Potential impact of sexual transmission of Ebola virus on the epidemic in West Africa

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Abstract

Ebola virus RNA can persist in seminal fluids of male convalescent patients after they recover from Ebola virus disease (EVD). We developed a novel compartmental EVD transmission model, Monte Carlo simulations, and performed sensitivity analyses to assess the potential impact of sexual transmission on the epidemic dynamics. Though few extra cases are expected due to sexual transmission from male survivors, the length of the epidemic tail is significantly affected. Fitting the model to weekly incidence data from Sierra Leone, we found that a 0.1% per sex act transmission probability and a convalescence period of 3 and 6 months could extend the EVD epidemic by 83 days (95% CI: 68–98 days) and 540 days (95% CI: 508–572 days), respectively. The latter would double the current length of the epidemic in Sierra Leone and highlights the importance of ongoing surveillance efforts in West Africa.

Introduction

Recent reports suggesting the potential for sexual transmission of Ebola virus from convalescent survivors have raised a number of important questions regarding its impact on the final phase of the epidemic in West Africa [1,2]. Even once the worst hit countries of Guinea, Liberia, and Sierra Leone are declared free of Ebola virus disease (EVD), rare cases may still arise from the large number of remaining survivors. Perhaps the most crucial element for bringing the epidemic to an end is maintaining vigilance in the community and preventing new chains of transmission. Historically occurring in sparsely-populated isolated communities, often killing the vast majority of victims [3], the unprecedented number of cases – and survivors – in densely populated urban areas presents novel challenges for bringing the outbreak to an end. Although sexual transmission of EVD is likely to be rare, it is important to investigate its potential impact on the transmission dynamics in general, and on the tail of the ongoing epidemic in particular.

Follow-up studies on survivors of the 1995 outbreak in the Democratic Republic of Congo [4] and the 2000 [5] and 2007 [6] outbreaks in Uganda have raised awareness of what is now being termed "post-Ebola syndrome" (post-Ebola sequelae) – debilitating illnesses from myalgia to uveitis – which can persist for at least 21 months after the onset of symptoms. Though the virus is no longer detected in the blood after symptoms disappear, active (replicating) virus has been documented in ocular fluid, rectal fluids, vaginal fluids, and semen [4,7]. Two recent reports indicate that this is also the case for survivors of the current (2013-2015) epidemic in West Africa, having documented

58 ongoing viremia in ocular [8] and seminal [1] fluids many months after falling ill.
59 Importantly, molecular evidence from a woman who contracted EVD in Liberia after
60 unprotected vaginal intercourse with a survivor nearly 6 months after his recovery from
61 EVD supports the hypothesis that direct sexual transmission from asymptomatic
62 convalescent survivors can and does occur [2]. Transmission to sexual partners was never
63 confirmed in earlier outbreaks, but was suspected to have occurred in at least one instance
64 [4]. Similarly, cases of sexual transmission of other hemorrhagic fever infections, notably
65 by the closely related Marburg virus, have been suspected in the past [9,10].
66
67 Of particular epidemiological interest is the question of how long active Ebola virus in
68 semen, vaginal, and rectal fluids of convalescent survivors poses a threat for sexual
69 transmission. The previous studies identified active virus as late as 82 days after onset of
70 symptoms in seminal fluid from one male patient; samples positive for viral RNA were
71 identified as late as 29 days (rectal) and 33 days (vaginal) after onset of symptoms in one
72 female patient of six sampled, and 101 days after onset of symptoms in seminal fluid
73 from four out of five male patients [4,7]. The studies from the West African outbreak,
74 showing viremia in semen 4-6 months after onset of symptoms in 65% of men tested (7-9
75 months in 26%) [1] and confirming occurrence of transmission from a survivor 179 days
76 after onset of symptoms [2], suggest that sexual transmission from convalescent men may
77 pose a threat for far longer than previously anticipated.
78
79 Sexual transmission of Ebola virus from convalescent survivors is likely a rare event, but
80 researchers have warned that it is feasible and should be considered in epidemiological

models that are used to predict the trajectory of the outbreak [11]. To this end, we devised a novel mathematical model of EVD transmission and studied the epidemic dynamics in absence and presence of sexual transmission from convalescent men. To obtain baseline parameter estimates in the absence of sexual transmission, we fitted the model to weekly incidence of confirmed and probable cases from Sierra Leone (as reported from the patient database by the World Health Organization [12]; Table 1, Fig. S1); the largest population of recovering survivors from the current West Africa epidemic. We performed sensitivity analysis to understand the impact of key unknown parameters, such as the duration of the convalescent period and the transmission probability per sexual contact. We also performed Monte Carlo simulations to explore the impact of sexual transmission on the epidemic tail in Sierra Leone.

