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Rabies control in rural Africa: Evaluating strategies for effective domestic dog vaccination

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Abstract

Effective vaccination campaigns need to reach a sufficient percentage of the population to eliminate disease and prevent future outbreaks, which for rabies is predicted to be 70%, at a cost that is economically and logistically sustainable. Domestic dog rabies has been increasing across most of sub-Saharan Africa indicating that dog vaccination programmes to date have been inadequate. We compare the effectiveness of a variety of dog vaccination strategies in terms of their cost and coverage in different community settings in rural Tanzania. Central-point (CP) vaccination was extremely effective in agro-pastoralist communities achieving a high coverage (>80%) at a low cost (<US$2/dog) and was robust under various socio-economic, cultural and spatial factors. In pastoralist communities CP vaccination was costly (>US$5/dog) and inadequate (<20% coverage); combined approaches using CP and either house-to-house vaccination or trained community-based animal health workers were most effective with coverage exceeding 70%, although costs were still high (>US$6 and >US$4/dog, respectively). No single vaccination strategy is likely to be effective in all populations and therefore alternative approaches must be deployed under different settings. CP vaccination is cost-effective and efficient for the majority of dog populations in rural Tanzania and potentially elsewhere in sub-Saharan Africa, whereas a combination strategy is necessary in remote pastoralist communities. These results suggest that rabies control is logistically feasible across most of the developing world and that the annual costs of effective vaccination campaigns in Tanzania are likely to be affordable.

Keywords

Cost-effectiveness; Vaccination strategy; Rabies; Vaccination coverage

1. Introduction

Among the zoonoses whose control continues to pose global public health challenges rabies is one of the world's major diseases. Mass vaccination has been used successfully in Western Europe and North America [1,2], illustrating that the disease can be controlled and

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eliminated by vaccination of reservoir animal populations. Japan, the first country to implement mass vaccination of dogs, successfully eliminated rabies in 1956 [3]. Compulsory vaccination and destruction of strays in Malaysia in 1952 brought rabies under control [4], demonstrating that the disease could be controlled even in less developed countries. In Africa, both Zimbabwe [5] and Uganda [6] reported dramatic declines in canine rabies cases over the 10 years prior to 1961.

In developing countries, the majority of confirmed and reported cases and over 90% of human exposures are from domestic dogs [7]. Despite the availability of safe, relatively cheap and effective vaccines for dogs, rabies remains uncontrolled throughout most of Africa and Asia [8-10]. The failure of current control programmes may be attributed to insufficient funding compounded by lack of awareness about the true burden of the disease which has resulted in rabies being perceived as a low priority relative to other health programmes. This may have been exacerbated by the adoption of inappropriate strategies (e.g. dog culling) which highlights the need to develop appropriate and cost-effective strategies.

To qualify as epidemiologically worthwhile, a vaccine delivery strategy needs to be effective in both coverage and cost. Theoretical and empirical analyses indicate that vaccination of 70% of dogs should be sufficient to prevent epidemics and eliminate endemics rabies infection [11], but this level of coverage is rarely achieved in dog vaccination programmes in Africa [12,13]. Dog accessibility for parenteral vaccination, hence coverage levels and cost per dog vaccinated, vary in different settings. For instance, coverage levels achieved using central-point (CP) dog vaccination campaigns in high-density urban and rural areas of Kenya and Tanzania have been sufficient to cause declines in dog rabies [12-14], although none of the studies quantified the delivery costs. In contrast, preliminary efforts at implementing parenteral dog vaccination in low-density Maasai communities of Tanzania and Kenya, using CP or door-to-door campaigns, have resulted in poor levels of coverage and vaccine delivery has proven to be more costly than in agro-pastoral communities [15,16], underlining the need to explore different strategies under different circumstances and settings. Reasons for the failure of parenteral dog vaccination strategies in the latter areas include the nomadic pastoralist lifestyle of the Maasai, living at low densities in remote and operationally difficult areas.

Accessibility of domestic dogs for parenteral vaccination is likely to be affected by various socio-economic, cultural and spatial factors and dog characteristics (i.e. age and degree of restriction), which need to be accounted for in the design of control strategies. In medical immunization programmes in Bangladesh, socio-economic and cultural disparities were identified as important factors contributing to low child vaccination coverage in disadvantaged areas [17]. These findings may also apply to veterinary vaccination programmes. In the case of domestic dog vaccination, socio-economic and cultural factors are likely to influence dog–human relationships and community awareness of and attitudes towards rabies. In some situations in Africa, attitudes towards dogs (e.g. religious and cultural beliefs) can compromise dog vaccination programmes. For example, in the Bale mountains of Ethiopia, parenteral dog vaccination resulted in relatively low coverage levels partly due to reluctance of the predominantly Muslim community to handle dogs (Knobel, unpublished data). A similar observation has been documented in Maasai communities of northwestern Tanzania where people are not used to handling and restraining dogs [15]. Village and household characteristics, such as distance from district headquarters and hospitals and from the central vaccination point, are also likely to influence coverage levels, as observed in Tanzania and Kenya [15,16], and should be considered in the design of CP vaccination programmes. Finally, dog characteristics such as age at which dogs are first vaccinated or degree of dog restriction (hence accessibility for vaccination) may affect overall herd immunity. Although some laboratory trials indicate that vaccine-induced active immunity is likely to be affected by the presence of maternally derived antibodies (MDAs) in puppies (dogs younger than 3 months) [18], other studies show that puppies are capable of responding to rabies vaccination without any significant interference by MDAs [19,20]. Given the high birth rate of rural African dog populations, including puppies in vaccination programmes is likely to be important to maintain sufficient herd immunity for rabies control [12,15,16], although the 3-month age cutoff has been adopted as a policy in many countries [21].

