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Lessons for rabies control and elimination programmes: a decade of One Health experience from Bali, Indonesia

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Summary

Since the emergence of rabies on Bali, Indonesia, in 2008, the Indonesian Government and other stakeholders have implemented disease control and prevention activities with the aim

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of re-securing Bali's freedom from dog-mediated rabies. The authors report on the lessons learned during these efforts, and their applicability to other regions where canine rabies is endemic, as well as to rabies-free populations that are at risk from incursions. To eliminate rabies from Bali will require time and commitment, as well as a combination of approaches employing the principle of One Health. Efforts should be directed towards well-coordinated, high-coverage, annual dog vaccination campaigns using high-quality vaccines, and enhanced surveillance focused on investigations of biting animals. Bali, an island, is an ideal target for achieving freedom from rabies, but the logistics of vaccinating its very large, free-roaming dog population are challenging. Lessons can be drawn from Bali for other large and dense dog populations, where dog management and rabies control appear difficult. Well-trained teams with nets can rapidly catch and vaccinate large numbers of dogs where central-point vaccination is insufficient, and post-vaccination surveys of collared dogs can be used to evaluate coverage and target supplementary vaccination. However, careful planning is required to ensure that all communities are reached during such campaigns and that sufficient vaccine is available over the following years. Effective communication strategies are needed to coordinate intersectoral activities, and to keep communities engaged, particularly during the 'end game', when the risk of rabies appears only minimal. An effective One Health approach to eliminate rabies requires long-term planning, multisectoral communication and coordination, and sustained effort, using tried and tested methods.

Keywords

Bali; Canine rabies; Dog-mediated rabies; Elimination programme; Indonesia; Mass dog vaccination; Neglected zoonotic disease; One Health; Outbreak management; Rabies control; Surveillance

Background

Rabies is the archetypal One Health disease. Over 99% of human rabies deaths result from dog-mediated transmission (1). Post-exposure prophylaxis (PEP) is highly effective in preventing the onset of rabies if delivered promptly after a person is bitten by a rabid animal. However, in countries in which canine rabies is endemic, many people die because their access to PEP is limited. Mass dog vaccination can eliminate rabies from the source population (domestic dogs) but requires sustained effort and is not conducted systematically or at scale in most low- and middle-income countries (LMICs). Thus, although canine rabies is preventable, and has been eliminated in high-income countries, its neglect in LMICs means that it remains a major public health concern and economic burden.

International agencies are now advocating the global elimination of dog-mediated rabies to achieve zero human rabies deaths by 2030 (2). As a result, efforts are being made to undertake mass dog vaccination programmes and to improve access to PEP. At the same time, incursions of dog-mediated rabies recorded around the world highlight the risk that rabies poses as an emerging disease (3, 4, 5, 6).

The emergence of rabies in 2008 on the island province of Bali, in Indonesia, is a prime example. Although rabies has circulated in Indonesia since the 1880s (7), Bali had

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historically been rabies-free. Over the last decade, the Indonesian Government, together with other stakeholders, has implemented control and prevention activities with the aim of re-securing Bali's freedom from rabies. In this paper, the authors report lessons learned from these efforts and their applicability to other regions where canine rabies is endemic or which are rabies-free at present but at risk from incursions of the disease.

When the first suspected human case of rabies, in a fou-year-old child, was detected in Bali in September 2008, health authorities were ill equipped to cope and there was no PEP on the island. The hope was that the outbreak could be confined to the Bukit Peninsula at the southern tip of Badung Regency (county) and that control efforts would prevent its spread to the rest of the island (Fig. 1).

Initial control efforts in late 2008 and early 2009 involved localised culling of dogs with strychnine (the majority of dogs in Bali are owned but free-roaming) and fixed-point vaccinations in the Bukit Peninsula. But, by late 2009, rabies had crossed the isthmus. Its increasing incidence and animal welfare concerns led multiple stakeholders to become involved in the situation, including international agencies, local and international non-governmental organisations, and development/aid agencies in the region, as well as local and national government agencies in the health, veterinary, legal and education sectors. Continuing control efforts have now reduced the incidence of the disease, but there have been many setbacks in attempting the complete interruption of virus transmission to achieve a rabies-free Bali. The authors review a decade of experience from Bali and discuss the insights that it has provided into rabies control, surveillance and management, in the context of the One Health approach.

Control strategies

The main approach recommended for the control of rabies in dog populations is mass vaccination (8). Dog population management activities are also conducted with the intention of controlling rabies (9), and culling dogs is often the first response to outbreaks in LMICs. When rabies was first detected on Bali, there were several obstacles hampering effective control measures. Vaccinating dogs was illegal and perceptions of an excessively large dog population contributed to culling as the first response from local government. However, dog vaccines were soon brought into Bali and local dog owners were advised to take their dogs to central points on the outbreak-affected peninsula where government staff could vaccinate their animals. Vaccines produced in Indonesia (Rabivet Supra 92) were used at this time. However, these were less effective for mass vaccination campaigns than those vaccines recommended by the World Organisation for Animal Health (OIE), as they required a re-vaccination booster after three months to generate an acceptable level of immunity. Although over 90% of dogs on Bali are owned, they are mostly free-roaming and not easily brought to vaccination stations.