Methods

Transmission model. We extended a SEIR (susceptible-exposed-infected-recovered) modeling framework, which has been extensively used to describe EVD transmission [13–15], by adding a component for sexual transmission from convalescent survivors who maintain active Ebola virus replication (Fig. 1). The resulting SEICR model has five states: susceptible, S, exposed, E, symptomatic and infectious, I, convalescent, C, fully recovered and immune, R, and dead, D. The model is represented by the following set of ordinary differential equations (ODEs):

$$
\begin{aligned}
\frac{dS}{dt} &= -\beta(t)SI - \beta_S pC\frac{S}{N} \\
\frac{dE}{dt} &= \beta(t)SI + \beta_S pC\frac{S}{N} - \sigma E \\
\frac{dI}{dt} &= \sigma E - \gamma I \\
\frac{dC}{dt} &= (1-f)\gamma I - \alpha C \\
\frac{dR}{dt} &= \alpha C \\
\frac{dD}{dt} &= f\gamma I
\end{aligned}
\tag{1}
$$

where $N = S + E + I + C + R$ denotes the total population size. We assumed the non-sexual transmission rate, $\beta(t)$, to be initially constant (β_0) before it starts to decay exponentially due to the effect of control interventions and behavior change after time τ: $\beta(t) = \beta_1 + (\beta_0 - \beta_1)e^{-k(t-\tau)}$ [13]. The sexual transmission parameter, β_s, can be described as the product of two parameters ($\beta_s = \eta q$) that we will consider separately: η is the per sex act transmission probability of Ebola virus from convalescent men, and q is the daily rate at which they engage in sexual intercourse. The number of convalescent individuals are scaled by p, which is the proportion of convalescent survivors who are sexually active men. $1/\sigma$ and $1/\gamma$ represent the average durations of incubation and symptomatic infection, respectively. f is the case fatality rate. The average duration after which convalescent patients recover completely and shed no further replicating Ebola virus from their body is given by $1/\alpha$. We assumed that sexual transmission is frequency-dependent [16–18], i.e., the probability that the sexual partner of a convalescent man is susceptible is given by S/N.

117 ***Model parameters.*** The basic reproductive number, R_0, for the SEICR model can be
118 calculated using the next-generation matrix method [19,20] and is given by

119 $$R_0 = \frac{\beta S_0}{\gamma} + \frac{(1-f)\, p\, \beta_S}{\alpha},$$

120 where S_0 is the initial number of susceptible individuals (see *Supplementary Material*).
121 When α goes to infinity or either $\beta_s = 0$ or $p = 0$, the equation reduces to the basic
122 reproductive number in absence of sexual transmission: $R_{0,N} = \frac{\beta S_0}{\gamma}$. Thus, the second
123 term represents the contribution of sexual transmission from convalescent patients to the
124 overall R_0: $R_{0,C} = \frac{(1-f)\, p\, \beta_S}{\alpha}$.

125

126 We fitted the deterministic EVD transmission model to weekly incidence of confirmed
127 and probable cases in Sierra Leone as reported in the WHO patient database [12]
128 (*Supplementary Material* Fig. S1). The data set was extended with weekly incidence from
129 the situation report for the most recent weeks when no data was available in the patient
130 database. In order to account for variability in the accuracy of reporting, we assumed that
131 the number of reported cases follows a negative binomial distribution with mean as
132 predicted by the model and dispersion parameter ϕ [21]. We derived maximum
133 likelihood estimates (MLE) of the following model parameters [15,22]: the baseline
134 transmission rate β_0, the time τ at which transmission starts to drop, the rate k at which
135 transmission decays, and the dispersion parameter ϕ. For the fitting procedure, we
136 assumed that there were no sexual transmission events, i.e., we set β_S to zero. The basic
137 reproductive number in absence of sexual transmission is $R_{0,N} = \beta_0 N_0/\gamma$, and the
138 reproductive number in presence of partially effective control interventions is $R_{1,N} =$

