Synchronous cycles of domestic dog rabies in sub-Saharan Africa and the impact of control efforts

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Rabies is a fatal neurological pathogen that is a persistent problem throughout the developing world where it is spread primarily by domestic dogs. Although the disease has been extensively studied in wildlife populations in Europe and North America, the dynamics of rabies in domestic dog populations has been almost entirely neglected. Here, we demonstrate that rabies epidemics in southern and eastern Africa cycle with a period of 3–6 years and show significant synchrony across the region. The observed period is shorter than predictions based on epidemiological parameters for rabies in domestic dogs. We find evidence that rabies prevention measures, including vaccination, are affected by disease prevalence and show that a simple model with intervention responses can capture observed disease periodicity and host dynamics. We suggest that movement of infectious or latent animals combined with coordinated control responses may be important in coupling populations and generating synchrony at the continental scale. These findings have important implications for rabies prediction and control: large-scale synchrony and the importance of intervention responses suggest that control of canine rabies in Africa will require sustained efforts coordinated across political boundaries.

Results

Periodicity. Inspection of the data and wavelet analyses and periodograms (Fig. 1 and SI Fig. 5) suggest that rabies epidemics cycle with a period of 3–6 years. This finding is consistent with previous observations (11, 21). Using standard spectral analysis techniques, significant periodicity was detected in six of nine countries (P < 0.05 for Botswana, Kenya, Namibia, South Africa, Sudan, and Zimbabwe) and in a combined series based on all nine time series (P = 0.006, one-tailed). These results were robust under a more conservative statistical test using permuted spectra.

Intrinsic epidemic cycles are predicted from “natural enemy” dynamics as a result of feedback between host and pathogen populations (31). However, simple models of rabies parameterized for domestic dog populations generate oscillatory dynamics in disease incidence with periods that are considerably longer than those observed in these data (9, 32) and corresponding large oscillations in dog population densities for which there is no empirical evidence.

The attitudes and actions of dog owners, local communities, and national governments likely play a major role in determining the dynamics of rabies in domestic dog populations and may explain these disparities. Interventions such as dog vaccination and killing of exposed and rabid animals tend to increase with rabies incidence (11, 33). Given the slow time scale of rabies epidemics, reactive vaccination programs and increased killing

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of exposed and rabid animals have the potential to reduce the final epidemic size. Such responses may reinforce natural cycles of disease incidence and decrease the interepidemic period, because surviving animals continue to breed, replenishing susceptibles more rapidly than in populations depleted by disease-induced mortality. We therefore developed a model to test whether localized, national, and possibly international responses to increasing rabies incidence could act as a strong density-dependent force that may drive cycles over the periods observed.

We found that incorporating vaccination responses into models of rabies in domestic dogs produces epidemic periodicity that is consistent with the frequencies observed (Fig. 2). The delays before implementation of intervention responses lead to reduced oscillations in dog populations to levels that would be barely detectable and greater persistence of oscillations in disease incidence, which otherwise dampen quickly. Although other mechanisms could maintain oscillations in rabies incidence, none of these produce the correspondence between observed dynamics and those predicted from models that include human responses, which suggests that reactive vaccination may play an important role in modulating the dynamics of rabies in domestic dogs.

Available data from Africa are insufficient to test this hypothesis, but data on vaccine use and rabies incidence in Zimbabwe, South Africa, and Kenya lend qualitative support (Fig. 3): vaccine use tends to increase after large outbreaks of rabies and large outbreaks occur after years of very low vaccine coverage. Historical records from domestic dog populations elsewhere in the world are also corroborative. Domestic dog vaccines were first developed in Japan in 1918 and rapidly deployed together with strict licensing laws to bring rabies under control (34). However, in the aftermath of World War II an outbreak occurred that was controlled through reactive measures and increased, sustained vaccination coverage during a second cycle led to its eventual eradication (ref. 35 and Fig. 3). After Japan’s initial example, vaccine production was undertaken in many countries around the world. As a result, rabies in domestic dogs was controlled in several regions, including Malaysia, North America, and Europe, and most recently considerable success has been achieved in South America, Mexico, and the Caribbean (36–40). Where measures were insufficient or not sustained, relatively short (~5 year) cycles are evident (41–43) until the implementation of intensive vaccination programs when cycles disappear (35, 42, 44–47). Conversely, when intensive control programs lapsed, rabies outbreaks rapidly emerged from remnant foci or neighboring endemic regions (refs. 44, 45, and 47–50, Fig. 3, and SI Fig. 7). The few records available from before the vaccination era suggest the occurrence of larger, longer-lived outbreaks (35, 39, 50).