A lack of coordination sometimes led to culling vaccinated dogs (although dog vaccinations were recorded, vaccinated dogs were not marked and culling began in haste). Owners also quickly replaced their killed dogs, usually with unvaccinated puppies and dogs brought in from elsewhere, further risking the importation of rabies. The confluence of these factors

meant that only low and short-lived vaccination coverage was achieved and, by mid-2010, rabies had spread across the entire island (10).

In response to these problems, the Bali Animal Welfare Association (BAWA) developed a technique for vaccinating dogs using trained dog catchers, equipped with nets (11). From December 2009 to September 2010, four teams of six people (four dog catchers, one vaccinator, one recorder) carried out door-to-door vaccination throughout neighbouring Gianyar and Bangli Regencies, using long-lasting vaccines donated by the Australian Government. Coloured collars were used to mark dogs at the time of vaccination, and post-vaccination surveys were carried out in the following days, counting marked (vaccinated) and unmarked dogs. In ten months, these four teams vaccinated over 73,000 dogs in the two regencies, with coverage estimated to exceed 70% in almost all *banjars* (sub-villages). BAWA's proven approach, that high coverage could be reliably achieved and monitored, even in areas with high densities of unconfined dogs, was adopted. Local and international stakeholders, including BAWA, the Balinese provincial government and World Animal Protection (WAP, formerly the World Society for the Protection of Animals), planned the first island-wide mass dog vaccination programme and, from October 2010 to April 2011, more than 70% of dogs were vaccinated in most *banjars* across the island (Fig. 1). Since 2011, island-wide vaccination programmes have been conducted annually by the Balinese Government, with technical and operational support from the Food and Agriculture Organization of the United Nations (FAO). To date, 31 teams of dog catchers have been trained, providing the capacity for large numbers of dogs to be rapidly vaccinated. During 2015 and 2016, improvements in the techniques for catching and handling unconfined dogs were developed and competition between the teams was intensified to increase their engagement in and the impact of vaccination campaigns.

In addition to vaccination activities, control strategies to reduce the dog population were carried out with varying intensity and sub-optimal results. Culling, implemented primarily through strychnine darts, was officially advised against by local and international welfare groups. The first island-wide mass vaccination campaign in late 2010 was supported by BAWA and WAP under an agreement that culling would be discontinued. However, some dog culling was conducted in response to reports of human and animal rabies deaths, when demanded by local communities, and sometimes in localities where the government considered the dog population to be too large. Culling was also frequently opposed by local communities and many people complained when their owned and often vaccinated dogs were killed.

Ultimately, culling did not contain rabies spread. On the contrary, it was probably counterproductive, since dogs were moved to avoid culls, possibly transporting dogs with latent rabies. The rate at which rabies reached all regencies of Bali, including the island of Nusa Penida, indicated the involvement of human transportation in the spread of the disease, in addition to the running behaviour of infectious dogs (11). Moreover, evidence demonstrates that rabies transmission is largely independent of population density, meaning that approaches based on reducing the dog population will not control rabies (11). As a result, national policy in Indonesia now officially condemns indiscriminate culling and recommends selective and targeted euthanasia of suspected rabid dogs for rabies control.

Although mass dog vaccination strategies successfully controlled rabies on Bali after the first epidemic and its subsequent re-emergence, the long-term goal of achieving rabies freedom has yet to be accomplished. To achieve freedom from rabies requires sustained effort and commitment. Even when the incidence is declining, coverage must be maintained with mass vaccination for at least two years after a period of six consecutive months with no detected cases (11). Yet the reduced rabies incidence on Bali led to a false sense of security. Island-wide mass vaccination is a substantial logistical and financial undertaking, and changes in vaccine procurement and roll-out disrupted the programme's success. For instance, a new vaccine was used for the annual vaccination campaign in 2014, but only after a resurgence of rabies in 2015 (Fig. 1) did the relative efficacy of different vaccines become apparent (Fig. 2). Measures were taken to improve subsequent campaigns; first and foremost through the procurement of high-quality vaccines during the sixth campaign in 2015. Supplementary vaccinations were conducted immediately after the main campaign, targeting puppies, free-roaming dogs, and unvaccinated dogs, and were also carried out in villages where coverage was estimated to be less than 70%. In addition, reactive vaccinations were undertaken in areas with the most detected cases.

These challenges highlight the long-term nature of disease elimination programmes and the difficulties of sustaining control efforts during their final stages. The relaxation or failure of control measures can considerably set back progress but maintaining the necessary financial commitment required to undertake such extensive operations, in addition to continually re-motivating personnel, is difficult. Long-term planning for elimination must include budgeting for high-quality vaccines, with procedures in place to prevent delays in securing the vaccine and its delivery to the field. Monitoring and surveillance, including good data management, are also necessary to ensure that progress is on track. Although they were conducted only intermittently over the ten-year period (in 2010, 2011 and 2016), post-vaccination transects were essential in estimating vaccination coverage and dog population sizes on Bali, and directly informed vaccine procurement and delivery plans. Political 'buy-in' and increased public awareness are crucial for vaccination campaigns to be conducted throughout all communities, as are micro-planning and post-vaccination monitoring to ensure that the campaign's goals are being achieved. Computational modelling, motivated by a lack of engagement in one of the regencies on Bali before the first island-wide vaccination programme, clearly demonstrates that unvaccinated communities jeopardise prospects for achieving freedom from rabies (11).

