zero by 30: the global strategic plan to end human deaths from dog-mediated rabies by 2030. Available at: https://www.who.int/publications/i/item/9789241513838 (accessed 16th June 2024)

2) World Health Organization (2018) WHO Expert Consultation on Rabies: WHO TRS N°1012. Available at: https://www.who.int/publications/i/item/WHO-TRS-1012 (accessed 27th June 2024)
3) Mpolya, E.A., Lembo, T., Lushasi, K., Mancy, R., Mbunda, E.M., Makungu, S., Maziku, M., Sikana, L., Jaswant, G., Townsend, S. and Meslin, F.X., 2017. Toward elimination of dog-mediated human rabies: experiences from implementing a large-scale demonstration project in southern Tanzania. *Frontiers in veterinary science*, *4*, p.21. Available at: https://doi.org/10.3389/fvets.2017.00021
4) Tidman, R., Thumbi, S.M., Wallace, R., De Balogh, K., Iwar, V., Dieuzy-Labaye, I., Song, J., Shadomy, S., Qiu, Y., Torres, G. and Hutchison, J., 2022. United against rabies forum: the one health concept at work. *Frontiers in public health*, *10*, p.854419. Available at: https://doi.org/10.3389/fpubh.2022.854419
5) Gibson, A.D., Yale, G., Corfmat, J., Appupillai, M., Gigante, C.M., Lopes, M., Betodkar, U., Costa, N.C., Fernandes, K.A., Mathapati, P. and Suryawanshi, P.M., 2022. Elimination of human rabies in Goa, India through an integrated One Health approach. *Nature Communications*, *13*(1), p.2788. Available at: https://www.nature.com/articles/s41467-022-30371-y

References

Bingham, J., Foggin, C.M., Wandeler, A.I. (Alexander I.), Hill, F.W.G., 1999. The epidemiology of rabies in Zimbabwe. 2. Rabies in jackals (*Canis adustus* and *Canis mesomelas*).

Changalucha, J., Steenson, R., Grieve, E., Cleaveland, S., Lembo, T., Lushasi, K., Mchau, G., Mtema, Z., Sambo, M., Nanai, A., Govella, N.J., Dilip, A., Sikana, L., Ventura, F., Hampson, K., 2019. The need to improve access to rabies post-exposure vaccines: Lessons from Tanzania. Vaccine, Scientific and Operational Updates on Rabies 37, A45–A53. https://doi.org/10.1016/j.vaccine.2018.08.086

Cleaveland, S., 2002. Estimating human rabies mortality in the United Republic of Tanzania from dog bite injuries. Bull. World Health Organ.

Hampson, K., Coudeville, L., Lembo, T., Sambo, M., Kieffer, A., Attlan, M., Barrat, J., Blanton, J.D., Briggs, D.J., Cleaveland, S., Costa, P., Freuling, C.M., Hiby, E., Knopf, L., Leanes, F., Meslin, F.-X., Metlin, A., Miranda, M.E., Müller, T., Nel, L.H., Recuenco, S., Rupprecht, C.E., Schumacher, C., Taylor, L., Vigilato, M.A.N., Zinsstag, J., Dushoff, J., Prevention, on behalf of the G.A. for R.C.P. for R., 2015. Estimating the Global Burden of Endemic Canine Rabies. PLoS Negl. Trop. Dis. 9, e0003709. https://doi.org/10.1371/journal.pntd.0003709

Hampson, K., Dobson, A., Kaare, M., Dushoff, J., Magoto, M., Sindoya, E., Cleaveland, S., 2008. Rabies Exposures, Post-Exposure Prophylaxis and Deaths in a Region of Endemic Canine Rabies. PLoS Negl. Trop. Dis. 2, e339. https://doi.org/10.1371/journal.pntd.0000339

Haydon, D.T., Cleaveland, S., Taylor, L., Laurenson, M.K., 2002. Identifying Reservoirs of Infection: A Conceptual and Practical Challenge. Emerg. Infect. Dis. 8, 1468–1473. https://doi.org/10.3201/eid0812.010317

Hayes, S., Lushasi, K., Sambo, M., Changalucha, J., Ferguson, E.A., Sikana, L., Hampson, K., Nouvellet, P., Donnelly, C.A., 2022. Understanding the incidence and timing of rabies cases in domestic animals and wildlife in south-east Tanzania in the presence of widespread domestic dog vaccination campaigns. Vet. Res. 53, 106. https://doi.org/10.1186/s13567-022-01121-1

Johnson, N., Mansfield, K.L., Marston, D.A., Wilson, C., Goddard, T., Selden, D., Hemson, G., Edea, L., van Kesteren, F., Shiferaw, F., Stewart, A.E., Sillero−Zubiri, C., Fooks, A.R., 2010. A new outbreak of rabies in rare Ethiopian wolves (*Canis simensis*). Arch. Virol. 155, 1175–1177. https://doi.org/10.1007/s00705-010-0689-x

Kat, P.W., Alexander, K.A., Smith, J.S., Munson, L., 1997. Rabies and African wild dogs in Kenya. Proc. R. Soc. Lond. B Biol. Sci. 262, 229–233. https://doi.org/10.1098/rspb.1995.0200

Knobel, D.L., Cleaveland, S., Coleman, P.G., Fèvre, E.M., Meltzer, M.I., Miranda, M.E.G., Shaw, A., Zinsstag, J., Meslin, F.-X., 2005. Re-evaluating the burden of rabies in Africa and Asia. Bull. World Health Organ.