In this paper, we report the results of different vaccination strategies in two distinct settings, the agro-pastoralist and pastoralist communities of the Serengeti ecological region of northwestern Tanzania, in terms of (a) vaccination coverage achieved in the dog population and (b) *per capita* cost of dog vaccination. Moreover, we evaluate the influence of village – (i.e. distance from district headquarters and hospitals), household – (i.e. socio-economic status, ethnicity, number of dogs per household, livestock ownership and distance from a CP) and dog-related (i.e. sex, age and movement restriction status) factors on vaccination coverage in socially and culturally heterogeneous settings within the agro-pastoralist community. We discuss the implications of these results for the development of effective rabies control programmes in communities in rural Tanzania and elsewhere in Africa.

2. Materials and methods

2.1. Study area

The study area in the Serengeti ecological region of northwestern Tanzania (34°−36°E, 1°30′−3°7′S) was divided into two zones based on characteristics of human and dog populations living adjacent to Serengeti National Park (SNP) (Fig. 1). The vaccination zone to the west of SNP, categorised as the agro-pastoral zone, was inhabited by large multi-ethnic communities, predominantly Sukuma and Kurya, with production systems based on livestock and crop-cultivation. Other tribes in the area include the Jita, Luo, Ikizu and Zanaki. The vaccination zone to the east of SNP was categorised as the pastoral zone, inhabited by low-density Maasai and Sonjo pastoralist communities. Previous studies have demonstrated marked differences in dog densities between the two zones [15], with densities currently exceeding 10 dogs/km^2 in the agropastoral zone compared to <5 dogs/km^2 in pastoral communities [22]. Likewise, human density in the agro-pastoral zone is higher (16.4 people/km^2) than in the pastoral zone (7.4 people/km^2) [23]. In the agro-pastoral zone two villages were selected randomly from each of the six districts (Tarime, Serengeti and Bunda in the Mara Region, Magu in the Mwanza Region, and Bariadi and Meatu in the Shinyanga Region) for a more intensive post-vaccination survey. Nine villages were randomly selected within the Loliondo Game Controlled Area (LGCA) of Ngorongoro District in the pastoral zone for intensive follow up.

2.2. Vaccination strategies in the agro-pastoral communities

Vaccination campaigns in the agro-pastoral zone were implemented in 145 villages with a human population of 466,989 based on the 2002 census [23]. A village-based CP vaccination strategy was adopted using previously described methods [14]. In brief, the vaccination date was communicated to dog owners at least 1 week in advance through official letters to village authorities, and posters were posted in popular places within the village including schools, shops, markets, courts, political party and village offices. One day before the vaccination, an advertising team delivered a reminder to schools and village leaders. In the advertisements, dog owners were informed that vaccination was free of charge and were asked to bring their dogs to the CP. On the vaccination day, a vaccination station at a CP within the village was set up by a team of four livestock officers. Dogs were registered and data recorded on the name of the owner, name of the dog, its age, sex and previous vaccination history. Dogs were subcutaneously injected with 1 ml Nobivac Rabies vaccine (Intervet SA (Pty.) Ltd.) and 1 ml Puppy DP vaccine (Intervet SA (Pty.) Ltd.) against canine distemper and canine parvovirus. Plastic ribbons were affixed to animals as temporary collars to indicate they had been vaccinated and certificates for each dog vaccinated were given to owners. In this study, costs were considered only for the rabies component of vaccination. Disposable needles and syringes were used. Needles were used only once for each dog while syringes were recycled for every 20 dogs.

2.3. Vaccination strategies in the pastoral communities

In the pastoral zone, vaccinations were conducted in 21 villages with a human population of 45,218 [22]. Two combined approaches using parenteral vaccines were implemented: (1) CP and house-to-house (HH) and (2) CP and use of community-based animal health workers (CAHW). These combinations allowed investigation of three vaccine delivery strategies: (a) CP strategy, (b) combined CP and HH (CP-HH), and (c) combined CP and community-based strategies (CP-CAHW). The CP campaigns were carried out in all the villages (n = 21) by a team of three livestock officers as described above. Villages were then assigned at random to one of the remaining groups (b) or (c). The CP-HH campaigns were conducted in 10 villages by a team of 2 people who visited each selected village after the CP vaccination and each household within the village, and, where dogs had not been vaccinated in the CP campaign, carried out the vaccination, dog registration and issuing of vaccination certificates. The combined CP-CAHW strategy involved village animal health or primary health workers who were trained in the administration of vaccine and provided with vaccine, consumables and bicycles to access cold-chain facilities. The CAHWs were responsible for carrying out the vaccination in the remaining 11 villages after the CP vaccination according to their method of choice (CP or HH).