**Synchrony.** A surprising feature of the data is the degree to which peaks and troughs in cases appear coincident in time. A randomization test of the pairwise correlations in oscillations between all nine time series found significant evidence of phase synchrony \((P = 0.008)\), implying some synchrony between rabies epidemics over extremely large spatial scales. Higher-resolution temporal and spatial data further support these findings; monthly data from distinct regions within Zimbabwe each followed the same oscillations as the nationwide data and were closely synchronized (11); data from Swaziland (51) and Lesotho (52) indicate peaks in rabies cases coincident with those in South Africa, and there is evidence for synchronous rabies outbreaks in northern Tanzania (unpublished data). The degree of phase synchrony tends to decay with distance between countries (Fig. 4), although this relationship is not significant at the 5% level \((P = 0.07)\) when tested with appropriately conservative randomization procedures for nonindependent time series.

The observed synchrony is unlikely to be an artifact of surveillance bias and contagion of reporting. Courin et al. (21) were unable to find surveillance biases based on levels of (and correlations between) epidemiological surveillance indices in monthly data from the central stock-ranching district of Namibia, a data set that follows the same qualitative patterns as the countrywide data. Furthermore, where data are available, numbers of human rabies deaths and postexposure treatments correlate closely with numbers of confirmed animal cases (33, 53, 55, 56)\(^\dagger\) even though medical and veterinary authorities operate independently.

Synchrony of disease cycles usually occurs through external forcing. For example, large-scale synchronous epidemics of measles, cholera, influenza, and meningitis are forced climatically or seasonally by social aggregation (31, 57–59). It is possible that the synchrony observed in rabies outbreaks is driven by a common climate variable, although it is hard to determine the

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The proportion of rabid dogs may act as superspreaders (unpublished data), infecting many others or transmitting the disease over large distances. Similarly, transportation of latent, or infectious, dogs, by people as well as infections in wildlife that commute long distances (e.g., hyenas), potentially carry the disease even further. Previous studies have illustrated that even small amounts of relatively local dispersal can generate synchrony in cyclical dynamics over large spatial scales (63) and that the resulting synchrony tends to decline as distance increases and varies through time (64). The pronounced phase synchrony in rabies epidemics for distances up to 1,000 km (Fig. 4) and the lack of relationship across larger distances lends further support to the argument that dispersal could be linking dog rabies epidemics in different countries. Additionally, large-scale control efforts, such as regional or national government vaccination campaigns, could strengthen within-country phase coherence (67), which would increase the rate of disease dispersal across international boundaries during countrywide epidemics. More research is needed to conclusively determine the mechanism synchronizing rabies epidemics, but a combination of dispersal and coordinated responses seems to be the most plausible explanation.

Discussion
Rabies has proved a remarkably valuable system for exploring ecological processes of disease transmission. A vast array of modeling and statistical techniques has been used to investigate dynamics and analyze spatiotemporal trends in rabies surveillance data (14–16, 18). However, these methods have been almost exclusively applied to wildlife rabies in North America and Europe. Although the resolution and length of available time series limit the extent to which the dynamics of rabies in domestic dog populations can be interpreted, our analyses indicate cycles synchronized over very large spatial scales in Africa and should provide impetus for improving surveillance, reporting, and international collaboration. More detailed analysis of higher-resolution data from across scales is necessary to determine the mechanisms that underlie patterns of canine rabies circulation and to develop a more predictive understanding of spatiotemporal dynamics in Africa and elsewhere in the world. This important research goal would promote further pan-African collaboration and provide insight into the longer-term persistence and spatial spread of rabies in Africa.

The finding that rabies dynamics are periodic across much of Africa has important practical implications. Evaluating effectiveness of control efforts is difficult if the disease's natural oscillating tendencies are not considered. We suspect that control efforts generally increase during periods of high rabies incidence and that as incidence declines rabies falls from the agenda. More generally, control efforts for all oscillating pathogens will be prone to such problems to a lesser, or greater, extent, depending on the length of the interepidemic period, the perceived risk, and the capacity of the agencies concerned. The lack of consistent control efforts, together with rapid growth of domestic dog populations, may be responsible for the increase in and general persistence of rabies in Africa, which disconcertingly suggests that the burden of rabies will only worsen unless concerted and prolonged efforts are directed toward its control.

