

SUPPLEMENTAL INFORMATION

S1 MODEL

We developed a continuous-time, stochastic compartmental model that takes into account Ebola transmission within and between the community, hospitals, and funerals (Figure 1). We tracked the number of people susceptible (S), latently infected but not yet infectious (E), infectious people (J and I), deceased victims who may transmit the disease during funerals (F), deceased victims who are buried (D), and recovered people with immunity (R). The J compartments ensure that the duration of infection for hospitalized Ebola victims is the same whether they were initially in the general community or were hospital patients. To distinguish different types of exposure to Ebola, we divided the susceptible population into four separate groups: the general community (subscript G), hospital patients (subscript H), health-care workers (subscript W), and people attending funerals (subscript F).

Figure 1 shows the per-capita transition hazards for each transition; see Supplemental Table 1 for parameter definitions and values. The forces of infection are as follows:

$$\begin{aligned}\lambda_G &= \beta_I \frac{I_G + I_W}{N_G + N_W} \\ \lambda_F &= \beta_I \frac{F_G + U_{\text{hf}}(F_H + F_W)}{F_T + \frac{N_T}{e\gamma_F}} \\ \lambda_H &= \beta_I \frac{J_H + J_W + I_H + I_W}{N_H + N_W} \\ \lambda_W &= \beta_W \frac{J_H + J_W + I_H + I_W}{N_H + N_W}\end{aligned}\quad (\text{S1})$$

where ω is the relative risk of infection at funeral with respect to general community transmission and U_{hf} is a switch parameter that allows for hygienic burial of Ebola victims in hospital.

The transition rate to funerals is

$$f_{\text{GF}} = \left[\frac{N_T}{e} + (1 - \theta)\delta_G\gamma_{\text{DG}}I_G + \delta_H\gamma_{\text{DH}}(I_H + I_W) \right] \frac{M_F}{N_G - S_F}, \quad (\text{S2})$$

which accounts for non-Ebola funerals (N_T/e) and Ebola funerals.

The total number of Ebola funerals is $F_T = F_G + F_H + F_W$, the number of people in the general population is $N_G = S_G + S_F + E_G + I_G + R_G + V$, the number of people in hospitals is $N_H = S_H + E_H + J_H + I_H + R_H$, the number of health care workers is $N_W = S_W + E_W + J_W + I_W + R_W$, and the total number of people is $N_T = N_G + N_H + N_W$. All other per-capita transition rates are constant with respect to the number of people in each compartment. The following are composites of the basic model parameters:

$$\begin{aligned}\gamma_{\text{FG}} &= \delta_G(1 - \theta)\gamma_{\text{DG}} \\ \bar{\gamma}_{\text{RG}} &= (1 - \delta_G)(1 - \theta)\gamma_{\text{RG}} \\ \gamma_{\text{FH}} &= \delta_H\gamma_{\text{DH}} \\ \bar{\gamma}_{\text{RH}} &= (1 - \delta_H)\gamma_{\text{RH}}\end{aligned}\quad (\text{S3})$$

Thus, susceptible people (S) who become infected move into latent compartments (E). After the incubation period,

latently infected people (E) move to either the infectious compartments (I_G , J_H , and J_W). Infectious people in the general community can be hospitalized, moving into (I_H). People who are hospitalized when they become symptomatic (J_H , J_W) move into the second infectious class (I_H , I_W) at the same rate to ensure that people who became infected in the general community and are later hospitalized have the same total duration of infection as those who became infected at the hospital. Infectious people either recover with immunity (R) or die. If patients die, they are buried in a funeral ceremony (F) from which funeral attendees may be infected. After the funeral, the deceased Ebola victim is buried (D) and no longer contributes to transmission.

Susceptible people from the general community (S_G) who were hospitalized (S_H) in the beginning of epidemic for reasons other than Ebola (e.g., childbirth) may leave the hospital and return to the general community (S_G) without contracting Ebola in the hospital. However, if they contract Ebola in the hospital, they remain in the hospital (J_H). A proportion θ of people who acquire infection in the general community (I_F) are then hospitalized (I_H). Similarly, an individual from the community (S_G) can attend a funeral (S_F) and then return to the general community as susceptible (S_G) or latently infected (E_G).