2.4. Household questionnaire surveys

Household questionnaires were conducted within a month of the CP vaccination day in order to assess vaccination coverage and to collect data on household (i.e. tribe and livestock ownership) and dog (i.e. sex, age and dog handling practices) characteristics, and, for unvaccinated dogs, reasons for failure to bring dogs for vaccination. Interviewees were asked to produce vaccination certificates as proof of dog vaccination. In cases where a vaccination certificate was not available names of the dog and its owner were recorded for certification of dog's vaccination status from the vaccination register. No attempt was made to evaluate rate of loss of vaccination certificates. The location of each household was recorded using a Global Positioning System (GPS). The sampling methodology of households in agro-pastoralist communities was based on random selection of 10-cell units (known locally as *balozis*). All households within units were sampled (accounting for ~2.5% of the population in vaccinated villages). Due to numerically fewer and higher dispersion of Maasai households, the use of 10-cell units was not logistically feasible in this community. Therefore 10% of traditional Maasai homesteads (known locally as *bomas*) in a village were selected at random (accounting for ~4% of the population in vaccinated villages) and each *boma* was treated as a single household. An open-ended questionnaire was conducted in a language understandable to respondents (mainly Swahili) and in local language whenever necessary by a well-trained team of four people, with the same team carrying out the questionnaires in each of the districts. As adult household members assume responsibility for overall household matters including authorization of dog vaccination, the household head, or, in his/her absence, any adult (>18 years) was interviewed. Households were assigned a socio-economic status according to the number of cattle owned (cows, bulls, heifers, and calves) and house quality. Individuals were classified as high socio-economic status if they owned more than 50 head of cattle and, if they did not own cattle, owned houses constructed of cement block and roofed with corrugated iron sheet.

2.5. Direct observation of collared dogs

Previous studies have demonstrated that the proportion of feral dogs in these communities is likely to be very small [14,24]. Nevertheless, attempts were made to estimate the proportion of feral dogs present in the population and their impact on the vaccination coverage achieved in high dog density agro-pastoral communities. Within 24 h of the vaccination campaign in each of the intensively followed up villages, one person travelled along all major roads, garbage points and popular village centres to observe the proportion of collared and un-collared dogs. Direct observations were carried out from 1700 to 1900 and 0630 to 0830 as unrestricted and feral dogs are likely to be more active when human activity is low and the weather is cool.

2.6. Vaccination coverage

Vaccination coverage was estimated from: (a) the household questionnaire survey as the proportion of vaccinated to unvaccinated dogs in households, adjusting for the proportion of the dog population which is feral (based on observations of collared dogs) and inaccessible for CP parenteral vaccination and (b) from doses of vaccine delivered as a proportion of the total dog population (estimated from the dog-to-human ratio for 2003). The human population was determined from the 2002 national census data for each village and projected at a 2.9% annual growth rate [23]. The vaccination coverage estimates were compared with a multivariate linear mixed effect model, using maximum likelihood to evaluate consistency in coverage. Confidence intervals for the vaccination coverage estimates were calculated using the exact binomial distribution (Epi Info Version 3.3.2, CDC). The sample size required for estimation of vaccination coverage was calculated using standard methods [25-27] so as to obtain a minimum expected difference of 15%:

$$N=2\cdot\left[Z_{\mathrm{crit}}\frac{\sqrt{2p\,(1-p)}+Z_{\mathrm{pwr}}\sqrt{p_1\,(1-p_1)+p_2\,(1-p_2)}}{D^2}\right]^2$$

where N = the required sample size, p_1 and p_2 are pre-study estimates of vaccination coverage, D = the minimum expected difference, $p = (p_1 + p_2)/2$, $Z_{\mathrm{crit}} = 1.96$ (significance level), $Z_{\mathrm{pwr}} = 0.8$ (statistical power). This required observation of at least 276 dogs in a village and therefore a minimum of 230 households assuming a household to dog ratio of 1:1.2 [24]. This sample size gives 80% statistical power with 95% confidence.

2.7. Cost per dog vaccinated

Cost analysis was carried out from the animal health provider perspective with costs assumed as being incurred by the Tanzanian Government alone. Private household costs were not estimated for two reasons: (i) observations at CPs indicated that the majority (>80%) of people who brought dogs for vaccination were children <14 years old who are generally considered to be economically inactive, making estimation of opportunity costs due to lost time difficult and (ii) rabies control was considered a public rather than a private good and vaccination was provided free of charge [28]. The cost per dog vaccinated was derived from the total cost of the vaccination programme divided by the total number of dogs vaccinated. Vaccination costs for supplies and consumables (vaccine, needles and syringes) were estimated from 2003 market prices and *per diem* and overnight allowances were based on 2003 applicable government rates for livestock officers. Capital costs were amortised on a 6% discount rate and 5- and 10-year life span for capital equipment (vehicles and refrigerators, respectively). The annualised cost was multiplied by the number of days the capital equipment was used for the vaccination campaign, then divided by the number of days in 1 year assuming capital equipments were productively used throughout the year. Expenses related to cold chain, transportation, vehicle repairs, community mobilisation and sensitisation, supervision and training of vaccinators were included in the costing. Costs (summarized in Table 4) were based on expenditure in Tanzanian shillings (TZS) at the time the study was undertaken, then converted to US dollars (US$) at the 2003 applicable exchange rate of TZS 1080/US$. To allow for uncertainty and variability, probability distributions were assigned to input variables. Normal probability distributions were assigned to variables for which means and confidence intervals could be estimated and triangular probability distributions for variables that showed peaked distribution. Input variables were sampled iteratively 1000 times using a Monte Carlo simulation procedure (@Risk Pro 4.5, Palisade Corp., Newfield, New York). The mean cost per dog vaccinated and the 5th and 95th percentiles were calculated.

