Strategies for containing Ebola in West Africa

Abhishek Pandey,†* Katherine E. Atkins,†* Jan Medlock, Natasha Wenzel, Jeffrey P. Townsend, James E. Childs, Tolbert G. Nyenswah, Martial L. Ndeffo-Mbah, Alison P. Galvani†*

1Center for Infectious Disease Modeling and Analysis, Yale School of Public Health, New Haven, CT, USA. 2Department of Biomedical Sciences, Oregon State University, Corvallis, OR, USA. 3Department of Biostatistics, Yale School of Public Health, New Haven, CT, USA. 4Department of Epidemiology of Infectious Diseases, Yale School of Public Health, New Haven, CT, USA. 5Ministry of Health and Social Welfare, Monrovia, Liberia.

†These authors contributed equally to this work.

†Corresponding author. E-mail: alison.galvani@yale.edu

The ongoing Ebola outbreak poses an alarming risk to the countries of West Africa and beyond. To assess the effectiveness of containment strategies, we developed a stochastic model of Ebola transmission between and within the general community, hospitals, and funerals, calibrated to incidence data from Liberia. We find that a combined approach of case isolation, contact tracing with quarantine and sanitary funeral practices must be implemented with utmost urgency in order to reverse the growth of the outbreak. Under status quo intervention, our projections indicate that the Ebola outbreak will continue to spread, generating a predicted 224 (95% CI: 134–358) cases daily in Liberia alone by December, highlighting the need for swift application of multifaceted control interventions.

A multinational Ebola outbreak of unprecedented magnitude was declared a Public Health Emergency of International Concern by the World Health Organization (WHO) on August 8, 2014 (1). From Guinea, the outbreak has spread to the neighboring nations of Liberia and Sierra Leone, subsequently expanding into Nigeria and Senegal (2). Imported Ebola cases have recently led to transmission in the US and Spain (2). As of 15 October, over 9,000 cases and 4,000 fatalities have been reported, with the majority of both occurring in Liberia (2).

Initial Ebola symptoms include fever, malaise, myalgia, and headache, followed by pharyngitis, vomiting, diarrhea and maculopapular rash (3). Severe and fatal stages are accompanied by hemorrhagic diathesis and multi-organ dysfunction (3). Human-to-human transmission occurs primarily via contact with body fluids (3). Inadequate and improper use of personal protective equipment (PPE), compounded by staff shortages in isolation wards pose major risks of infection for healthcare workers (4, 5), leading to nosocomial transmission that can cripple health services (5). Ebola transmission is further exacerbated by traditional West African funeral practices that may involve washing, touching, and kissing the body (5–7). The current lack of licensed therapeutic treatments and vaccines (8), near-term measures to curb transmission must rely on non-pharmaceutical interventions, including quarantine, case isolation, contact precautions, and sanitary burial practices that consist of disinfecting the cadaver before inclosure in a body bag that is further disinfected.

To evaluate the effectiveness of non-pharmaceutical interventions for curtailing the epidemic in Liberia, we developed a stochastic model of Ebola disease transmission that takes into account Ebola transmission within and between the community, hospitals, and funerals (FS1, SOM). We parameterized our model using epidemiological data on disease progression and on delay from symptom onset to hospital admission obtained from the current outbreak in Liberia (9) (table S1), as well as using demographic data from the 2008 National Housing Census of Liberia (10). In the absence of data on the number of infections due to funeral transmission for the current outbreak, we parameterized the elevated risk posed by funeral attendance using odds ratios calculated from data collected during a previous Ebola outbreak in the Democratic Republic of the Congo (11). We tracked the density of individuals in the following epidemiological classes: susceptible (S), latently infected (E), infected and infectious (I), deceased (F), recovered with sterilizing immunity (R), and buried (D). To account for heterogeneity in contact and transmission between individuals in different locations, we further stratified each epidemiological class into compartments that correspond to foci of Ebola transmission: the general community, hospitals and funerals. Hospitals were further stratified into patients and staff, and hospital workers. We parameterized hospital visits per patient and rate of funeral attendance per death based on the number of family members in a Liberian household (10).