The model incorporated stochasticity such that the number of individuals that move from one epidemiological or location class to another was sampled from a Poisson distribution, the rate of which was determined by the current number of people in each class over time. This stochasticity allowed the model to capture uncertainty in the number of new cases that arises in part from stochastic fluctuations because the outbreak is both relatively small and comprises multiple spatial chains of cases that accrue to comprise the full epidemic trajectory.

The stochastic model was simulation by Gillespie's tau-leap method,¹⁰ with a time step of 1 day. The initial conditions for each simulation (at $t = 0$, June 9, 2014) were $I_G(0)$, $S_W(0)$ and $N_T(0)$ as shown in Supplemental Table 1, $S_H(0) = 5S_W(0)$, $S_F(0) = 0$, $S_G(0) = N_T(0) - S_H(0) - S_W(0)$ and all other compartments 0.

SUPPLEMENTAL REFERENCES

1. Central Intelligence Agency, 2014. *The World Factbook: Liberia*. Available at: <https://www.cia.gov/library/publications/the-world-factbook/geos/li.html>. Accessed August 24, 2014.
2. Liberia Institute of Statistics and Geo-Information Services, 2009. *2008 National Population and Housing Census Final Results*. Available at: http://www.emansion.gov.lr/doc/Population_by_County.pdf. Accessed January 10, 2015.
3. World Health Organization, 2012. *Liberia: Health Profile*. Available at: <http://www.who.int/gho/countries/lbr.pdf?ua=1>. Accessed August 24, 2014.
4. World Health Organization, 2012. *World Health Statistics*. Available at: http://www.who.int/gho/publications/world_health_statistics/EN_WHS2012_Full.pdf. Accessed August 24, 2014.
5. WHO Ebola Response Team, 2014. Ebola virus disease in West Africa—the first 9 months of the epidemic and forward projections. *N Engl J Med* 371: 1481–1495.
6. Baize S, Leroy E, Georges A, Georges-Courbot M-C, Capron M, Bedjabaga I, Lansoud-Soukate J, Mavoungou E, 2002. Inflammatory responses in Ebola virus-infected patients. *Clin Exp Immunol* 128: 163–168.
7. Legrand J, Grais R, Boelle P, Valleron A, Flahault A, 2007. Understanding the dynamics of Ebola epidemics. *Epidemiol Infect* 135: 610–621.
8. Wang H, Dereje T, Harris B, 2010. *USAID: Who Benefits from Government Subsidies to Public Health Facilities in Liberia?*