2.8. Analyses

Vaccination coverage and costs were compared between agro-pastoral and pastoral communities for the CP strategy. Within the pastoral community, the two strategies (CP-HH and CP-CAHW) were compared. To investigate factors influencing vaccination coverage, data were analysed at (a) the village level; (b) the household level; and (c) the individual dog level. The data were analysed using generalised linear models with binomial errors and mixed effects. At the village level, distance from district headquarters, distance from the nearest district hospital and village population size were fixed effects with district assigned as a random effect. At the household level, fixed effects included number of livestock owned, number of dogs owned, number of people in a household, distance from a CP to a household with district and village as random effects. At the dog level the fixed effects included dog age class, sex and whether a dog is restricted or not, with random district, village and household effects. The distances for each village from the nearest district hospital, district headquarters and the distance of each household interviewed from the CP were estimated from GPS locations. Distances from nearest district hospital and headquarters were categorised as near if ≤10 km and far if >10 km. Within 10 km individuals do not commonly pay for public transport and often either walk or use bicycles to travel to the nearest district hospital.

3. Results

3.1. Dog:human ratio

Summary household data obtained during the household questionnaire survey and dog-to-human ratio for the agro-pastoral and pastoral zones are shown in Table 1.

3.2. Coverage

Vaccination coverage attained using the CP strategy in agro-pastoralist communities and CP, CP-HH and CP-CAHW strategies in pastoralist communities are shown in Table 2. The CP strategy in agro-pastoralist communities and combined CP-HH and CP-CAHW strategies in pastoralist communities all achieved coverage of >70%. The CP strategy alone was ineffectual in the pastoralist communities (<20% coverage). There were no significant differences detected between vaccination coverage estimates from the household questionnaire survey and vaccine doses used as a proportion of the total dog population estimated from dog-to-human ratio ($F_{2,10} = 2.7$, $p = 0.11$). The proportion of feral dogs, as estimated from direct observation of collared dogs, ranged from 3.0 to 5.4% (Table 3) reflecting their negligible impact on vaccination coverage achieved. Except for only one village the overall vaccination coverage achieved in each study district within the agro-pastoral communities was >70% even after adjusting for the proportion of feral and unrestricted dogs (Table 3, Fig. 2).

3.3. Per capita cost of dog vaccination

As indicated in Table 2, the *per capita* cost for the CP strategy was less in the agro-pastoral zone than in the pastoral zone, with an average cost per dog vaccinated of US$1.73 (95% CI: 0.84-2.69 US$) and US$5.55 (95% CI: 3.83-7.43 US$), respectively. In pastoralist communities, the CP-CAHW strategy resulted in the lowest *per capita* cost. Table 4 shows the costs by line item on a per dog vaccinated unit basis in the agro-pastoral and pastoral settings and a comparison with an urban African setting [29]. The largest expense in the agro-pastoral zone was vaccine, whereas 70% of the costs in the pastoral zone were associated with vehicle use (capital costs, maintenance and fuel) owing to the low density and dispersed nature of these communities.

3.4. Coverage according to village characteristics

Summary vaccination coverage achieved in agro-pastoralist communities according to village, household and dog-related factors is shown in Table 5. There were no significant differences in vaccination coverage achieved using CP in the agro-pastoral communities in relation to distance from district headquarters and nearest district hospitals ($F_{1,4} = 6.14$, $p = 0.07$ and $F_{1,4} = 0.90$, $p = 0.39$, respectively). Vaccination coverage achieved in the 12 intensively followed up villages in the six study districts is shown in Fig. 2 reflecting insignificant influence of district and village in vaccination coverage. Coverage achieved ranged from 66.6 to 90.8% for villages and 75.0 to 87.3% for districts. The mean number of dogs vaccinated at a CP in the agro-pastoral communities was 197 (range 17-717 dogs, $n = 145$).

3.5. Coverage according to household characteristics

Coverage was also high irrespective of socio-economic status, with no significant differences observed ($F_{1,684} = 0.24$, $p = 0.78$), however coverage was more variable among households of low socio-economic status (Table 5). Similarly, no significant differences were detected between different ethnic groups ($F_{4,1362} = 0.80$, $p = 0.52$). Although a significantly greater proportion of households with livestock owned dogs (84.50% [95% CI: 82.63-86.22%]) in comparison with those that did not own livestock ($\chi^2 = 290.58$, d.f. = 1, $p < 0.0001$), the number of dogs owned did not affect the probability that a dog was vaccinated ($F_{1,684} = 0.16$, $p = 0.69$). Vaccination coverage decreased with household distance from the vaccination point ($F_{1,684} = 5.3$, $p = 0.02$), although coverage was generally greater than 70% even at 5 km from the CP (Fig. 3).