Surveillance

The lack of formal rabies surveillance on Bali, in both humans and animals, and the ban on dog vaccination before the emergence of rabies in 2008 contributed to the relatively late detection of the disease. By this point, substantial secondary transmission had already occurred within the dog population. Had rabies been detected earlier, and effective control measures enacted, it is likely that the disease could have been contained without causing such major public health and economic impacts (13).

Rabies was only suspected to be circulating in Bali after unusual encephalitis fatalities were reported from the Bukit Peninsula (Fig. 1). The Australian Government supported

the re-establishment of the direct fluorescent antibody test, the gold standard for rabies diagnosis, at the regional Disease Investigation Center (DIC) in Denpasar. From this point on, the DIC conducted laboratory surveillance for the province. In line with outdated recommendations to sample 0.02% of the dog population for rabies surveillance (14), large numbers of indiscriminately culled animals were tested for rabies at considerable expense. Efforts were subsequently made to target surveillance and integrated bite-case management (IBCM) was introduced, whereby veterinary officers investigated suspected biting animals following incidents reported by bite victims. This approach to surveillance significantly improved the case detection rate (Fig. 1); however, IBCM was not maintained and case detection declined, possibly giving the sense that rabies was under control.

Following the disease's re-emergence in 2014−2015, IBCM was reintroduced, with refresher training provided for personnel, and case detection again increased.

Surveillance data from the last ten years provide valuable insights to inform rabies control. Initially, cases were detected only on the Bukit Peninsula, suggesting a single source of introduction (Fig. 1). This was subsequently confirmed by genetic characterisation. Viruses on Bali were related to those previously circulating in Kalimantan and Sulawesi, and it is thought that fishermen inadvertently brought a latently infected dog to Bali, although the source of the outbreak has not been pinpointed (15, 16). Human-mediated movement was shown to have played a significant role in the early spread of the disease (11), but the spatio-temporal pattern of cases in subsequent years showed that local movements of rabid dogs were responsible for the vast majority of transmissions. These patterns did not reveal any environmental or population variables predictive of rabies transmission, only that new cases were strongly associated with recent nearby cases (Fig. 3).

Nonetheless, this finding has important management implications. If cases can be detected promptly and response measures enacted swiftly, they can stem local transmission, but vaccinations must be conducted rapidly and over a sufficiently wide radius. Otherwise, the disease will continue to circulate unabated, beyond the area of control.

The detection of cases through effective surveillance is critical to maintaining commitment to control efforts. If surveillance is targeted and effective, then declines in the number of detected cases mark the impact of successful control measures. But, if surveillance lapses, then declines in the number of cases will be falsely attributed to successful rabies control. Care must therefore be taken in communicating messages about progress from surveillance data and, in all circumstances, the vital importance of not discontinuing control measures prematurely must be highlighted. Indeed, case detection should be used to emphasise the continuing need for vaccination until an area can be declared entirely free from disease.

In the case of rabies, dog bites by suspect animals are a highly sensitive sentinel for the presence of rabies (17). A One Health approach that includes close collaboration and information sharing among the veterinary, medical and public health sectors is therefore crucial for improving case detection and a key factor of rabies prevention and control (Fig. 4).

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Management and coordination

The success of rabies control programmes is often hindered by limited community engagement and misconceptions about rabies, with a ‘disconnect’ between research, policy and implementation. Bali offers an interesting and complicated story on the evolution of multi-partner and multisectoral collaboration for disease control, highlighting practices necessary to bridge this gap.

The lack of surveillance and effective control measures at the time of the rabies incursion into Bali led to a tragic and costly situation. Resources were limited at the onset of the outbreak when investment was required to set up surveillance and control measures. Likewise, towards the end of the epidemic, when cases were declining, reduced investment in and prioritisation of the control programme reflected fatigue and under-budgeting. At such times, planning rabies interventions is done under enormous pressure and often with limited experience. For example, until the outbreak, vaccines were incorrectly believed to cause rabies rather than to prevent it, and culling seemed to many stakeholders to be a more intuitive strategy to combat the disease, given the large population of free-roaming dogs on Bali. Technical support is therefore invaluable to ensure the effective planning and implementation of control measures when outbreaks occur, and to aid the objective of elimination. Further modelling of the effectiveness of control activities and their optimisation would greatly benefit Bali and other communities facing these dilemmas.