139 $\beta_1 N_0/\gamma$, with N_0 being the population size of Sierra Leone. The other parameters were
140 based on published values from the literature (Table S1). We explored value ranges for
141 sexual transmission parameters (Table 1) based on information from the current epidemic
142 [23] and studies of human immunodeficiency virus [24,25].
143
144 ***Deterministic model and sensitivity analysis.*** We solved the system of ODEs
145 numerically using the function *ode* from the *deSolve* package in the R software
146 environment for statistical computing [26]. We compared the following response
147 variables of the model: the epidemic peak number of exposed, E, acute, I, and
148 convalescents, C, cases; the cumulative number of EVD cases, deaths, and recoveries; the
149 date at the epidemic peak; the daily and cumulative incidence of sexual transmission; and
150 the date at which the last symptomatic case either died or entered into convalescence
151 ("day of last case"). We defined the day of last case as the time when the number of
152 symptomatic and infectious individuals, I, dropped below 0.5. We considered the
153 following parameters for the sensitivity analysis: the per sex act transmission probability
154 of Ebola virus from convalescent men (η), the proportion of convalescent survivors who
155 are sexually active men (p), the rate at which they engage in sexual intercourse (q), and
156 the rate at which convalescent patients recover completely and shed no further replicating
157 Ebola virus from their body (α). The sensitivity of the response variables to changes in R_0
158 was explored simultaneously as a comparison. We generated 1000 parameter
159 combinations from the uniform ranges, log-transformed [0.5x – 2x] for the parameter
160 values for η, p, q, and α, given in Table 1 via Latin hypercube sampling using the
161 Huntington and Lyrintzis correlation correction method (function *lhs* from R package

162 *pse*) [27]. We then calculated partial rank correlation coefficients (PRCCs) using 50
163 bootstrap replicates [28].
164
165 ***Monte Carlo simulations.*** We performed stochastic simulations of the SEICR model
166 with and without sexual transmission using Gillespie's algorithm [29]. We specifically
167 investigated the following response variables from the simulations: the cumulative
168 number of EVD cases, the size and date of the epidemic's peak incidence (daily number
169 of new symptomatic infections), and the date of last case (last day that symptomatic
170 infections, I, fell below 1). Summary statistics were based on the results of 1000
171 simulation runs for each transmission scenario. We calculated the average of the peak and
172 total cumulative number of EVD cases by including all simulations runs, i.e., also the
173 simulations that rapidly go extinct. In contrast, the average dates of the epidemic peak
174 and last case were based on the simulated epidemic trajectories over which 50 or more
175 cases were accumulated.
176
177 **Results**
178 ***Contribution of sexual transmission to overall R_0.*** Using the baseline parameter values
179 from Table 1, the reproductive number of a convalescent infection, $R_{0,C}$, is 0.0024. This
180 corresponds to only 0.12% of the overall R_0 of 2.0224. Increasing the convalescent period
181 from 3 to 6 months, the contribution of $R_{0,C}$ (0.0051) to the overall R_0 rises to 0.25%. The
182 equation for $R_{0,C}$ (see *Methods*) illustrates that doubling the per sex act transmission
183 probability has the same impact as doubling the convalescent period. It is important to
184 note that the relative contribution of sexual transmission to the overall reproductive

number rises as the effective reproductive number drops during the epidemic due to the effects of control interventions (see *Supplementary Material,* Fig. *S2*).

Effect of sexual transmission parameters on epidemic dynamics. The two key unknown parameters of sexual transmission are the per sex act transmission probability, η, and the rate at which convalescent survivors fully recover, α. Both parameters were found to have very small effects on the peak number of infected or exposed patients (Fig. 2A; Fig. 3A; Figs. 4A, 4B, 4C; Fig. S2; Fig. S3). The duration of the convalescent period has the biggest impact on the peak number of convalescent individuals, while η does not (compare Fig. 2A and Fig. 3A). The total number of recovered individuals is reached more slowly the longer the convalescent period (Fig. 2B), which is not an effect caused by η (Fig. 3b). While the convalescent periods ($1/\alpha$ = [3 – 9 months]) and the low values of η (η = [0.0005 – 0.002]) we explored create very few extra cases (Fig. 2B and Fig. 3B), sensitivity analyses revealed that a higher per sex act transmission probability, a higher proportion of sexually active convalescent individuals, p, or a higher frequency of sex acts, q, could have larger impacts on the total number of cases than would proportional increases in the convalescent period (see *Supplementary Material*, Fig. *S3A*). Sensitivity analyses also revealed that these sexual transmission parameters could produce a small delay on the epidemic peak, more so than by changes in the convalescent period (see *Supplementary Material*, Fig. *S3B*).