3.6. Coverage according to dog characteristics

There was no significant effect of the sex of a dog on its vaccination status ($F_{1,599} = 1.60$, $p = 0.21$). Significantly fewer puppies than juvenile and adult dogs were vaccinated ($F_{2,599} = 158.4$, $p < 0.0001$). Furthermore, the major reason cited by interviewees that did not bring at least one of their dogs to the vaccination point was ‘dog young’ (≤3 months old) (Fig. 4), with a significantly higher proportion of households expressing this reason over all other reasons ($F_{2,599} = 138.4$, $p < 0.0001$). There was no significant difference in coverage between restricted and unrestricted dogs ($F_{1,599} = 0.36$, $p = 0.55$).

4. Discussion

Few mass dog vaccination programmes in Africa have achieved, and sustained coverage at the recommended level of 70% needed to prevent rabies outbreaks. This study demonstrates that not only can CP vaccination achieve this coverage in agro-pastoralist communities, which in Tanzania represent the majority of the population, but also that the cost per dog vaccinated is less than two dollars. Our findings are consistent with other studies in rural Tanzania and Kenya [15,16] in demonstrating that, despite the success of CP vaccination in agro-pastoralist communities, CP alone is not a viable strategy in remote pastoral communities: the coverage attained was well below the recommended target and relatively expensive compared to vaccinating in agro-pastoral areas. In Maasai pastoral communities, households are dispersed, the population is nomadic and dogs are not used to restraint. These factors make it difficult for individuals to bring animals to a designated CP, therefore alternative innovative strategies are necessary for these communities.

The combined CP-HH vaccination achieved the recommended 70% coverage in the pastoral zone, but was less cost-effective and operationally difficult; vaccinating each dog was time consuming and required substantial investment in labour and capital. It may therefore be difficult for this strategy to be undertaken independently and sustained by most district veterinary offices in Tanzania given limited resources. The combined CP-CAHW strategy attained the highest vaccination coverage in the pastoral communities indicating that use of CAHWs is a potentially viable alternative to increase the coverage and cost-effectiveness of rabies vaccination in these areas. More generally, the effectiveness of the CAHW model in areas with limited government veterinary services, logistical problems, and poor infrastructure demonstrates their potential as alternative service models for the veterinary sector where conventional models have failed [30].

Accurate estimates of the *per capita* costs of dog vaccination are needed to plan effective and sustainable rabies control programmes. The cost of CP vaccination in agro-pastoral communities (US$1.73 per dog) compares well with studies from elsewhere, which vary between US$1.19 and 4.27 in the Philippines [31], ~US$1.3 in Tunisia and Thailand [32] and US$1.8 (US$2.6 including private costs) in Chad [29] (Table 4). The costs of the most effective and economical strategies in pastoralist communities are considerably higher (exceeding US$6 and US$4 per dog with combined CP-HH, and CP-CAHW strategies, respectively). However, these costs may be shared more equitably amongst stakeholders through intersectoral collaborations such as combined public health and animal vaccination campaigns [33,34] or in specific instances through conservation organizations due to the benefits for wildlife [22].

Implementation of CP vaccination depends on owners’ active participation, which may be influenced by social, cultural and economic factors [35,36]. Factors linked with household social, cultural and economic status did not significantly affect vaccination coverage nor did distance from district headquarters and hospitals, even though communities situated close to major medical and veterinary services or administrative centres were expected to exhibit some complacency. Vaccination coverage was consistently high amongst all the agro-pastoralist tribes, but this should be extrapolated cautiously since study communities were predominantly Christian and attitudes towards dogs may differ in Muslim areas. Households with livestock owned significantly more dogs than households without livestock, probably because dogs are primarily kept for livestock security. The number of dogs owned did not influence the chances of a dog being vaccinated indicating that dog owners were likely to vaccinate all their dogs.

Determining the optimal vaccination catchment area for CPs is critical to the success of a programme, as coverage declines progressively with increasing distance from the CP. In vaccination trials in a Maasai pastoral community in Kenya coverage decreased by 95.3% with a 1 km increase in distance from the CP [16]; this may also be why CP vaccination achieved such low coverage in the pastoralist communities in this study. In the agro-pastoral communities coverage decreased with distance from the CP, though generally remained above the lower critical bound of 55% [11] up to over 5.5 km from the central vaccination point and always exceeded 70% within a 2 km catchment area. It is unclear why this level of coverage is considerably higher than a previous small-scale study [15], but the influence of distance depends on the degree of active community participation and may be affected by general rabies awareness.

The sex of a dog and whether it was restricted did not significantly affect vaccination coverage. In contrast, dogs 3 months of age were less likely to be vaccinated than older animals, which is consistent with other studies [15,16,37,38]. Theoretical and empirical studies have shown that inclusion of pups in rabies vaccination campaigns is likely to result in substantial epidemiological and economic benefits [15,16]. Dogs less than 6 months old are both significantly more important in rabies transmission to humans [39] and more likely to be accessible for parenteral vaccination than older dogs. However, dog owners are apparently doubtful about the appropriateness of vaccinating pups, with low vaccination coverage in this age class, despite advertising efforts. Of all age classes, pups suffer highest mortality, sometimes exceeding 50% [16,40]. Consequently vaccinating pups would result in some vaccine wastage and there is a potential danger that pup deaths could erroneously be linked to vaccination, which could generate hostility towards future campaigns. Nonetheless, the active inclusion of pups in rabies vaccination programmes would be the single most effective way to improve coverage levels and is likely to be associated with low *per capita* costs. Improving education efforts to encourage owners to bring puppies for vaccination should therefore be considered.