One of the most useful lessons learned from the response to rabies in Bali is the importance of partnership and effective communication across the many stakeholders, high-level government policy-makers, and donors. The dramatic decline in rabies incidence in late 2010 resulted from the effective coordination of resources and capacity, rapidly learned from pilot activities. While donations of long-lasting vaccines from the Australian Government initiated the process, successful implementation would not have been possible without the technical efforts and capacity building provided by in-country partners.

The lack of human resources and operational funds for training staff and administering vaccines was initially considered a severe limitation. However, BAWA generated evidence to show that large numbers of free-roaming dogs could be rapidly vaccinated, and this led to further support from local and national government, and technical support projects implemented by the government, with assistance from international organisations, such as FAO. Nonetheless, misperceptions still had to be overcome and persuading some local stakeholders of the need to vaccinate in all communities was critical (10). Data management systems and technical support, with data analysis from FAO, have continued to play a key role in engaging government partners and supporting local implementation. Managing and coordinating donors and partners was, in itself, a challenge, particularly given the political sensitivities associated with control mishaps and differing cultures and understandings of rabies and its control.

Whilst multi-partner relations produced positive results, multisectoral collaboration remains challenging. Limited infrastructure and communication between human and veterinary health workers hindered surveillance at the start of the outbreak and, until IBCM

was implemented, investigations of human and animal rabies cases were undertaken independently. Strong communication and shared responsibilities between all relevant sectors are, however, imperative for effective rabies control and prevention (Fig. 4). Targeted surveillance of dogs suspected to have rabies, identified through dog-bite patients, makes it easier to detect animal cases and leads to more appropriate PEP recommendations, thereby reducing the associated economic costs (17, 18, 19, 20, 21). Successful rabies control in dogs directly benefits human health. Therefore, the One Health approach, which is rooted in effective multisectoral and transdisciplinary partnerships and communication, is key to rabies elimination efforts. Indeed, rabies provides a test-bed system for other zoonotic diseases.

Successful rabies control programmes involve local communities, engage stakeholders and carry out culturally acceptable and effective control activities. Misconceptions about rabies often lead to counterproductive actions and reduced participation. As a result of the resurgence of rabies in 2015, hard-won confidence in vaccination programmes was lost, and some politicians promoted culling as an alternative, claiming it would be cheaper than more dog vaccinations. While subsequent island-wide dog vaccination has brought rabies back under control, poor intervention choices had damaging and extremely costly implications − likely setting back Bali's prospects of achieving rabies freedom by at least five years.

Outreach programmes are essential to achieving and maintaining buy-in, and should focus on educating communities on the risk of rabies and available control and prevention measures. Between December 2016 and April 2017, the FAO conducted a pilot study in Pejeng Village, in Gianyar Regency. This study was aimed at increasing community compliance with rabies control through a series of educational workshops and by promoting responsible dog ownership, supported by village health workers and backed up by local law enforcement. The results encourage optimism that actions taken locally can lead to increased public engagement and awareness of rabies risk in the community, while fostering daily dialogue between veterinary and public health personnel.

The elimination of rabies is achievable if there is long-term commitment to effective control strategies and surveillance. The time needed to complete the interruption of rabies virus transmission and declare freedom from the disease is typically longer than anticipated by both politicians and academics. This is because, in practice, delivering surveillance and control activities at scale in all communities is often much harder than it might appear. Therefore, maintaining momentum when cases are declining is particularly important. The government must continue to commit sufficient resources and not disengage prematurely.

Communication strategies must stress this need for sustained effort and manage expectations about the amount of time and investment required − both for practitioners and high-level stakeholders. Misinformation poses a major threat to the control of rabies in an emergency situation and can compromise achievements when progress has been made and elimination is being approached. The development of a coordinated communication strategy involving all relevant sectors is therefore a key component of control efforts to make rabies-free Bali a reality, and prevent the further spread of rabies across South-East Asia.

Conclusions

The development and implementation of control options for rabies require careful consideration of the availability of resources, as well as stakeholder engagement and support to carry out interventions. Given the financial, technical and structural constraints in LMICs, it is important to identify the most appropriate strategies and allocate resources accordingly.

To eliminate rabies from Bali will require time and commitment; efforts should be directed towards well-coordinated, high-coverage, annual dog vaccination campaigns, using high-quality vaccines and enhanced surveillance, instead of ineffective activities, such as dog culling and the indiscriminate sampling of apparently healthy animals for surveillance. The isolated nature of Bali, an island, makes it an ideal target for achieving freedom from rabies, but the logistics of vaccinating large numbers of mostly free-roaming dogs also make it challenging. Lessons drawn from Bali (Box 1) are applicable to other large and dense canine populations, where dog management and rabies control may appear overwhelming.

To achieve rabies elimination on Bali, a One Health approach, including appropriate technical training and continuous efforts to ensure public engagement and awareness, with multisectoral support from both governmental and non-governmental partners, has demonstrated that promising results can be achieved if partnerships, political will, and local and national commitment are cultivated.