Lembo, T., Hampson, K., Haydon, D.T., Craft, M., Dobson, A., Dushoff, J., Ernest, E., Hoare, R., Kaare, M., Mlengeya, T., Mentzel, C., Cleaveland, S., 2008. Exploring reservoir dynamics: a case study of rabies in the Serengeti ecosystem. J. Appl. Ecol. 45, 1246–1257. https://doi.org/10.1111/j.1365-2664.2008.01468.x

Lushasi, K., Brunker, K., Rajeev, M., Ferguson, E.A., Jaswant, G., Baker, L.L., Biek, R., Changalucha, J., Cleaveland, S., Czupryna, A., Fooks, A.R., Govella, N.J., Haydon, D.T., Johnson, P.C., Kazwala, R., Lembo, T., Marston, D., Masoud, M., Maziku, M., Mbunda, E., Mchau, G., Mohamed, A.Z., Mpolya, E., Ngeleja, C., Ng'habi, K., Nonga, H., Omar, K., Rysava, K., Sambo, M., Sikana, L., Steenson, R., Hampson, K., 2023. Integrating contact tracing and whole-genome sequencing to track the elimination of dog-mediated rabies: An observational and genomic study. eLife 12, e85262. https://doi.org/10.7554/eLife.85262

Lushasi, K., Hayes, S., Ferguson, E.A., Changalucha, J., Cleaveland, S., Govella, N.J., Haydon, D.T., Sambo, M., Mchau, G.J., Mpolya, E.A., Mtema, Z., Nonga, H.E., Steenson, R., Nouvellet, P., Donnelly, C.A., Hampson, K., 2021. Reservoir dynamics of rabies in south-east Tanzania and the roles of cross-species transmission and domestic dog vaccination. J. Appl. Ecol. 58, 2673–2685. https://doi.org/10.1111/1365-2664.13983

Meredith, C.D., Thomson, G.R., 1993. Rabies in bat-eared foxes in South Africa. Onderstepoort J. Vet. Res. 60, 399.

Mpolya, E.A., Lembo, T., Lushasi, K., Mancy, R., Mbunda, E.M., Makungu, S., Maziku, M., Sikana, L., Jaswant, G., Townsend, S., Meslin, F.-X., Abela-Ridder, B., Ngeleja, C., Changalucha, J., Mtema, Z., Sambo, M., Mchau, G., Rysava, K., Nanai, A., Kazwala, R., Cleaveland, S., Hampson, K., 2017. Toward Elimination of Dog-Mediated Human Rabies: Experiences from Implementing a Large-scale Demonstration Project in Southern Tanzania. Front. Vet. Sci. 4. https://doi.org/10.3389/fvets.2017.00021

Nel, L.H., 2013. Discrepancies in Data Reporting for Rabies, Africa. Emerg. Infect. Dis. 19, 529–533. https://doi.org/10.3201/eid1904.120185

Randall, D.A., Marino, J., Haydon, D.T., Sillero-Zubiri, C., Knobel, D.L., Tallents, L.A., Macdonald, D.W., Laurenson, M.K., 2006. An integrated disease management strategy for the control of rabies in Ethiopian wolves. Biol. Conserv., Infectious Disease and Mammalian Conservation 131, 151–162. https://doi.org/10.1016/j.biocon.2006.04.004

Sambo, M., Cleaveland, S., Ferguson, H., Lembo, T., Simon, C., Urassa, H., Hampson, K., 2013. The Burden of Rabies in Tanzania and Its Impact on Local Communities. PLoS Negl. Trop. Dis. 7, e2510. https://doi.org/10.1371/journal.pntd.0002510

Sambo, M., Ferguson, E.A., Abela-Ridder, B., Changalucha, J., Cleaveland, S., Lushasi, K., Mchau, G.J., Nanai, A., Nonga, H., Steenson, R., Johnson, P.C., Hampson, K., 2022. Scaling-up the delivery of dog vaccination campaigns against rabies in Tanzania. PLoS Negl. Trop. Dis. 16, e0010124. https://doi.org/10.1371/journal.pntd.0010124

Sambo, M., Johnson, P.C.D., Hotopp, K., Changalucha, J., Cleaveland, S., Kazwala, R., Lembo, T., Lugelo, A., Lushasi, K., Maziku, M., Mbunda, E., Mtema, Z., Sikana, L., Townsend, S.E., Hampson, K., 2017. Comparing Methods of Assessing Dog Rabies Vaccination Coverage in Rural and Urban Communities in Tanzania. Front. Vet. Sci. 4. https://doi.org/10.3389/fvets.2017.00033

Sillero-Zubiri, C., King, A.A., Macdonald, D.W., 1996. RABIES AND MORTALITY IN ETHIOPIAN WOLVES (CANIS SIMENSIS). J. Wildl. Dis. 32, 80–86. https://doi.org/10.7589/0090-3558-32.1.80

Swanepoel, R., Barnard, B.J.H., Meredith, C.D., Bishop, G.C., Bruckner, G.K., Foggin, C.M., Hubschle, O.J.B., 1993. Rabies in southern Africa. Onderstepoort J. Vet. Res. 60, 325.

Taylor, L.H., Nel, L.H., 2015. Global epidemiology of canine rabies: past, present, and future prospects. Vet. Med. Res. Rep. 6, 361–371. https://doi.org/10.2147/VMRR.S51147

World Health Organization, 2024. Rabies. URL https://www.who.int/news-room/fact-sheets/detail/rabies (accessed 7.23.24).

Youde, J., 2013. Cattle scourge no more: The eradication of rinderpest and its lessons for global health campaigns. Polit. Life Sci. 32, 43–57. https://doi.org/10.2990/32_1_43