One of the critical factors for the sustainability of vaccinations programmes is their affordability by developing country governments. For rabies, the question of the frequency of vaccination campaigns to maintain critical coverage levels required to prevent rabies outbreaks and eliminate endemic infections is likely to be paramount. Previous studies in the same region have demonstrated high turn-over rates of dog populations and consequently a notable annual temporal decline of vaccination coverage. As a result biannual vaccinations with campaigns repeated after every 6-8 months has been recommended in areas with high dog population turn-over rates [15]. Implementation of biannual rabies vaccination campaigns is likely to have significant cost implications and is less likely to be affordable by most developing countries. However, intensive inclusion of puppies in vaccination campaigns, as discussed elsewhere in this paper, is likely to substantially mitigate the effect of high turn-over rates and hence prevent vaccination coverage declining below the recommended lowest critical threshold of 55% [11]. Annual vaccination campaigns that repeatedly achieved coverage of around 70% led to significant declines in rabies [14], suggesting that at least in rural Tanzania annual campaigns may suffice, but further investigation is required to substantiate this claim.

The range of the dog:human ratio was consistent with findings from other studies in rural populations [15,16,40,41] indicating similar patterns of human dog association and dependency. The dog:human ratio is therefore probably a robust estimator for rural dog populations in many African countries. Assuming an annual human population growth rate of 2.9% and that pastoral communities compose 5% of the overall population, the extrapolated cost of an annual rabies vaccination programme for rural Tanzania (77% of Tanzania’s population live in rural areas) based on mobile teams would be less than US$6 million a year.

Although this paper only considers the cost per dog vaccinated, cost-effectiveness in terms of disability-adjusted life years (DALY) averted, is likely to be high because of reduced need for expensive human post-exposure prophylaxis (PEP) [41]. A full analysis is currently underway, with preliminary results indicating that dog vaccination would be considered highly cost-effective at ~US$25 per DALY averted (Cleaveland, unpublished data). As dog vaccination also provides an opportunity for canine rabies elimination in Tanzania [22], investments in sustained, high-coverage campaigns would represent even better value over the longer term.

In some low-density dog populations, rabies infection may not persist but may instead result from sporadic spillover from endemic higher density populations. If endemic infection in high-density populations can be eliminated through mass vaccination this may mitigate the need to vaccinate in very low-density populations that are relatively inaccessible and where costs of control are high. This is an important area for future research which could considerably reduce the costs of long-term national rabies elimination. But, in the Serengeti, while rabies persists in adjacent domestic dog populations, sustained vaccination in low-density communities is still likely to be important to prevent incursions and to protect wildlife known to be threatened by the disease.

Failure to control dog rabies across much of the developing world has been attributed to various factors including inappropriate vaccination strategy design, lack of political will, competing national health priorities and inadequate resources. Recent analyses quantifying the scale of rabies in Africa and Asia suggest the disease ought to be a world health priority [42,43], though work is needed to raise the status of rabies on national health agendas. This study demonstrates that with appropriate strategies high vaccination coverage can be achieved in a range of societies largely representative of rural communities in Africa and that these strategies are affordable. Specifically CP vaccination is robust and effective in rural agro-pastoralist communities and a combination of CP and CAHW vaccination is recommended in remote pastoral communities. The most important factors that compromise coverage are inclusion of puppies and the spatial distribution of households from CPs, but with intensive information dissemination preceding vaccination, proper involvement of community leaders and careful selection of CPs these factors can be addressed. Well-planned and implemented vaccination campaigns can substantially improve coverage with resultant reductions in rabies incidence in both dogs and humans [14,44] and considerable multi-sectoral benefits. Although economic and logistical factors have been identified as major constraints to effective dog rabies control [32], our results suggest that if given the attention it deserves rabies control in developing countries is economically and practically feasible.

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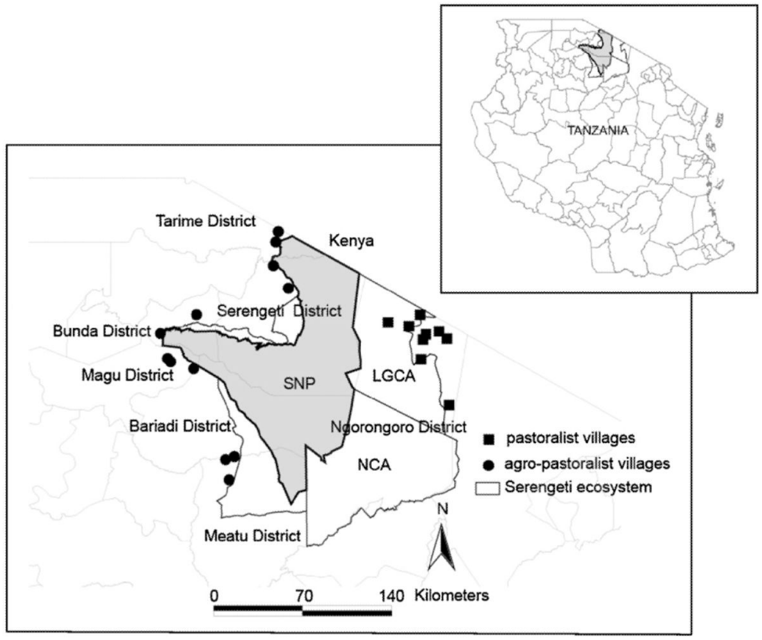

Fig. 1.