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Box 1

Recommendations drawn from the rabies control programme on Bali

Surveillance − routine animal surveillance on Bali detects only a small fraction of circulating cases in the dog population (<10%). Indiscriminate dog culling on the pretext of surveillance (laboratory testing of culled animals) is not effective for detecting rabies. In contrast, surveillance targeted through integrated bite-case management (IBCM), coupled with increased public awareness, is a sensitive and efficient way to increase case detection. Once disease incidence is reduced to low levels (an average of <10 canine cases detected per month through routine surveillance), an effort should be made to enhance surveillance. Using IBCM, following up high-risk bites is expected to detect 20−40% of probable rabid dogs, and sample recovery from investigations should at least double the number of confirmed canine cases when compared to routine surveillance (18, 19).

Vaccination − comprehensive island-wide mass campaigns should be conducted annually in all villages and aim to achieve high coverage (>70% across all areas, including sub-villages and remote settlements). At least two years of mass dog vaccination should be undertaken, without any case detection, under surveillance enhanced by IBCM, as part of the procedure to verify freedom from disease, before mass dog vaccination can be safely discontinued (8). Supplementary vaccinations should target puppies born after campaigns and unvaccinated dogs missed during campaigns. Emergency response vaccinations should be guided by IBCM, implemented rapidly (<10 days after case detection) and cover an extended radius; for example, villages within an approximate 10-km radius of the detected case.

Vaccines should be of high quality − quality vaccines are those that have sufficient appropriate antigenic content to produce rapid and long-lasting immunity in vaccinated animals with one application. Vaccines that require boosters greatly increase the effort and cost required to achieve sufficient coverage. Revaccination of dogs after short periods is logistically challenging and very expensive. Moreover, trust is often lost in vaccination programmes as a result of the adverse effects that can result from the use of poor-quality vaccines.

Planning is required to ensure that there are no legal, logistical and/or financial constraints to implementing rapid response vaccinations. This should include advance planning to ensure an adequate supply of internationally recognised vaccines from recommended suppliers for the duration of the programme, factoring in intensified vaccination as freedom is approached. Moreover, vaccination should be continued for two years after the last detected case to verify freedom from disease.

Appropriate delivery strategies are needed that can reach the vast majority of the dog population. It only became evident after initial local government vaccinations were carried out at central points that most dogs in Bali would not be reached in this way. The use of trained dog catchers with nets has now been tested extensively in Bali and shown to be very effective. This approach should also be considered for use in other settings where patterns of dog ownership are similar to those of Bali. International

organisations have now built up technical expertise in this approach, which should be sought as required.

Monitoring − vaccinated dogs should be tagged using long-lasting durable collars, to make monitoring easier during post-vaccination surveys to identify areas with low coverage. In addition, the numbers of dogs vaccinated should be compared with those of previous campaigns to further check performance. Collars on vaccinated dogs directly facilitate targeted supplementary vaccinations and emergency response vaccinations and should be promoted as part of responsible dog ownership.

Culling dogs is not recommended − it is not only inhumane, but also ineffective for rabies control. Specifically, dog owners often move their dogs to avoid culls, or bring in unvaccinated dogs from elsewhere to replace (often vaccinated) animals that have been culled. This increases the risk of rabies through human-mediated movement of dogs. Culling also creates tensions between local communities and government and can reduce the community's engagement and participation in more effective strategies, such as dog vaccination. Moreover, the population quickly returns to pre-cull levels, leaving culling ineffective, even as a dog population management tool.

Dog population management strategies should be implemented to encourage responsible dog ownership, with a focus on vaccinating dogs, particularly puppies, to maintain high levels of coverage.

Communication between stakeholders across the veterinary and medical sectors is vital to maintain engagement and support for ongoing control measures. Such stakeholders include all public health personnel, animal health officers, epidemiologists and laboratory technicians conducting surveillance activities, as well as the media, the public, the local community and high-level donors. Communication should be frequent and guided by surveillance, with a focus on effectively overcoming misinformation, which is likely to circulate during emergency situations. Communications should adopt a realistic timeframe of when elimination goals can be achieved.