Local vaccination programs in Africa have been effective in lowering rabies incidence in the short term (68), but few have been sustained. The widespread periodicity of rabies epidemics in Africa is consistent with the dynamics of rabies in domestic dog populations in other parts of the world before the effective implementation of sustained control programs. These dynamics highlight the need to maintain vaccination coverage at consistently high levels to prevent epidemics from reoccurring, which typically happens when control programs lapse and would be particularly likely in Africa given the finding of large-scale synchrony. On the other hand, synchronized dynamics also
provide optimism for prospects of rabies eradication if control efforts are coordinated across political boundaries. The evidence that proactive, sustained vaccination programs can control domestic dog rabies is overwhelming, and the tremendous recent successes throughout South America, Mexico, and the Caribbean from large-scale domestic dog rabies control programs should provide ample motivation and a practical model for the control of domestic dog rabies in Africa (4, 37, 42, 69, 70).

Methods

Data. Published data on national annual rabies cases (confirmed wild and domestic animal and human cases from Botswana, Kenya, and Namibia; confirmed canine, bovine, wildlife, and human cases from Zambia; confirmed wild and domestic animal cases from Zimbabwe; and confirmed domestic animal cases from South Africa and Ethiopia), suspect domestic animal cases (from Sudan) and human postexposure treatments (from Tanzania) were collated over the 30-year period 1971–2000 (refs. 19–29, www.who.int/rabies/rabnet/en, and SI Text).** The longest uninterrupted time series was constructed from available data for each country; however, the rabies index used was not consistent between countries (see above). For some countries several data sources were available, and occasionally annual totals from different sources did not exactly match, although the differences were minor. In those instances, we used the figure given in the source for which data were available for the longest interval.

Confirmed rabies cases are underestimates of actual rabies cases, and postexposure treatments are often delivered to victims of bites by healthy animals. Nevertheless, both provide relatively reliable and robust measures of rabies trends over this period. Although data are available for several other countries in the region, data sets were only included if they spanned at least a 10-year continuous period in this interval. For Namibia the time...
series was constructed by using nationwide data except for the year 1986. Here, data were extrapolated from central Namibia (21) by using the ratio between the nationwide data and the central Namibian data, because an uninterrupted time series was not available for the entire country due to political instability in the north of the country. Where data were available to compare, the central Namibian time series was consistent with nationwide patterns.

The African canid rabies lineage is established throughout the subcontinent (30) and has been identified from several different species, with the vast majority of cases coming from domestic dogs. In parts of southern Africa other variants of rabies have been identified that circulate endemically in specific wildlife hosts to which they appear well adapted (54). We include data from wild and domestic animals in our analysis (except for South Africa and Sudan where only data from domestic animals is presented), and we make no distinctions between rabies variants. However, we expect that because of the widespread abundance of the African canid lineage and the general bias in surveillance toward domestic animals, that most of the cases in our analyses belong to the African canid lineage.

**Analysis.** Statistical analysis was done by using R (www.r-project.org). Scripts are available on request. The long-term trends in each time series were removed by taking the residuals from a fitted, locally weighted, polynomial regression (the smoothing parameter included 75% of the observations and assumes Gaussian errors). The detrended data were normalized (mean = 0, variance = 1). The raw and detrended normalized data are presented in Fig. 1 and SI Fig. 5. Although spectral analysis techniques were not ideal for examining periodicity because of the low resolution of the time series, we calculated spectrograms based on first-order differences. The bias in estimated period (66) caused by differencing was minimal. Significance tests were based on comparisons of the spectra and the 97.5th percentile of 1,000 random permutations of the differenced data. Wavelet analyses are also presented, but are limited because of the low resolution and relatively short length of the time series.

To investigate synchrony, pairs of detrended, normalized time series were compared by using the sum of their products through time. Positive products indicate phase synchrony, and negative products indicate phase asynchrony. Simulated pairs were generated with one of the time series shuffled by an offset of between 1 and 30 years for all possible variations, and the sum of their product was calculated. For the country pairs only 30 variations were possible, making significance tests infeasible. An overall statistic, and significance level, was therefore generated from the sum of the pairwise products of all countries included in the analysis. Identical results were obtained by using cross-correlation functions and measures of regionwise synchrony (63). Additionally, the pairwise test statistics were plotted against the log of the distance between countries (from the central point in each country, with distance calculated by using the Haversine formula). To test the a priori hypothesis that correlation between countries decreases with distance we calculated the slope of a weighted regression (by the number of points in each time series) of the pairwise correlation statistic and the log distance between countries. We then randomized the distance between countries and recalculated the slope for 10,000 runs to estimate the probability of generating such a slope by chance.

