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 used a compartmental EVD transmission model, Monte Carlo simulations, and performed sensitivity analyses to assess the potential impact of sexual transmission on the epidemic dynamics. The rate of sexual transmission and the period during which convalescent men can transmit sexually both affect the number of excess EVD cases, while the latter also influences the duration of the epidemic. Assuming an average convalescent period of 3 months, and a per sex act transmission probability of 0.1%, we found that sexual transmission could extend the EVD epidemic in Sierra Leone by 123 days (95% CI: 110–137 days). These results show the importance of ongoing surveillance efforts in West Africa and call for a better understanding of the persistence and infectivity of Ebola virus RNA in convalescent patients.

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

59 ongoing viremia in ocular [8] and seminal [1] fluids many months after falling ill.
60 Importantly, molecular evidence from a woman who contracted EVD in Liberia after
61 unprotected vaginal intercourse with a survivor nearly 6 months after his recovery from
62 EVD supports the hypothesis that direct sexual transmission from asymptomatic
63 convalescent survivors can and does occur [2]. Transmission to sexual partners was never
64 confirmed in earlier outbreaks, but was suspected to have occurred in at least one instance
65 [4]. Similarly, cases of sexual transmission of other hemorrhagic fever infections, notably
66 by the closely related Marburg virus, have been suspected in the past [9,10].
67
68 Of particular epidemiological interest is the question of how long active Ebola virus in
69 semen, vaginal, and rectal fluids of convalescent survivors poses a threat for sexual
70 transmission. The previous studies identified active virus as late as 82 days after onset of
71 symptoms in seminal fluid from one male patient; samples positive for viral RNA were
72 identified as late as 29 days (rectal) and 33 days (vaginal) after onset of symptoms in one
73 female patient of six sampled, and 101 days after onset of symptoms in seminal fluid
74 from four out of five male patients [4,7]. The studies from the West African outbreak,
75 showing viremia in semen 4-6 months after onset of symptoms in 65% of men tested (7-9
76 months in 26%) [1] and confirming occurrence of transmission from a survivor 179 days
77 after onset of symptoms [2], suggest that sexual transmission from convalescent men may
78 pose a threat for far longer than previously anticipated.
79
80 Sexual transmission of Ebola virus from convalescent survivors is likely a rare event, but
81 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. 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 [12–14], 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 : $\beta(t) = \beta_1 + (\beta_0 - \beta_1)e^{-k(t-\tau)}$ [12]. 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 [15–17], i.e., the probability that the sexual partner of a convalescent man is susceptible is given by S/N .

Model parameters. The basic reproductive number, R_0, for the SEICR model can be calculated using the next-generation matrix method [18,19] and is given by

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

where S_0 is the initial number of susceptible individuals (see *Supplementary Material*). When α goes to infinity or either $\beta_s = 0$ or $p = 0$, the equation reduces to the basic reproductive number in absence of sexual transmission: $R_{0,N} = \frac{\beta S_0}{\gamma}$. Thus, the second

120 term represents the contribution of sexual transmission from convalescent patients to the
121 overall R_0: $R_{0,C} = \frac{(1-f)\, p\, \beta_s}{\alpha}$.
122
123 The model parameters were either based on published values from the literature or
124 adjusted to provide a good description of the EVD epidemic in Sierra Leone (Table 1).
125 We assumed that published estimates of R_0 do not include the contribution of sexual
126 transmission, i.e., the transmission rate during the early phase of the outbreak was given
127 by $\beta_0 = R_{0,N}\, \gamma/S_0$. We further assumed that the non-sexual reproductive number drops
128 below unity in the presence of partially effective control interventions [20] and set $\beta_1 =$
129 $0.5\, \gamma/S_0$. We used the weekly incidence and cumulative case counts of EVD from Sierra
130 Leone reported by the World Health Organization (WHO) Ebola Outbreak Situation
131 Reports (including updates according to the patient database) [21] as a comparison to the
132 model results.
133
134 ***Deterministic model and sensitivity analysis.*** We solved the system of ODEs
135 numerically using the function *ode* from the *deSolve* package in the R software
136 environment for statistical computing [22]. We compared the following response
137 variables of the model: the epidemic peak number of exposed, *E*, acute, *I*, and
138 convalescents, *C*, cases; the cumulative number of EVD cases, deaths, and recoveries; the
139 date at the epidemic peak; the daily and cumulative incidence of sexual transmission; and
140 the date at which the last symptomatic case either died or entered into convalescence
141 ("day of last case"). We defined the day of last case as the time when the number of
142 symptomatic and infectious individuals, *I*, dropped below 0.5. We considered the