To calibrate our model, we obtained data from Situation Reports provided by the Liberian Ministry of Health and Social Welfare (12) (table S1 in SOM). Outbreak control measures were not coordinated on a national scale in Liberia until August 8, 2014, when the Armed Forces of Liberia established checkpoints to restrict the movement from affected regions (13). To avoid potential confounding of behavior change as a result of interventions, we used the Ebola cases, deaths, healthcare worker infections and hospitalizations from Liberia reported between 8 June and 7 August 2014 to calibrate our model (Fig. 1, SOM). Given intervention assistance from the international community deployed on 20 September (14), we validated our model by comparing data between August 8 and September 19 to our model projection over that time period (Fig. 1).

In our study, we evaluated whether four WHO-recommended non-pharmaceutical interventions can efficiently control the current Ebola epidemic: 1) transmission precautions for healthcare workers, 2) sanitary burial, 3) isolation of infectious Ebola patients, and 4) contact tracing with follow-up and quarantine. In addition, we also assessed a fifth intervention, enforcement of a cordon sanitaire, implemented by Liberian authorities. We calculated the basic reproductive number ($R_0$)—the average number of secondary cases generated by an average primary case in an entirely susceptible population (15)—and quantified the contribution of transmission arising from each of the community, hospitals, and funerals.

We calculated $R_0$ for Ebola in Liberia to be 1.63 (95% CI: 1.59–1.66) prior to widespread interventions, consistent with other $R_0$ estimates for the current outbreak (16–18), but somewhat lower than those calculated for the previous outbreaks, which ranged between 1.8 and 2.7 (19–21). Our novel model structure allowed us to partition the contribution of different transmission routes in sustaining the epidemic. We calculated that in the absence of nosocomial transmission, $R_0 = 1.48$ (1.44–1.51); without community transmission, $R_0 = 1.39$ (1.35–1.42); if only funeral transmission were present, and both nosocomial and community transmission were eliminated, $R_0 = 1.16$ (1.13–1.18); and if funeral
transmission were absent (but community and hospital transmission were present), $R_0 = 0.93$ (0.87–0.99). These results for $R_0$ imply that reducing transmission in hospitals and the community is insufficient to stem the exponentially growing epidemic. To stem Ebola transmission in Liberia, it is imperative to simultaneously restrict traditional burials which are effectively serving as superspreader events (22, 23).

The close agreement between the epidemiological data and the temporal trajectory of our model between August 8 and September 19 suggests that the cordon sanitaire and curfews implemented in that period (13) have had little impact on the exponential increase of Ebola prior to September 19 (Fig. 1) and may have even been detrimental considering the civil unrest that was fuelled by these measures (24). This result is underscored by our $R_0$ analysis showing that removal of community-based transmission only has a marginal impact on $R_0$ value.

Under intervention efforts implemented through September 19, our model predicts that the epidemic will continue to spread, generating a predicted 224 (134–358) daily cases by December 1, 280 (184–441) by Dec 15 and 348 (249–545) by Dec 30. Reducing nosocomial transmission with the use of personal protection equipment is unquestionably fundamental to maintain medical infrastructure and to implement case isolation. Nevertheless, hospital-based measures alone, like community-based efforts alone, are insufficient to stem the Ebola outbreak in Liberia (Fig. 2, A to D). Instead, these efforts must be combined with sanitary burial practices (Fig. 2E) and ideally with contact tracing (Fig. 2F) in order to achieve a reasonable likelihood of epidemic control over the next six months. The potential for rapid control depends on the efficacies that can be achieved for each intervention. For example, the combination of case isolation, sanitary burials of hospital deaths, and reduction in nosocomial transmission, each applied with an efficacy of 95%, would reduce the number of daily cases in Liberia to a projected 24 (15–41) by December 1, whereas combining case isolation with contact tracing and quarantine, each with an efficacy of 90%, is predicted to reduce the number of daily cases in Liberia to 9 (5–23) by December 1 (Fig. 1) and may have even been detrimental considering the civil unrest that was fuelled by these measures (24).

To investigate the applicability of our national-scale results to a more local scale, we fit our model to data from Montserrado County (12). Here, too, our results show that swift control of the epidemic on a local level is only achievable through a combination of control strategies, consistent with our results on the national level (SOM, fig. S3).