- Evidence from Benefit Incidence Analysis*. Available at: [http://www.mohsw.gov.lr/documents/BIA-Liberia_August12TD\[1\]_Final.pdf](http://www.mohsw.gov.lr/documents/BIA-Liberia_August12TD[1]_Final.pdf). Accessed August 24, 2014.
9. Liberia Institute of Statistics and Geo-Information Services, 2009. *2008 National Population and Housing Census: Preliminary Results*, 23. Available at: <http://unstats.un.org/unsd/dnss/docViewer.aspx?docID=2075>. Accessed August 24, 2014.
 10. Gillespie DT, 2001. Approximate accelerated stochastic simulation of chemically reacting systems. *J Chem Phys* 115: 1716–1733.
 11. Telegraph (London), 2014. *Ebola Outbreak: Fight against Disease Hampered by Belief in Witchcraft Warns British Doctor*. Available at: <http://www.telegraph.co.uk/news/worldnews/africaandindianocean/>. Accessed September 10, 2014.
 12. ReliefWeb, 2014. *Liberia Shuts Schools in Battle Against Ebola: President*. Available at: <http://reliefweb.int/report/liberia/liberia-shuts-schools-battle-against-ebola-president>. Accessed February 10, 2015.
 13. Time, 2014. *Liberia's West Point Slum Reels from the Nightmare of Ebola*. Available at: <http://time.com/3158244/liberia-west-point-slum-ebola-disease-quarantine/>. Accessed February 10, 2015.
 14. Sabah D, 2014. *Liberia Imposes Curfew to Fight Spread of Ebola*. Available at: <http://www.dailysabah.com/africa/2014/08/20/liberia-imposes-curfew-to-fight-spread-of-ebola>. Accessed February 10, 2015.
 15. World Health Organization, 2014. *Spreading the Word about Ebola through Music*. Available at: <http://www.who.int/features/2014/ebola-through-music/en/>. Accessed February 10, 2015.
 16. Welle D, 2014. *CDC Director Says Liberia Ebola Outbreak to Get Worse*. Available at: <http://www.dw.de/cdc-director-says-liberia-ebola-outbreak-to-get-worse/a-17885550>. Accessed February 10, 2015.
 17. Music Times, 2014. *Ebola Rap Song Taking Over Liberia Radio*. Available at: <http://www.musictimes.com/articles/9268/20140826/ebola-rap-song-taking-over-liberia-radio-listen.htm>. Accessed February 10, 2015.
 18. UNICEF Connect, 2014. *Ebola in Liberia Bringing the Prevention Message to Communities*. Available at: <http://blogs.unicef.org/2014/08/27/ebola-in-liberia-bringing-the-prevention-message-to-communities/>. Accessed February 10, 2015.
 19. UNICEF-Liberia, 2014. *Ebola SitRep #50*. Available at: http://www.unicef.org/appeals/files/UNICEF_Liberia_Ebola_Virus_Disease_Epidemic__5_Sept_2014.pdf. Accessed February 10, 2015.
 20. WHO, 2015. *Ebola Situation Reports*. Available at: <http://apps.who.int/ebola/en/current-situation/ebola-situation-report>. Accessed February 10, 2015.
 21. UNICEF-Liberia, 2014. *Ebola SitRep no. 51*. Available at: http://www.unicef.org/appeals/files/UNICEF_Liberia_Ebola_Virus_Disease_Epidemic__12_September_2014.pdf. Accessed February 10, 2015.
 22. International Medical Corps, 2014. *International Medical Corps Opens Liberias Sixth Ebola Treatment Unit, Bringing New Hope to Liberians*. Available at: https://internationalmedicalcorps.org/PressRelease_BongCountyEbolaTreatmentUnitOpens. Accessed February 10, 2015.
 23. Heritage, 2014. *ArcelorMittal Liberia Turns Over 60-Bed Ebola Unit to Nimba*. Available at: <http://www.heritageliberia.net/heritage-news/index.php/2014-07-17-10-07-11/nimba/92-arcelormittal-liberia-turns-over-60-bed-ebola-unit-to-nimba>. Accessed February 10, 2015.
 24. Ministry of Health and Social Welfare, 2014. *Liberia Ebola SitRep Nos. 10–250*. Available at: http://www.mohsw.gov.lr/content_display.php?sub=report2. Accessed January 20, 2015.
 25. Nation News, 2014. *CMO under Ebola Quarantine*. Available at: <http://www.nationnews.com/nationnews/news/56284/cmo-ebola-quarantine>. Accessed February 10, 2015.
 26. UNICEF, Press center, 2014. *First Batch of 50,000 Household Protection Kits Arrives in Liberia*. Available at: http://www.unicef.org/media/media_76030.html. Accessed February 10, 2015.
 27. Daily Observer, 2014. *Ebola Kills 8 Soldiers*. Available at: <http://www.liberianobserver.com/news/ebola-kills-8-soldiers>. Accessed February 10, 2015.
 28. UNICEF-Liberia, 2014. *Ebola Situation SitRep No. 56*. Available at: <http://reliefweb.int/report/liberia/unicef-liberia-ebola-virus-disease-sitrep-56-15-october-2014>. Accessed February 10, 2015.
 29. USAID, 2014. *West Africa-Ebola Outbreak, Fact Sheet No. 6*. Available at: <http://www.usaid.gov/sites/default/files/documents/1864/11.05.14%20-%20USG%20West%20Africa%20Ebola%20Outbreak%20Fact%20Sheet%20%236%20FY%2015.pdf>. Accessed February 10, 2015.
 30. USAID, 2014. *News and Information: First U.S.-Constructed Ebola Treatment Unit Set to Open in Liberia*. Available at: <http://www.usaid.gov/news-information/press-releases/nov-10-2014-first-us-constructed-ebola-treatment-unit-set-open-liberia>. Accessed February 10, 2015.