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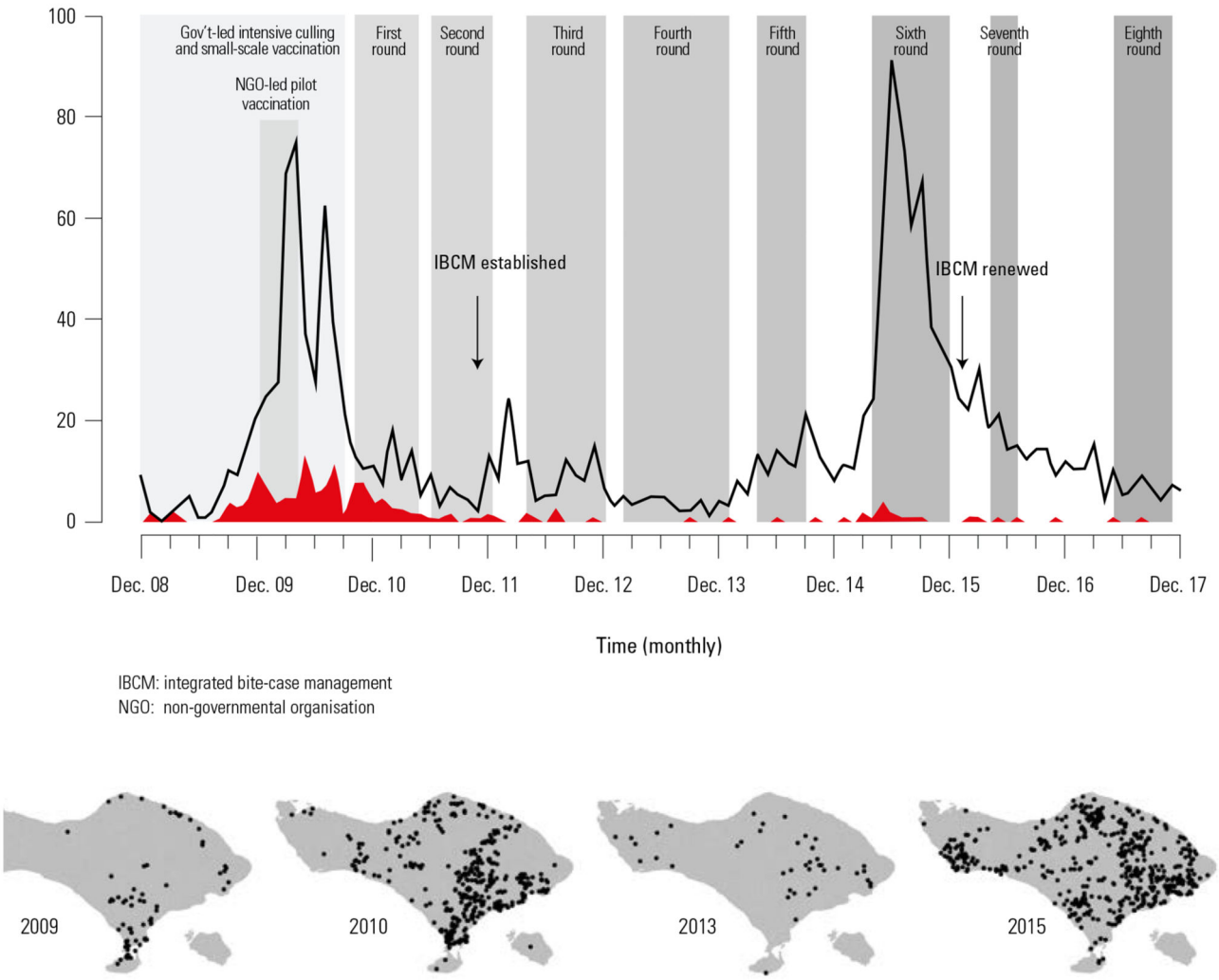

Fig. 1. Rabies incidence in Bali from December 2008 to December 2017

Confirmed dog rabies cases (black line) and human rabies deaths (red polygon), with grey shading showing the timing of dog vaccination campaigns. Different vaccines were used during this period. Culling unconfined dogs occurred most intensely at the beginning of the epidemic. In response to international pressure, culling was officially suspended in 2011 but, to date, has not been completely discontinued. In autumn 2015, the Balinese Government supported targeted culling of dogs in reaction to the second outbreak. Integrated bite-case management (IBCM) was established in late 2011 but, in spite of improved case detection, was not maintained. IBCM was re-introduced in late 2015. Maps illustrate the location of cases in the years after the outbreak: in 2009, when the spatial spread of rabies from the Bukit Peninsula was evident, and in 2010, when rabies was widely distributed. By 2013, many fewer cases were detected in foci across the island, but rabies subsequently re-emerged in 2014−2015 with occurrences throughout Bali