Recent reports by the WHO have suggested that cases in Liberia are under-reported, although it is difficult to know by how much (25). To evaluate the impact of under-reporting on our results, we refit our model to account for a range of plausible under-reporting. In addition we considered the possibility that under-reporting differs between community and hospital settings. When we recalculated intervention effectiveness using these new model fits (fig. S2), we found that under-reporting would reduce our estimates of intervention effectiveness. For example, an under-reporting rate of 20% predicts an average of 37 daily cases by March 15 compared to 8 daily cases for perfect reporting for the strategy of 80% case isolation as well as 50% contact-tracing and quarantining. Moreover, our results show that when only community cases are under-reported (fig. S2, D to F), the effectiveness of nosocomial interventions is reduced (fig. S2D) as there is proportionally greater transmission within the community than observed. This possibility for lower effectiveness that arises when accounting for under-reporting further argues for rapid application of diverse control interventions.

Under-reporting might also manifest via asymptomatic infections, which have been observed in previous outbreaks (26). While there is considerable empirical uncertainty regarding the proportion of infections that are asymptomatic, our sensitivity analysis indicates that the larger the proportion of asymptomatic infections, the greater the impact of intervention effectiveness (SOM, Fig. 4).

To evaluate the impact of uncertainty around epidemiological parameters on predicted outcomes, we analyzed the sensitivity and elasticity of intervention effectiveness to variation in epidemiological parameters (Fig. 4). Unsurprisingly, we find that lower transmissibility at funerals (9) reduces the effectiveness of the funeral-based interventions (SOM, Fig. 4). More generally, the effectiveness of an intervention that reduces transmission to healthcare workers and increases sanitary burial of hospital cases is most sensitive and elastic to the incubation period ($1/\gamma_0$), the durations from symptom onset to death ($1/\tau_{DG}$), and recovery ($1/\tau_{DR}$) (Fig. 4A). By contrast, when the intervention scenario focuses on community transmission alone, there is less sensitivity to these parameters (FABC).

It is important to consider the impact of feasibility, human behavior and likely adherence to recommendations (27) on the effectiveness of intervention strategies when making policy recommendations. As the epidemic unfolds, funeral attendance and traditional burial practices may decline with increased awareness of the disease, facilitating the enforcement of sanitary burial practices. By contrast, other behavior changes may hinder intervention efforts. For example, contact tracing has recently become more challenging due to relocation of contacts from urban to rural communities (28). Additionally, case isolation outside of Monrovia is hampered by scarcity of ambulances for prompt referral to Ebola-specific treatment centers (29). Similarly, the implementation of hospital-based interventions will depend on treatment center capacity and admission rates, such that an insufficient number of beds and low admission rates reduce the effectiveness of hospital-based interventions (Fig. 4, A and C). As our model does not explicitly account for hospital capacity, our predicted outcomes regarding hospital-based interventions may be optimistic, further underscoring the importance of combining hospital-based interventions with contact-tracing and quarantine. Additionally, we stress the protection of healthcare workers as an essential component for maintaining the medical infrastructure and for implementing any response strategy. Although recent cumulative case data over October 2014 from Liberia suggest that the exponential growth that has characterized the epidemic for both communities and healthcare workers may be slowing down (30), it is too early to tell whether this apparent reduction in the effective reproductive number is a result of control measures initiated toward the end of September.

While our predictions concur with an analysis of the 1995 Democratic Republic of Congo and 2000 Uganda outbreaks suggesting that funeral transmission is an important driver of Ebola transmission (20), our study also reveals that at this point in the current Liberian outbreak, sanitary burial alone is insufficient to swiftly contain disease spread unlike for past Ebola outbreaks. Other models assess country-wide intervention effectiveness (16, 31) but do not explicitly parse the specific intervention strategies that are effective in particular settings. In contrast, our model has the complexity to demonstrate that a combination of case isolation in the hospital settings, contact tracing in the community, and sanitary burials must be implemented to achieve a significant likelihood of controlling the outbreak over the next six months.

Until very recently, Ebola has been extremely neglected. Consequently, scarcity of data on both previous outbreaks and on the current outbreak limits the complexity of models that can be reasonably parameterized. In particular, there are no epidemiological data available with which to parameterize a spatially-explicit model of Ebola transmission. Such data would be useful for predicting not only the scale of interventions required, but also the geographical areas on which to focus control efforts and preparedness strategies.
Ebola poses an urgent threat not only to West Africa but also to the international community. The most effective approach to both limiting international spread of Ebola and minimizing local death toll is to control the disease at its source. We find that only a concerted suite of targeted non-pharmaceutical interventions has the potential to curtail the outbreak over the next few months. In the absence of immediate and effective multi-faceted action, our predictions suggest that hundreds of thousands will be logistically challenging even with substantial international aid, and the growth of the Ebola outbreak in impoverished West African countries will be logistically challenging even with substantial international aid, but impossible without it.