Where higher-resolution data are available over short intervals, observed oscillations are relatively smooth, providing more support for our coherence and periodicity statistics calculated from low-resolution annual data.

**Model.** We extend the classic susceptible-exposed-infectious (SEI) model for rabies (15) to include a vaccinated class (V), with vaccination implemented in response to rabies incidence (Eqs. 1–6). The vaccination rate v is determined by a response variable (R) that tracks incidence with characteristic time delay η, which represents reporting, logistical, and bureaucratic delays. The vaccination rate is scaled so that each case detected results in the delivery of approximately τ doses at equilibrium (the number is exactly τ in the limit of low equilibrium level of disease). As a consequence of the implementation delay, more vaccinations are delivered in the wake of epidemics than in the early stages.

$$dS/dt = aN - bS - γNS - βSI - vS + δV$$

$$dE/dt = βSI - bE - γNE - αE$$

$$dI/dt = αE - bI - γNI - αI$$

$$dV/dt = νS - bV - γNV - τV$$

$$dR/dt = \frac{τI - R}{η}$$

$$ν = (a + δ)R.$$
<table>
<thead>
<tr>
<th>Location (Country, City)</th>
<th>Period</th>
<th>Method</th>
<th>References</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ASIA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Singapore</td>
<td>1892</td>
<td>Stray dog elimination, enforcement of sanitary policy</td>
<td>(1)</td>
<td>Successful</td>
</tr>
<tr>
<td>Japan</td>
<td>1956</td>
<td>vaccination</td>
<td>(2)</td>
<td>First controlled in 1930, eliminated in 1956</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>1956</td>
<td>vaccination</td>
<td>(3, 4)</td>
<td>Elimination in 1956, but reintroduced in 1980</td>
</tr>
<tr>
<td>Malaysia</td>
<td>1953-56</td>
<td>vaccination</td>
<td>(5-8)</td>
<td>Successful until civil unrest led to a decline in control activities in 1970. Sporadic cases have been recorded since the 3 month outbreak.</td>
</tr>
<tr>
<td>Taiwan</td>
<td>1961</td>
<td>vaccination</td>
<td>(9)</td>
<td>Successful</td>
</tr>
<tr>
<td>Philippines (Dumagete, Siquijor, Coastal towns, Negros)</td>
<td>1964-72</td>
<td>vaccination</td>
<td>(10, 11)</td>
<td>Re-emergence when coverage dropped, rabies is now endemic across the country</td>
</tr>
<tr>
<td><strong>THE AMERICAS</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>USA</td>
<td>1950-65</td>
<td>vaccination, stray dog elimination and licensing laws</td>
<td>(9)</td>
<td>Eventually resulted in elimination of domestic dog rabies throughout the country</td>
</tr>
<tr>
<td>Alabama, USA</td>
<td>1937-44</td>
<td>vaccination</td>
<td>(13)</td>
<td>Small scale success but not enforced in all counties</td>
</tr>
<tr>
<td>New York State, USA</td>
<td>1946-48</td>
<td>vaccination</td>
<td>(14, 15)</td>
<td>Successful, although wildlife rabies is endemic</td>
</tr>
<tr>
<td>Memphis, USA</td>
<td>1948</td>
<td>vaccination</td>
<td>(16)</td>
<td>Successful</td>
</tr>
<tr>
<td>Houston, USA</td>
<td>1953-55</td>
<td>vaccination</td>
<td>(16)</td>
<td>Successful</td>
</tr>
<tr>
<td>Phoenix &amp; Maricopa, Arizona, USA</td>
<td>1962</td>
<td>vaccination</td>
<td>(17)</td>
<td>Successful</td>
</tr>
<tr>
<td>California</td>
<td>1952-57</td>
<td>vaccination</td>
<td>(18)</td>
<td>Successful, although wildlife rabies is endemic</td>
</tr>
<tr>
<td>Santiago, Chile</td>
<td>1962-64</td>
<td>vaccination</td>
<td>(19)</td>
<td>Carried out to control a serious outbreak</td>