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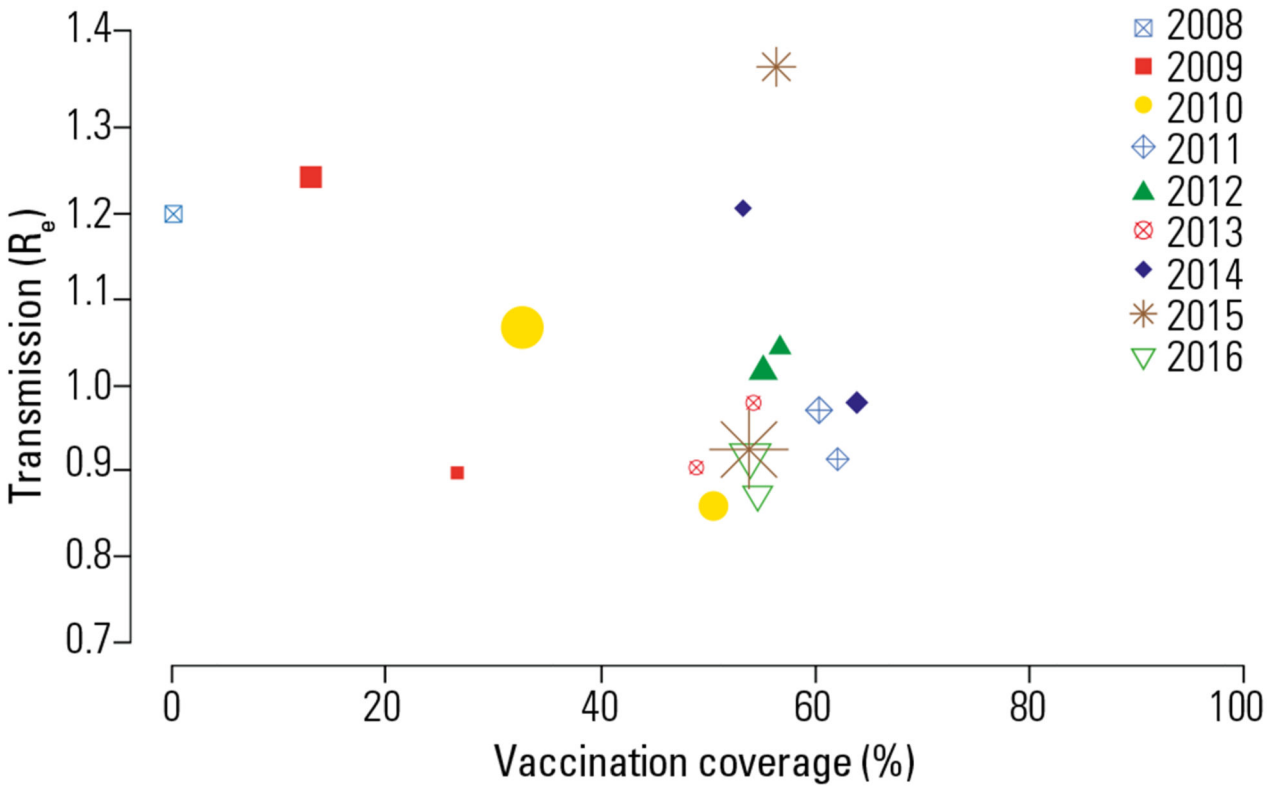

Fig. 2. The influence of vaccine type and vaccination coverage on rabies transmission

The relationship between mean vaccination coverage (%) and the effective reproductive number, R_e. Vaccination coverage was projected using data from vaccination campaigns and assumed to wane with demographic turnover of the dog population and vaccine longevity (11). R_e was estimated as the average number of secondary cases generated by each primary case, from the construction of 1,000 bootstrapped transmission trees, following previously described methods (12). Individual estimates of R_e and local vaccination coverage (both at the site of each rabies case) were averaged across six-month time windows, with symbols indicating the year of each six-month estimate, and scaled by the number of cases contributing to the estimate (17 data points in total, from the second half of 2008 until the end of 2016). There was a strong negative relationship between transmission and vaccination coverage, based on a weighted linear regression after removal of the outlier from the first half of 2015, following use of the ineffective vaccine (regression coefficient = −0.005, *p* value = 0.005, R-squared = 0.39)

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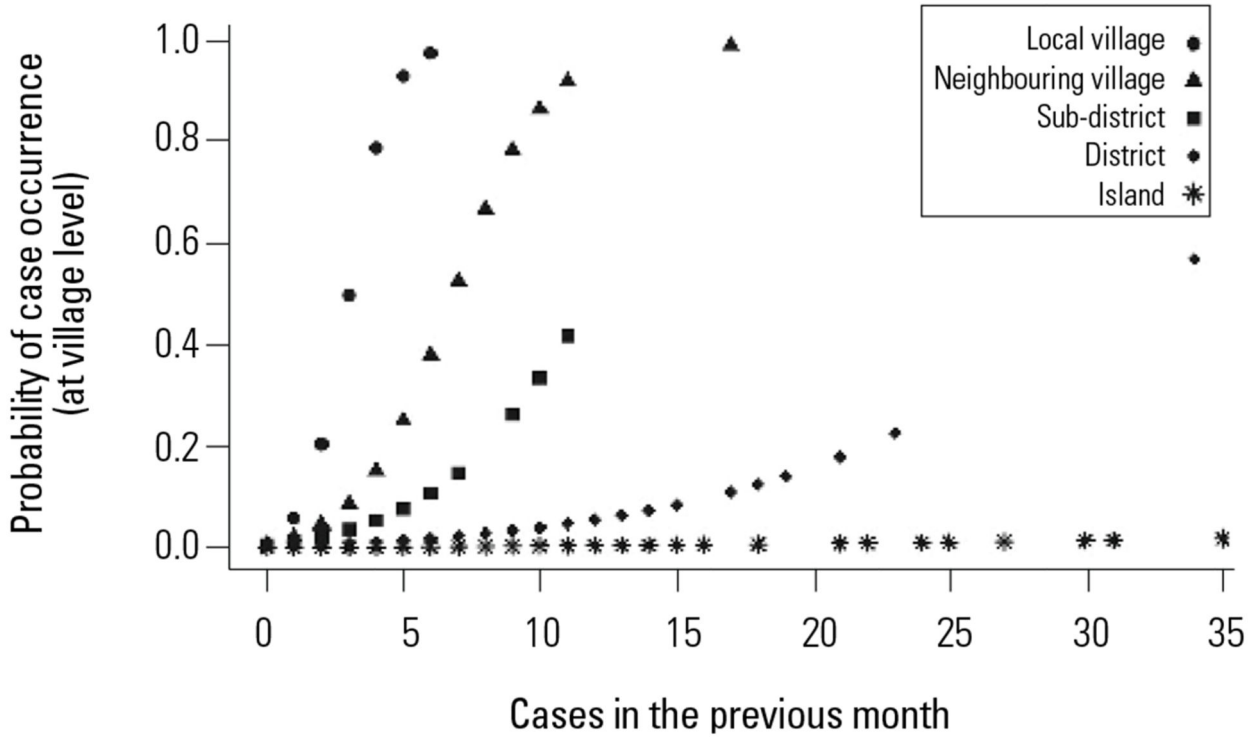