References and Notes


Acknowledgments: The research was supported by the National Institutes of Health (NIH 2 U01 GM087719 and 5 U01 GM105627) and the Notsew Orm Sands Foundation. The data reported in this paper are tabulated in the Supplementary Materials. We thank S.G. Gaffney, A. Hofmann, and M. Traina for helpful feedback on the manuscript. All model code and data are available via https://github.com/abhiganit/EbolaCodes/tree/master/Science_Code.

Supplementary Materials

www.sciencemag.org/content/science.1260612/DC1
Materials and Methods
Figs. S1 to S3
Table S1
References (32–42)

29 August 2014; accepted 21 October 2014
Published online 30 October 2014
10.1126/science.1260612
Fig. 1. Model fit to data. (A) cumulative non-healthcare worker cases, (B) cumulative deaths, (C) cumulative healthcare worker cases, (D) cumulative hospital admissions. Cumulative Ebola cases and fatalities obtained from the Liberian Ministry of Health and Social Welfare Situation Reports no. 10–89 (red circles), to which the model was fit. A 95% prediction interval was generated by 10,000 runs of the model with parameters randomly sampled from within their confidence intervals (gray fill, SOM). Validation of the model predictions was provided by comparison with data of the cumulative Ebola cases and fatalities from Situation Reports no. 89–127 (blue circles), representing August 12 to September 19, 2014, which were not used for model fitting.
Fig. 2. Non-pharmaceutical intervention effectiveness. Model predictions of the cumulative number of new cases after one, three, and six months, as well as the probability of fewer than one case daily after these months for (A) 80% reduction in transmission to healthcare workers combined with different reductions in community transmission, (B) increasing proportions of sanitary burial of hospital deaths, (C) increasing proportions of hospital case isolation, (D) 90% reduction in transmission to healthcare workers and increasing sanitary burial of hospital deaths, (E) 80% sanitary burial of hospitalized deaths with increasing sanitary burial of community deaths, and (F) 80% case isolation of hospitalized patients with concurrent contact tracing and quarantine of infected contacts. One thousand simulations of the stochastic model were used to generate the cumulative case count error bars (95% prediction interval) and to estimate the probability of less than one new case per day.
Fig. 3. Effectiveness comparison of individual and combined intervention strategies. Model predictions of the daily number of new and cumulative cases after six months for sanitary burial and hospital deaths, sanitary burial of community deaths, case isolation of hospitalized patients, contact tracing in the community and quarantine of infected contacts.
Fig. 4. Sensitivities and elasticities with respect to epidemiological parameters. Sensitivities and elasticities of cumulative cases under (A) 85% successful sanitary burial of hospital deaths with 95% reduction in transmissibility to healthcare workers for six months (Fig. 2D, blue line), (B) successful sanitary funeral of 90% hospital deaths and 50% community deaths, respectively, (C) 90% successful hospital case isolation with concurrent contact tracing and quarantine of 80% infected contacts. We varied the number of pre-outbreak healthcare workers \( S_W(0) \), the incubation period \( 1/\alpha \), the duration from symptom onset to death if not hospitalized \( 1/\gamma_{DG} \), the duration from symptom onset to recovery if not hospitalized \( 1/\gamma_{RG} \), the duration between symptom onset and hospitalization \( 1/\gamma_{H} \), the hospitalization rate per person for reasons other than Ebola \( h \), the duration of hospitalization for reasons other than Ebola \( 1/h_{HG} \), the number of funeral attendees with close contact to the body \( M_F \), the number of hospital visitors per patient \( M_H \), the transmission rate at funerals relative to general community \( \omega \), the fraction of asymptomatic infections \( 1 - \epsilon \), and the hospital admission rate \( \theta \). For each parameter varied, we re-calibrated and re-ran the model.
Strategies for containing Ebola in West Africa
Abhishek Pandey, Katherine E. Atkins, Jan Medlock, Natasha Wenzel, Jeffrey P. Townsend, James E. Childs, Tolbert G. Nyenswah, Martial L. Ndeffo-Mbah and Alison P. Galvani

published online October 30, 2014