Map of the Serengeti ecological region of northwestern Tanzania showing the location of the study villages in the agro-pastoral and pastoral zones, to the west and east of the Serengeti National Park (SNP), respectively. LGCA = Loliondo Game Control Area; NCA = Ngorongoro Conservation Area.

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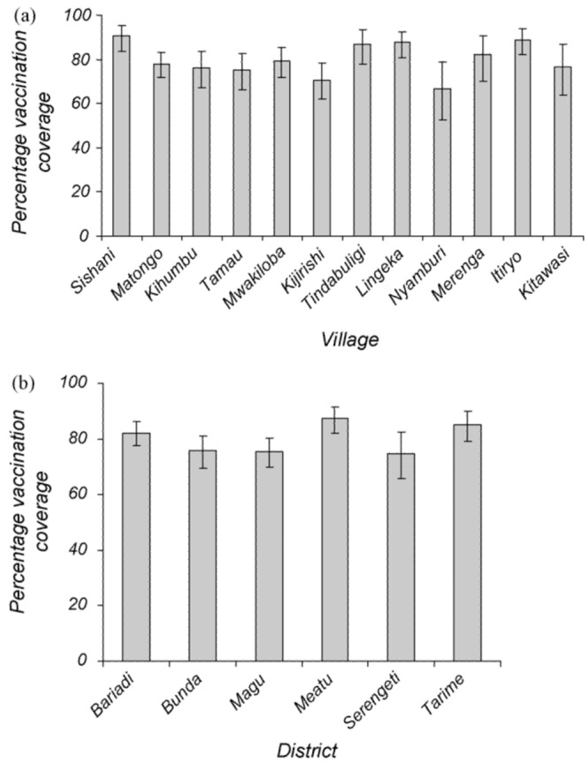

Fig. 2.

Variation in vaccination coverage estimated by household questionnaire survey: (a) vaccination coverage levels achieved in 12 intensively followed up villages and (b) overall vaccination coverage levels achieved in the 6 study districts.

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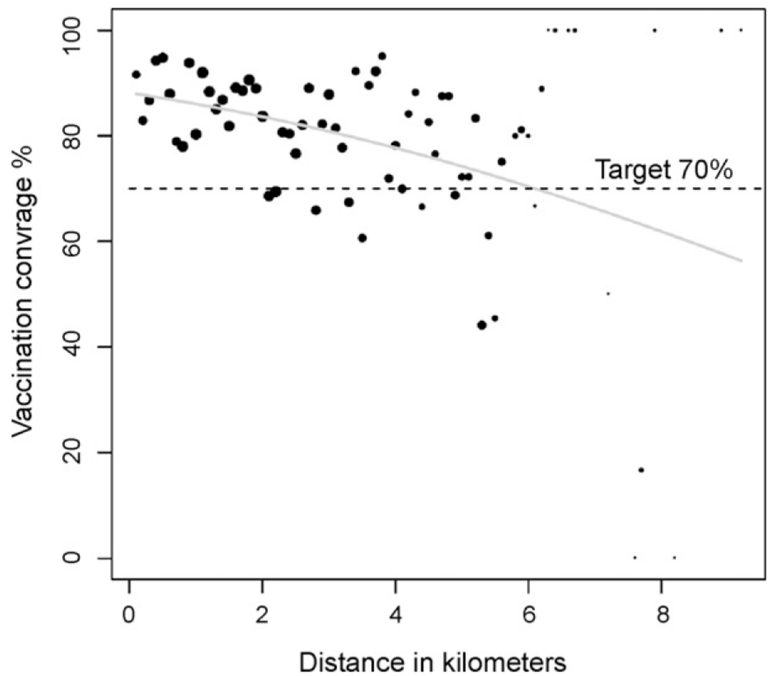

Fig. 3.

Vaccination coverage versus distance from the central vaccination point. A logistic regression with binomial errors fitted to the proportional data demonstrates that coverage declines with distance from the central-point ($p < 0.0001$, gray line). The sample size for each coverage estimate was used to weight the regression; points in the figure are scaled by the log of the sample size. The theoretical target coverage of 70% recommended to control dog rabies is marked with a dashed line. Although there was some evidence for over-dispersion in this data, a logistic regression fitted to binary data for individual dogs, with exact binomial errors, was also highly significant.

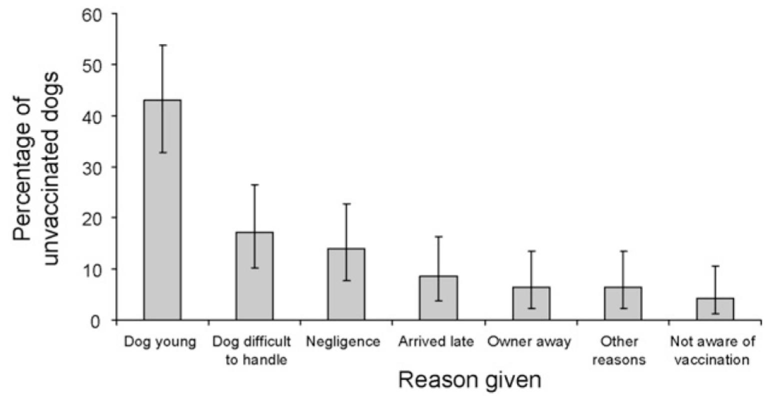

Fig. 4.
Reasons expressed by dog owners for not bringing dogs for vaccination.