The number of sexual transmission events expected from the baseline scenario (η = 0.001 and $1/\alpha$ = 3 months) is 31.2, the majority of which will occur around the peak of the

208 epidemic (Fig. 2C and Fig. 3D) and thus likely go undetected. Doubling either η or $1/\alpha$
209 results in almost equal increases in the incidence and cumulative number of sexual
210 transmission events (Fig. 2C, 2D and Fig. 3C, 3D), with either leading to roughly double
211 the number of sexually transmitted cases over the course of the whole epidemic (> 60
212 cases). It should be noted that the total number of cases increases more than by simply the
213 number of sexual transmission events, because each sexual transmission event results in a
214 new potential cluster of non-sexual transmission. The day of last case is affected more by
215 the convalescent period than the per sex act transmission probability (represented by
216 vertical lines in Fig. 2A and Fig. 3A), a result confirmed by the sensitivity analysis (see
217 *Supplementary Material*, Fig. *S3A*). The tail of the epidemic will depend on a small
218 number of events that are likely to be affected by stochastic processes, thus we used
219 Monte Carlo simulations to explore this behaviour.
220
221
222 ***Impact of sexual transmission on the epidemic tail.*** We performed stochastic
223 simulations of the EVD transmission model to investigate the epidemic dynamics when
224 the number of new cases becomes small, i.e, during the tail of the epidemic. Comparing
225 model simulations while assuming a convalescent period of 3 months to those without
226 sexual transmission confirmed the deterministic results that sexual transmission from
227 convalescent survivors does not lead to a significant increase in the cumulative number of
228 infected cases (non-STI: 11,092 +/- 627 cases; STI: 10,944 +/- 642 cases; Wilcox rank
229 sum test: W = 491990, p = 0.53), nor the size (non-STI: 77 +/- 4.1 new cases per day;
230 STI: 75 +/- 4.2 new cases per day; W = 493710, p = 0.62) or timing (non-STI: day 187

231 +/- 0.9; STI: day 187 +/- 0.9; t = 0.19, df = 1017.4, p = 0.85) of the epidemic peak
232 incidence (Fig. 4A, 4B, 4C). Strikingly, this conservative period of potential sexual
233 transmission, which has recently been shown to extend well beyond 3 months in at least
234 65% of patients [1], extended the average date on which the last active case could be
235 detected by nearly three months (non-STI: 548 +/- 4.0 days; STI: 630 +/- 6.6 days;
236 difference: 83 days [95% CI: 68-98 days], t = -10.8, df = 867.97, p < 0.0001; Fig. 4D, 4E,
237 4G, 4H). The width of the tail (s.d. = 151 days) was such that 23.4% of the 529 simulated
238 epidemics that accumulated at least 50 cases still experienced symptomatic individuals
239 730 days (two years) after the start of the epidemic (Fig. 4H). When the convalescent
240 period was extended from 3 months to 6 months, the projected length of the epidemic
241 increased to a mean of 1088 days (+/- 15.5), with 84.0% of the 538 sustained epidemics
242 taking over two years to end (Fig. 4F, 4I). Importantly, there is greater variance in the tail
243 of the epidemic when sexual transmission is considered, and this uncertainty grows with
244 the length of the convalescent period (Fig. 4G, 4H, 4I).
245

246 **Discussion**

247 Our study shows that sexual transmission of Ebola virus from convalescent men could
248 have a profound effect on the duration of the epidemic in Sierra Leone. Using a
249 mathematical transmission model, we found that an average duration of the convalescent
250 period of 3 months, and a per sex act transmission probability of 0.1% could extend the
251 EVD epidemic in Sierra Leone by 83 days (95% CI: 68–98 days). Such a scenario would
252 be consistent with the occurrence of a small number of sexual transmission events during
253 the end-phase of the epidemic. So far, the reported cases of sexual transmission of EVD

remain rare [1,2]. Hence, the per sex act transmission probability of Ebola virus from male convalescent survivors is unlikely to be higher than 0.1%, but might well be below this value. Our sensitivity analysis indicates that the duration of the EVD epidemic is heavily influenced by the period during which convalescent men can transmit sexually, calling for a better understanding of the persistence and duration of infectivity of Ebola virus RNA in convalescent patients.

To our knowledge, this is the first study using mathematical modeling to assess the potential impact of sexual transmission of Ebola virus on the epidemic in West Africa. We extended an accepted modeling framework that has been widely used to describe the epidemic trajectories of EVD outbreaks and epidemics [13–15]. We performed sensitivity analysis to account for the considerable uncertainty in key unknown parameters regarding sexual transmission. Given that chance will play a crucial role in sexual transmission of Ebola virus, we used stochastic simulations to explore the expected variability in the tail of the epidemic. In the absence of a better understanding of sexual transmission of EVD, mathematical modeling currently remains the only tool to explore its potential impact on the epidemic trajectory.