SUPPLEMENTAL TABLE 1
Model parameters

	Definition	Value	Reference
$N_T(0)$	Population of Liberia	4,090,000	1
	Population of Montserrado	1,180,000	2
	Population of Bong	333,481	2
	Population of Grand Cape Mount	127,076	2
	Population of Margibi	209,923	2
	Population of Grand Bassa	221,693	2
	Population of Lofa	276,863	2
$S_W(0)$	Health care workers	0.00028 $N_T(0)$	3*
e	Life expectancy	62 years	4
$1/\alpha$	Incubation period	9.5 days	5
$1/\gamma_{DG}$	Duration from symptom onset to death	7.9 days	5
$1/\gamma_{RG}$	Duration from symptom onset to recovery	9 days	6
$1/\gamma_H$	Duration between symptom onset and hospitalization	4.9 days	5
$1/\gamma_{DH}$	Duration from hospitalization to death	$1/\gamma_{DG} - 1/\gamma_H$	
$1/\gamma_{RH}$	Duration from hospitalization to recovery	$1/\gamma_{RG} - 1/\gamma_H$	
$1/\gamma_F$	Duration from death to burial	2 days	7
δ	Case-fatality risk	72%	5
δ_G	Case-fatality coefficient for general community	$\frac{\delta\gamma_{RG}}{(\delta\gamma_{RG} + (1 - \delta)\gamma_{DG})}$	†
δ_H	Case-fatality coefficient for hospitalized patients	$\frac{\delta\gamma_{RH}}{(\delta\gamma_{RH} + (1 - \delta)\gamma_{DH})}$	†
$1/f_{FG}$	Duration of funeral ceremonies	$1/\gamma_F$	
h	Per-capita hospitalization rate for non-Ebola reasons	62,131/ $N_T(0)$ /year	8
$1/f_{HG}$	Duration of non-Ebola hospital stay	7 days	8
M_F	Number of close contacts at funeral	4	9
β_I	Transmission parameter for the general community and hospital patients	Table 1	‡
β_W	Transmission parameter for health-care workers	Table 1	‡
θ	Proportion of infectious cases hospitalized	Table 1	‡
ω	Relative risk of funeral transmission compared with transmission in the general community	Table 1	‡
$I_G(0)$	Number of cases on June 9, 2014	Table 1	‡

*Includes physicians, nurses, and midwives.

†Computed so that overall case-fatality risk is δ .

‡Estimated by calibration of data.

SUPPLEMENTAL TABLE 2

Key intervention events arranged by implementation before September 20, 2014

Event	Approximate date of initiation	Classification	Counties affected	Source(s)
No touch policy	July 2014	Behavioral	Nationwide	11
Schools closed	July 30, 2014	Behavioral	Nationwide	12
West Point quarantine	August 19, 2014	Behavioral	Montserrado	13
9 PM curfew in effect	August 19, 2014	Behavioral	Nationwide	14
“Ebola Rap” rap song by Charles Yegba	August 19, 2014	Awareness	Nationwide	15
CDC’s Frieden met with Ellen Johnson	August 25, 2014	Awareness	Nationwide	16
Sirleaf and endorsed the no touch policy				
“Ebola is Real” rap song by FA Soulfresh and Den G	August 26, 2014	Awareness	Nationwide	17
About 100 animators and communicators deployed by UNICEF to educate at household level	August 27, 2014	Awareness	Montserrado, Lofa	18
Mobile laboratory at ELWA-3 operational	September 4, 2014	Health care	Montserrado	19
“Core group” of social mobilization finalized posters on Ebola signs, symptoms, and prevention	September 5, 2014	Awareness	Nationwide	19
UNICEF hygiene promotion	September 5, 2014	Awareness	Montserrado, Gbarpolu, Grand Cape Mount, Nimba, Grand Gedeh, River Gee, Maryland, Grand Kru	19
MSF increases hospital capacity in Monrovia by 40 beds	September 5, 2014	Health care	Montserrado	20
Training began for county health teams in infection control	September 10, 2014	Health care	Nationwide	21
IMC opened ETU	September 12, 2014	Health care	Bong	22
“Wash Away Ebola” strategy announced	September 12, 2014	Awareness	Nationwide	21
UNICEF WASH efforts in West Point including significant donation of soap, aquatab tablets, and plastic buckets	September 12, 2014	Behavioral	Montserrado	19
Bong opened ETU	September 18, 2014	Health care	Bong	20
Renovation of Ganta Hospital	September 18, 2014	Health care	Nimba	23
Safe burial trainings	September 18, 2014	Behavioral	Montserrado	20
Significant door-to-door social mobilization efforts	September 19, 2014	Awareness	Nationwide	20
CHES Ebola sensitization campaign	September 19, 2014	Awareness	Nimba	24
European Union mobile laboratory team operational	September 19, 2014	Health care	Lofa	20