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Table 1

Summary of household information obtained from questionnaire surveys.

Setting	Households sampled	Total people	Total dogs	Dogs per household	Dog:human ratio
Agro-pastoralist	1444	11598	1597	1.10	7.26
Pastoralist	323	5222	692	2.14	7.55

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Table 2

Vaccination coverage of the owned dog population attained in agro-pastoralist and pastoralist communities using different vaccination strategies. Coverage was determined from household questionnaire surveys conducted after vaccination campaigns. The cost per dog vaccinated is also indicated.

Setting	Strategy	Vaccination coverage % (95% CI)	Cost per dog vaccinated US$ (5th percentile lower limit, 95th percentile upper limit)
Agro-pastoralist	CP[a]	80.3 (78.0–82.4)	1.73 (0.84–2.69)
Pastoralist	CP	19.2 (11.4–27.0)	5.55 (3.83–7.43)
	CP-HH[b]	80.1 (75.0–85.2)	6.13 (4.90–7.41)
	CP-CAHW[c]	86.3 (81.8–90.7)	4.07 (3.41–4.77)

[a]Central-point.

[b]House-to-house.

[c]Community-based animal health worker.

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Table 3

Overall vaccination coverage achieved in each study district as estimated from the household questionnaire survey (owned dog population) and adjusted for the proportion of feral dog population.

District	Coverage estimated from household questionnaire survey (95% CI)	Coverage adjusted for proportion of feral dogs (95% CI)	Estimated proportion of feral dogs (95% CI)
Bariadi	82.0 (77.6–86.2)	78.8 (71.9–84.7)	3.2 (1.5–5.7)
Bunda	75.6 (69.5–81.1)	72.2 (65.1–78.6)	3.4 (2.5–4.6)
Magu	75.4 (69.8–80.3)	72.4 (68.8–86.1)	3.0 (1.2–4.3)
Meatu	87.3 (82.2–91.4)	81.9 (71.9–89.5)	5.4 (3.1–7.5)
Serengeti	75.0 (65.8–82.4)	69.6 (55.9–81.2)	5.4 (3.6–7.2)
Tarime	85(78.9–89.7)	81.4 (72.4–88.4)	3.6 (1.4–5.8)

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Table 4

Cost per dog for the central-point vaccination campaigns in the agro-pastoral communities (145 villages with 27,400 dogs vaccinated), the pastoral communities (21 villages with 1165 dogs vaccinated) in rural Tanzania and a comparison with an urban vaccination in Africa [29].

Variable	Agro-pastoral communities			Pastoral communities			Urban (Chad)		
	Cost	L95% CI	U95% CI	Cost	L95% CI	U95% CI	Cost	L95% CI	U95% CI
Disposables (syringes, needles, certificates, registers, collars)	0.10	0.07	0.12	0.14	0.13	0.15	0.27	0.27	0.27
Fuel	0.17	0.14	0.20	0.79	0.70	0.86	0.10	0.10	0.10
Allowances for vaccination	0.26	0.23	0.30	0.90	0.78	0.99	0.43	0.42	0.45
Stationery and miscellaneous	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.01
Vaccine	0.50	0.44	0.54	0.59	0.45	0.69	0.74[a]	0.74[a]	0.74[a]
Vehicle maintenance	0.38	0.36	0.41	1.80	1.62	1.89	0.23	0.21	0.27
Capital costs (vehicle and fridge)	0.32	0.27	0.35	1.32	1.08	1.56	0.02[b]	0.02[b]	0.02[b]
Total cost per dog	1.73	1.30	2.25	5.55	5.33	5.77	1.80 (2.56)[c]	1.76 (2.52)[c]	1.86 (2.63)[c]

[a] Includes certificates and information posters.

[b] Ice bars.

[c] Including private costs.

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Table 5

Vaccination coverage of the owned dog population attained in agro-pastoralist communities according to village, household and dog characteristics.

Level	Characteristics	Categories	Vaccination coverage % (95% CI)
Village	Distance from district headquarters	Far	79.9 (76.7–82.9)
		Near	83.5 (80.3–86.4)
	Distance from district hospitals	Far	82.7 (80.3–84.9)
		Near	76.6 (70.4–81.9)
House-hold	Socio-economic status	High	80.4 (77.9–82.7)
		Low	81.7 (75.7–86.8)
	Ethnicity	Sukuma tribe	83.1 (80.5–85.5)
		Kurya tribe	84.6 (80.8–88.0)
		Others	93.4 (84.0–98.2)
	Livestock ownership	With livestock	80.0 (78.0–83.0)
		Without livestock	82.0 (76.0–87.0)
Dog	Sex	Male	80.1 (77.2–82.8)
		Female	80.6 (77.0–83.9)
	Age	Pup	24.7 (17.1–33.8)
		Juvenile	82.9 (78.9–86.4)
		Adult	86.6 (84.1–88.8)
	Restriction	Restricted	76.7 (67.8–84.2)
		Unrestricted	82.3 (80.0–84.5)