Our study provides a preliminary picture of the potential epidemiological consequences of sexual transmission of Ebola virus on the epidemic in West Africa. Consequently, there are a number of limitations that should be considered when interpreting the results. First, we limited our analysis to sexual transmission from convalescent men who remain infectious through the presence of Ebola virus in their semen. However, our modeling

277 framework could be easily extended to account for transmission by other routes, e.g.,
278 through infectious vaginal secretions from female survivors. Second, we assumed a
279 homogeneously mixing population to describe both non-sexual and sexual transmission
280 of EVD. Spatial structure might play an important role in the spread of EVD [30] as close
281 contact with infected bodily fluids is typically required even for non-sexual transmission.
282 In particular, close contact limited to family or community members during the
283 convalescence period, often accompanied by decreased activity levels due to post-Ebola
284 sequelae, may help limit the chances of sexual transmission. Third, asymptomatic
285 infection may occur [31], and is predicted to lower epidemic projections due to increased
286 levels of immunity in the population [32]. Fourth, the model does not incorporate
287 potential heterogeneity in sexual behavior [16], and we assumed that all sexually active
288 male survivors have the same average numbers of sex acts per month. The assumed
289 frequency of sex acts (8.3 sex acts per month) came from a study of heterosexual couples
290 in sub-Saharan Africa [24], and is on the high end of estimates gathered from studies of
291 other populations (e.g., [24,33,34], but see the wide range in individual frequencies in
292 [35]); the sexual activity of convalescent Sierra-Leonean EVD survivors has not been
293 reported. Fifth, EVD is known to exhibit superspreading characteristics [36,37], and we
294 did not include this in our model. Superspreading events could lead to explosive regrowth
295 of the epidemic after the occurrence of a new case through sexual transmission [36]. On
296 the other hand, 72% of infected individuals in transmission chains in Guinea did not
297 generate further cases [36], suggesting that some cases of sexual transmission of EVD
298 might not be detected at all. Sixth, we assumed a single compartment for convalescent
299 survivors with an exponentially distributed period of convalescence. Recent data

300 indicates that the time during which convalescent men remain positive for Ebola virus
301 RNA could be better described by a unimodal distribution [1]. Seventh, it remains to be
302 determined whether the virus found in semen of male convalescent survivors is
303 replication competent, and the time window during which these men remain infectious
304 could be shorter than the duration they remain positive for Ebola virus RNA. Finally, like
305 other negative-sense single-stranded RNA ((-)ssRNA) viruses [38], the species currently
306 circulating in West Africa has been estimated to have high substitution rates [39–41].
307 This rapid evolution detected throughout the current outbreak zone suggests that within-
308 or between-host adaptation of the virus leading to pro-longed persistence in the seminal
309 fluids is possible.
310
311 Awareness of the potential for sexual transmission has led to WHO issuing
312 recommendations that ask convalescent men to abstain from sexual activity as much as
313 possible and to use condoms for up to 6 months after the onset of symptoms [42].
314 Condom use and social awareness of the risks of sexual transmission during
315 convalescence should have an impact on the per sex act transmission probability (η) and
316 the frequency of sex acts (q), respectively. Our results show that condom use should
317 reduce the number of sporadic sexual transmission events during the tail of the epidemic
318 and after discharge of all remaining symptomatic individuals. However, the time during
319 which the public health community must stay vigilant is not reduced because these
320 interventions will not affect the time during which convalescent survivors can shed
321 infectious virus ($1/\alpha$). This is especially poignant since adherence to these
322 recommendations will never be 100%. Better knowledge about the rate at which

convalescent survivors recover completely and shed no further replicating Ebola virus from their body is thus urgently needed to plan continued surveillance efforts.

The EVD epidemic in Sierra Leone was declared to be over on 7 November 2015 [43]. Our modeling results show that sporadic events of sexual transmission of Ebola virus – potentially leading to small transmission clusters – could continue to occur in the months to come. Sexual transmission of EVD is likely to be rare, but recent events such as the suspected infection of a 16-year-old girl through sexual transmission in Makeni, Sierra Leone, during September 2015 exemplify the continued risks [44]. In addition, the considerable uncertainty around the infectivity of convalescent men who test positive for Ebola virus RNA, and the duration of this period, asks us to remain vigilant. We must monitor and quantify this phenomena in order to help us better prepare health networks, and to provide convalescent survivors with sound advice that balances protection of the community with the harm that could come from unnecessary stigmatization [45–47]. As more data about the convalescent survivors of EVD becomes available, this and future mathematical modeling studies will help to better understand the potential epidemiological consequences of sexual transmission on the EVD epidemic in West Africa.

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490 **Table 1: Model parameters describing EVD transmission in Sierra Leone.** The
491 indicated parameter ranges are used for the sensitivity analysis (partial rank correlation
492 coefficients, PRCC) only.

Table S1: Model parameters describing EVD transmission in Sierra Leone. The indicated parameter ranges are used for the sensitivity analysis (partial rank correlation coefficients, PRCC) only.