Fig. 3. The influence of recent rabies cases on future rabies occurrence at different spatial scales

A fitted relationship between cases detected in the previous month at the specified spatial scale (*x*-axis, point-typed) and the probability of observing cases in the focal village in the current month (*y*-axis)

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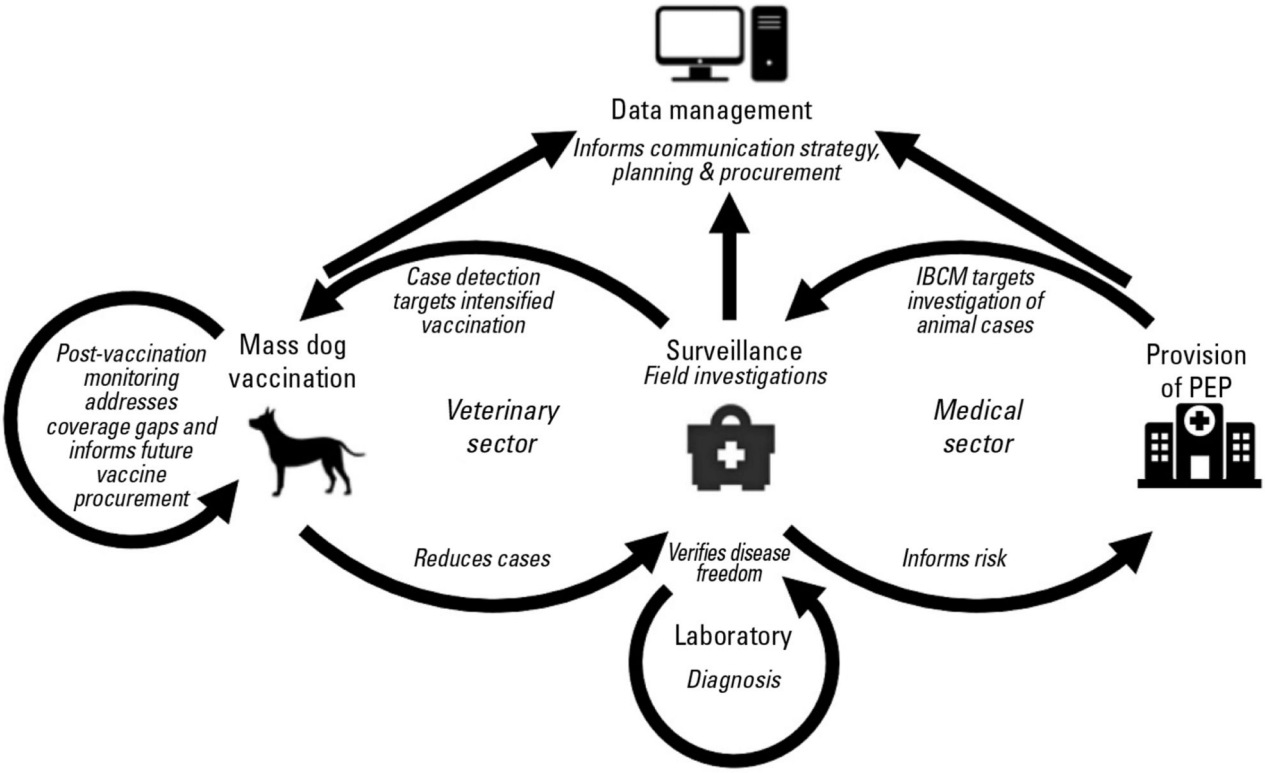

Fig. 4. Schematic illustrating a One Health approach for a rabies elimination programme

The medical and veterinary sectors have key responsibilities for the provision of post-exposure prophylaxis (PEP) and mass dog vaccination, respectively, that directly affect their corresponding intersectoral partner. Integrated surveillance (interactively informed by both the public and animal health sectors) is at the intersection of all activities: it is used to monitor progress and inform management actions, including the procurement of human and animal vaccines. The use of integrated bite-case management (IBCM), in which the identification of suspicious animal bites informs investigations, is a direct channel of communication across sectors and a sensitive method for enhancing surveillance, to verify freedom from disease and for a rapid outbreak response in areas at risk of incursion