CDC = Centers for Disease Control and Prevention; CHES = Community Health Education and Social Services; ETU = Ebola treatment unit; IMC = International Medical Corps; MSF = Médecins Sans Frontières; UNICEF = the United Nations Children’s Fund.

SUPPLEMENTAL TABLE 3

Key intervention events arranged by implementation between September 20 and October 4, 2014

Event	Approximate date of initiation	Classification	Counties affected	Source(s)
Distribution of motorbikes for contact tracing	September 21, 2014	Awareness	Nimba	24
42 members of Ebola response team trained and equipped	September 22, 2014	Health care	Sinoe	24
21 cases of EVD were transferred to the Island clinic ETU	September 22, 2014	Health care	Margibi	24
Radio voice allotted 1 hour daily for Ebola updates	September 23, 2014	Awareness	Grand Kru	24
Liberia’s chief medical officer opted for 21-day self-quarantine	September 25, 2014	Awareness	Nationwide	25
UNICEF’s first shipment of 50,000 protection kits	September 25, 2014	Health care	Montserrado	26
The Health Promotion Division conducted a training on social mobilization activities	September 26, 2014	Awareness	Montserrado	24
Community health-care workers and leaders trained by MoHSW	September 26, 2014	Health care	Sinoe	24
gCHVs trained on Ebola awareness	September 27, 2014	Awareness	Grand Kru	24
Previously hostile youth cooperating with Ebola task force	September 9, 2014	Awareness	Sinoe	24
New referral unit opened	October 1, 2014	Health care	Sinoe	20
Press about the story of eight Liberian soldiers who contracted and died of EVD at barracks	October 3, 2014	Awareness	Nationwide	27

EVD = Ebola virus disease; ETU = Ebola treatment unit; gCHVs = general community health volunteers; MoHSW = Ministry of Health and Social Welfare; UNICEF = the United Nations Children’s Fund.

SUPPLEMENTAL TABLE 4

Key intervention events arranged by implementation between October 4 and December 4, 2014

Event	Approximate date of initiation	Classification	Counties affected	Source(s)
U.S. Navy mobile laboratories opened	December 5, 2014	Health care	Bong, Montserrado	20
Ebola-related radio broadcasts on 50 stations	December 5, 2014	Awareness	Nationwide	28
Establishment of Ebola task force	December 8, 2014	Awareness	Nationwide	20
Training of additional dead-body-management teams by the Liberian Red Cross	December 8, 2014	Behavioral	Montserrado	20
CCC opened	December 15, 2014	Health care	Bong, Montserrado	20
Liberia National Nurses Association completed training	December 28, 2014	Health care	River Cess	24
Opening of 200-bed ETU at the Ministry of Defense site	December 31, 2014	Health care	Montserrado	29
Liberian National Crusaders for Peace conducted training	November 4, 2014	Awareness	Nimba	24
Ebola task force received an ambulance from Global Communities	November 6, 2014	Health care	River Cess	24
WHO safe and dignified burial protocol	November 7, 2014	Behavioral	Nationwide	20
Africare trained 30 gCHVs on contact tracing	November 18, 2014	Awareness	Nimba	24
First U.S.-funded ETU opened in in Tubmanburg	November 10, 2014	Health care	Montserrado	30
Only 2% of planned beds in CCCs are operational	November 19, 2014	Health care	Nationwide	20

CCC = community care center; ETU = Ebola treatment unit; gCHVs = general community health volunteers; WHO = World Health Organization.