Parameter		Value (Range)	Comments and References
Basic reproductive number without sexual transmission	$R_{0,N}$	2.13 (1.26 - 2.53)	Estimated - Range explores estimates from (*2*, *12*)
Basic reproductive number in presence of control interventions	$R_{1,N}$	0.67	Estimated
Date of onset of symptoms in index case		April 23, 2014	(*2*, *12*, *13*)
Rate at which transmission rate decays	k	0.011 d^{-1}	Estimated
Time at which transmission rate starts to decay	τ	51.0 d	Estimated
Incubation period	$1/\sigma$	11.4 d	(*14*)
Infectious period	$1/\gamma$	3.9 d	Together with the incubation period results in a generation time of 15.3 d (*14*)
Dispersion parameter	ϕ	0.050	Estimated
Initial population size	N_0	6.316×10^6	Based on 2014 estimate (*15*)
Sexual transmission probability (per coital act)	η	0.001 (0.0005 – 0.002)	Roughly based on sexual transmission probability of HIV per coital act from infected men (*16*)
Case fatality rate	f	0.69	(*14*)
Frequency of sex acts	q	0.272 d^{-1} (0.136 – 0.544)	8.27 coital acts per month (*17*)
Proportion of convalescent survivors who are infectious and sexually active	p	0.347 (0.1725-0.694)	Of 47.4% male survivors, 73.1% are aged 15-45 (*14*)
Rate at which convalescent survivors recover completely	α	1/87.35 d^{-1} (1/174.7 – 1/43.7)	3 months after onset of symptoms (*18*, *19*) and assuming an infectious period of 3.9 days

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Figure 1. Schematic illustration of EVD transmission model including sexual transmission from convalescent patients. The elements in black form the base model without sexual transmission [13–15]. The red elements (convalescent individuals and additional transmission term) were added to account for sexual transmission.