</tr>
<tr>
<td>Chile</td>
<td>1960</td>
<td>vaccination</td>
<td>(20, 21)</td>
<td>Within ten years rabies was reduced to very low levels. No human deaths since 1990</td>
</tr>
<tr>
<td>Greater Buenos Aires, Argentina</td>
<td>1976</td>
<td>vaccination</td>
<td>(22)</td>
<td>Nation wide decline in domestic dog rabies</td>
</tr>
<tr>
<td>Argentina</td>
<td>1977-82</td>
<td>vaccination</td>
<td>(9, 22)</td>
<td>Nation wide decline in domestic dog rabies</td>
</tr>
<tr>
<td>Lima-Callau, Peru</td>
<td>1982</td>
<td>vaccination</td>
<td>(22)</td>
<td>free of dog rabies, but later reintroduced</td>
</tr>
<tr>
<td>Peru</td>
<td>1985</td>
<td>vaccination</td>
<td>(23)</td>
<td>Reduced levels of canine rabies</td>
</tr>
<tr>
<td>Sao Paulo, Brazil</td>
<td>1969</td>
<td>vaccination</td>
<td>(22)</td>
<td>Successful city wide control</td>
</tr>
<tr>
<td>Brazil</td>
<td>1981</td>
<td>vaccination</td>
<td>(24)</td>
<td>Nationwide decline in domestic dog rabies</td>
</tr>
<tr>
<td>Quayaquil, Ecuador</td>
<td>1985-86</td>
<td>vaccination</td>
<td>(25)</td>
<td>When intensive vaccination campaigns implemented rabies was controlled</td>
</tr>
<tr>
<td>Mexico and the Caribbean</td>
<td>1990s</td>
<td>vaccination</td>
<td>(22, 27)</td>
<td>Dramatic reductions in incidence and human deaths</td>
</tr>
<tr>
<td><strong>EUROPE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scandinavian countries</td>
<td>pre 1900</td>
<td>Stray dog elimination, enforcement of sanitary policy</td>
<td>(16)</td>
<td>Successful</td>
</tr>
<tr>
<td>Prussia</td>
<td>1875</td>
<td>Stray dog elimination, enforcement of sanitary policy</td>
<td>(1)</td>
<td>Initial success</td>
</tr>
<tr>
<td>UK</td>
<td>1886-1903</td>
<td>Stray dog elimination, enforcement of sanitary policy</td>
<td>(28)</td>
<td>Eliminated rabies until an outbreak from 1918-22 following WWI. Eradicated through muzzle and leash restrictions and elimination of strays.</td>
</tr>
<tr>
<td>Hungary</td>
<td>1935-44</td>
<td>vaccination</td>
<td>(30, 31)</td>
<td>Early success</td>
</tr>
<tr>
<td>Italy</td>
<td>1950-75</td>
<td>vaccination</td>
<td>(32)</td>
<td>1 case in northern from Italy 1957-68, no cases in central Italy since 1970, since 1977 sylvatic rabies only</td>
</tr>
<tr>
<td>Yugoslavia</td>
<td>1946-91</td>
<td>vaccination</td>
<td>(32)</td>
<td>Successful</td>
</tr>
<tr>
<td>Vojvodina</td>
<td>1946-63</td>
<td>vaccination</td>
<td>(32)</td>
<td>Successful</td>
</tr>
<tr>
<td>Malaga, Spain</td>
<td>1975-75</td>
<td>vaccination</td>
<td>(33)</td>
<td>outbreak controlled through vaccination and stray elimination</td>
</tr>
<tr>
<td>Spain</td>
<td>1950-1990</td>
<td>vaccination</td>
<td>(34)</td>
<td>no terrestrial cases since 1979, since 1966 no human cases (except imports)</td>
</tr>
<tr>
<td><strong>MIDDLE EAST &amp; NORTH AFRICA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Israel</td>
<td>1951</td>
<td>vaccination</td>
<td>(35-37)</td>
<td>Field trial from late 1951-early 53. Subsequent implementation of compulsory vaccination and stray elimination</td>
</tr>
</tbody>
</table>
References

Domestic dog rabies vaccination campaigns in Bogota and Cali began in Colombia.

Regional program began in Ecuador.

Citywide vaccinations began in Peru.

Regional program began in Bolivia.

National Programme implemented in Brazil.

Regional program began in Mexico.

Regional program began in Venezuela.

Regional program began in Santa Cruz, Bolivia.