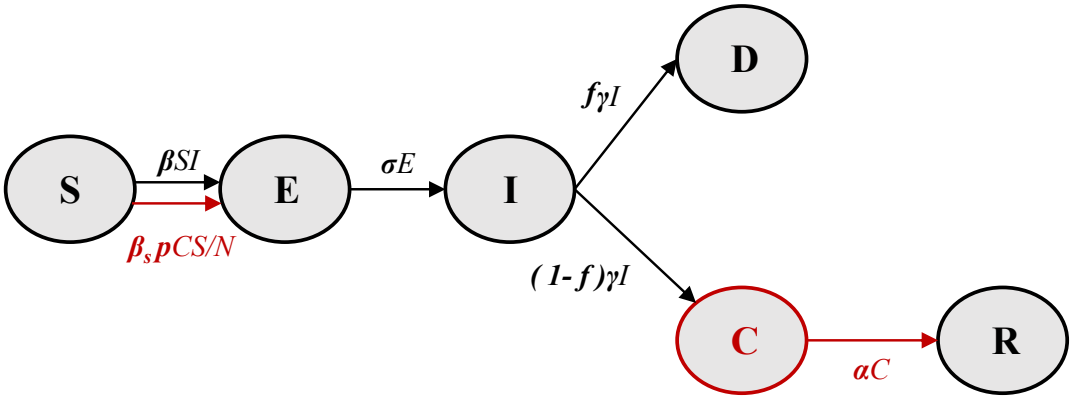
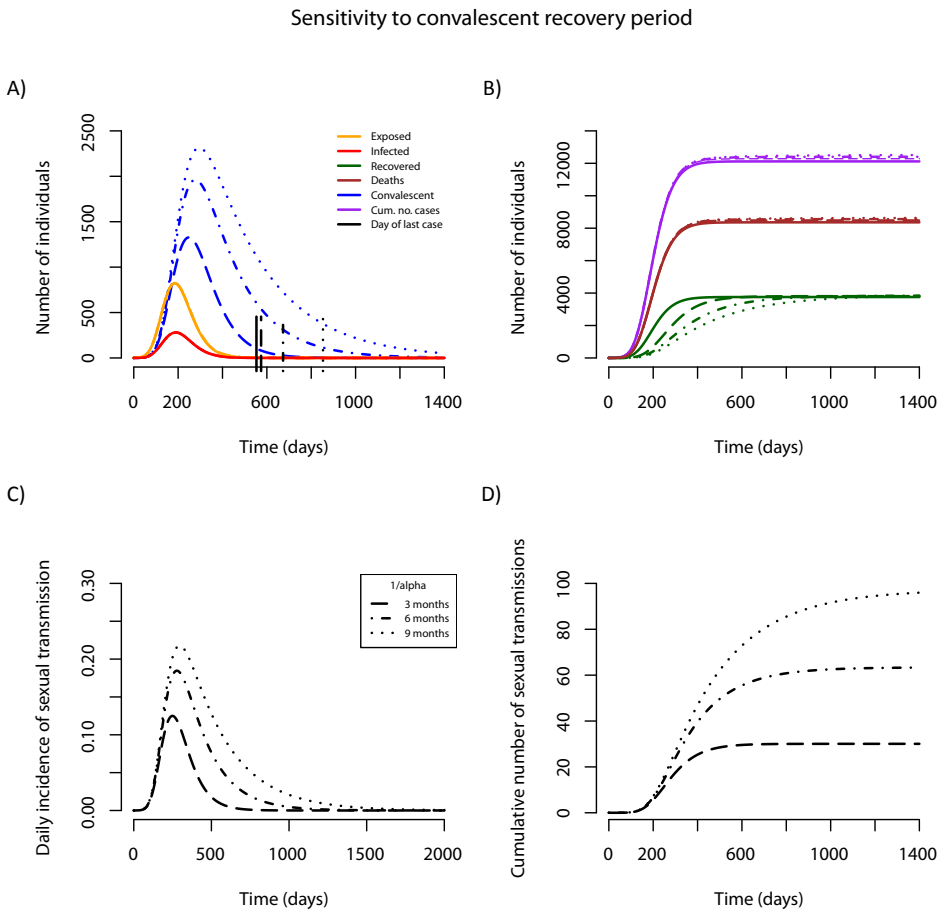
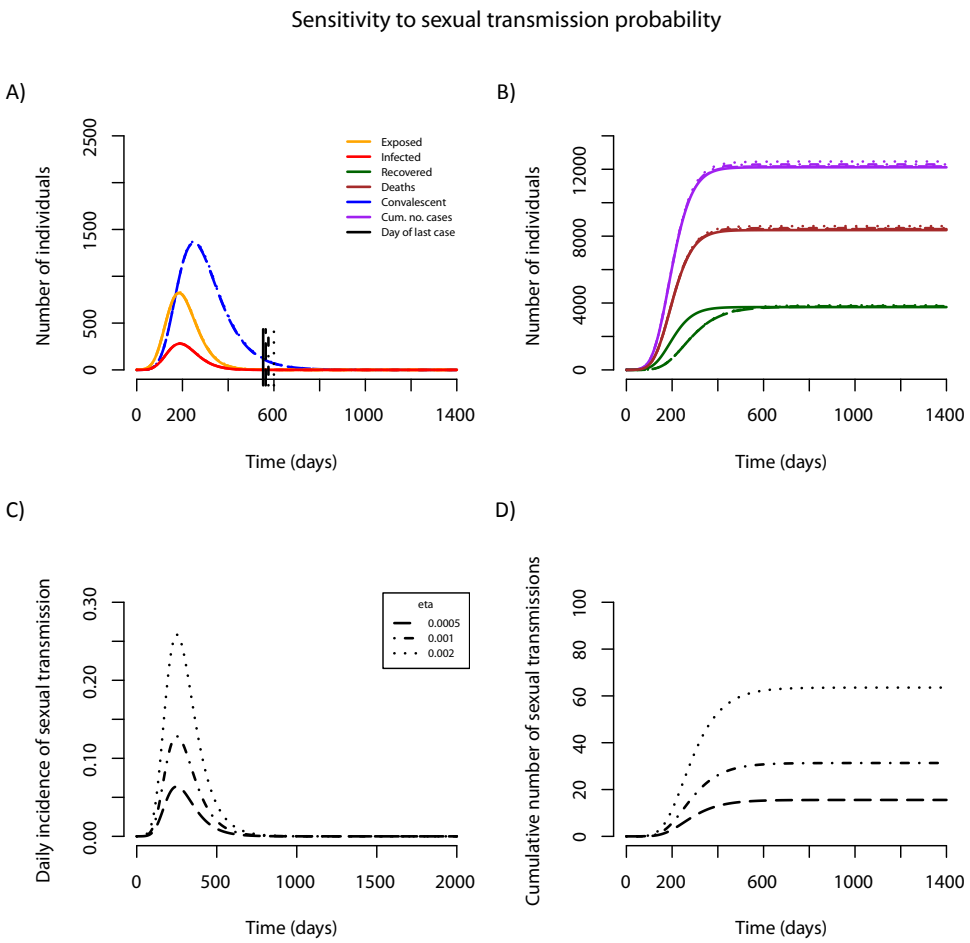


Figure 2. Effect of convalescent period on EVD epidemics. The average duration of the convalescent period ($1/\alpha$) is varied between 3 and 9 months. (A, B): Epidemic trajectories in presence (broken lines) and absence of sexual transmission (solid lines). Vertical lines mark the day of last symptomatic case. (C) Daily incidence of sexual transmission. (D) Cumulative number of sexual transmission events. Note that the vertical axes vary across panels.



506 **Figure 3. Effect of per sex act transmission probability on EVD epidemics.** The per
507 sex act transmission probability (η) is varied between 0.05% and 0.2%. (A, B): Epidemic
508 trajectories in presence (broken lines) and absence of sexual transmission (solid lines).
509 Vertical lines mark the day of last symptomatic case. (C) Daily incidence of sexual
510 transmission. (D) Cumulative number of sexual transmission events. Note that the
511 vertical axes vary across panels.



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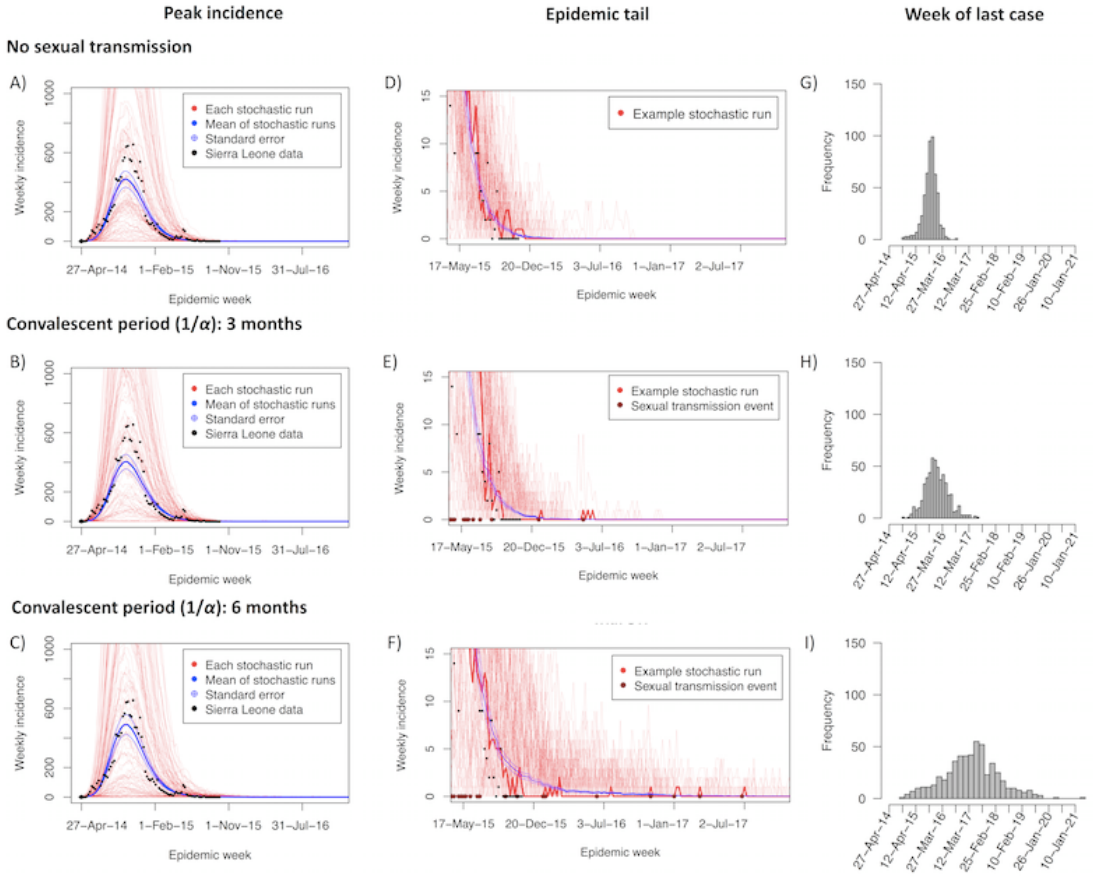
515 **Figure 4. Impact of convalescent period on the tail of the EVD epidemic.** Monte
516 Carlo simulations of the weekly incidence of new cases (A, B, C) and the sporadic

occurrence of sexual transmission events at the epidemic tail (D, E, F), assuming no sexual transmission (A, D), and sexual transmission with a 3 (B, E) and 6 months (C, F) convalescent period. Thin red lines show the result of 200 simulated trajectories, with corresponding mean (thick blue line) and standard errors (thin blue lines). Black dots denote incident cases in Sierra Leone as reported by the WHO [12]. The thick red lines in (D), (E), and (F) highlight a single representative trajectory, and the dark red dots along the horizontal axis indicate a sexual transmission event. Histograms of the day of the last EVD case from 1,000 simulated epidemics in absence of sexual transmission (G) and for a convalescent period of 3 (H) and 6 (I) months.