143 following parameters for the sensitivity analysis: the per sex act transmission probability
144 of Ebola virus from convalescent men (η), the proportion of convalescent survivors who
145 are sexually active men (p), the rate at which they engage in sexual intercourse (q), and
146 the rate at which convalescent patients recover completely and shed no further replicating
147 Ebola virus from their body (α). The sensitivity of the response variables to changes in R_0
148 was explored simultaneously as a comparison. We generated 1000 parameter
149 combinations from the uniform ranges, log-transformed [0.5x – 2x] for the parameter
150 values for η, p, q, and α, given in Table 1 via Latin hypercube sampling using the
151 Huntington and Lyrintzis correlation correction method (function *lhs* from R package
152 *pse*) [23]. We then calculated partial rank correlation coefficients (PRCCs) using 50
153 bootstrap replicates [24].
154
155 ***Monte Carlo simulations.*** We performed stochastic simulations of the SEICR model
156 with and without sexual transmission using Gillespie's algorithm [25]. We specifically
157 investigated the following response variables from the simulations: the cumulative
158 number of EVD cases, the size and date of the epidemic's peak incidence (daily number
159 of new symptomatic infections), and the date of last case (last day that symptomatic
160 infections, I, fell below 1). Summary statistics were based on the results of 1000
161 simulation runs for each transmission scenario. We calculated the average of the peak and
162 total cumulative number of EVD cases by including all simulations runs, i.e., also the
163 simulations that rapidly go extinct. In contrast, the average dates of the epidemic peak
164 and last case were based on the simulated epidemic trajectories over which 100 or more
165 cases were accumulated.

166

167 **Results**

168 ***Contribution of sexual transmission to overall R_0.*** Using the baseline parameter values
169 from Table 1, the reproductive number of a convalescent infection, $R_{0,C}$, is 0.0024. This
170 corresponds to only 0.12% of the overall R_0 of 2.0224. Increasing the convalescent period
171 from 3 to 6 months, the contribution of $R_{0,C}$ (0.0051) to the overall R_0 rises to 0.25%. The
172 equation for $R_{0,C}$ (see *Methods*) illustrates that doubling the per sex act transmission
173 probability has the same impact as doubling the convalescent period. It is important to
174 note that the relative contribution of sexual transmission to the overall reproductive
175 number rises as the effective reproductive number drops during the epidemic due to the
176 effects of control interventions (see *Supplementary Material,* Fig. *S1*).

177

178 ***Effect of sexual transmission parameters on epidemic dynamics.*** Simulating the
179 deterministic transmission model using the baseline parameter values from Table 1
180 resulted in a good description of the EVD epidemic in Sierra Leone (see *Supplementary*
181 *Material*, Fig. *S2*). The two key unknown parameters of sexual transmission are the per
182 sex act transmission probability, η, and the rate at which convalescent survivors fully
183 recover, α. The duration of the convalescent period has the biggest impact on the peak
184 number of convalescent individuals, while η does not (compare Fig. 2a and Fig. 3a). Both
185 parameters have extremely small effects on the peak number of infected or exposed
186 patients (Fig. 2a and Fig. 3a). The total number of recovered individuals is reached more
187 slowly the longer the convalescent period (Fig. 2b), which is not an effect caused by η
188 (Fig. 3b). While the convalescent periods ($1/\alpha$ = [0 – 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 31.5, the majority of which will occur around the peak of the epidemic (Fig. 2c and Fig. 3c) and thus likely go undetected. Doubling either η or $1/\alpha$ results in almost equal increases in the incidence and cumulative number of sexual transmission events (Fig. 2c, 2d and Fig. 3c, 3d), with either leading to roughly double the number of sexually transmitted cases over the course of the whole epidemic (> 60 cases). It should be noted that the total number of cases increases more than by simply the number of sexual transmission events, because each sexual transmission event results in a new potential cluster of non-sexual transmission. The day of last case is affected more by the convalescent period than the per sex act transmission probability (represented by vertical lines in Fig. 2a and Fig. 3a), a result confirmed by the sensitivity analysis (see *Supplementary Material*, Fig. *S3a*). The tail of the epidemic will depend on a small number of events that are likely to be affected by stochastic processes, thus we used Monte Carlo simulations to explore this behaviour.

212

213

214 ***Impact of sexual transmission on the epidemic tail.*** We performed stochastic
215 simulations of the EVD transmission model to investigate the epidemic dynamics when
216 the number of new cases becomes small, i.e, during the tail of the epidemic. Comparing
217 model simulations while assuming a convalescent period of 3 months to those without
218 sexual transmission confirmed the deterministic results that sexual transmission from
219 convalescent survivors does not lead to a significant increase in the cumulative number of
220 infected cases (non-STI: 11,086 +/- 599 cases; STI: 11,517 +/- 622 cases; Wilcox rank
221 sum test: W = 493156.5, p = 0.59; *Supplementary Material*, Fig. *S3*), nor the size (non-
222 STI: 86 +/- 4.4 new cases per day; STI: 89 +/- 4.6 new cases per day; W = 494255, p =
223 0.65) or timing (non-STI: day 200 +/- 0.7; STI: day 199 +/- 0.6; t = 1.1681, df = 991.14,
224 p = 0.24) of the epidemic peak incidence (Fig. 4a, 4b, 4c). Strikingly, this conservative
225 period of potential sexual transmission, which has recently been shown to extend well
226 beyond 3 months in at least 65% of patients [1], extended the average date on which the
227 last active case could be detected by nearly four months (non-STI: 497 +/- 2.9 days; STI:
228 619 +/- 6.0 days; difference: 123 days [95% CI: 110-137 days], t = -18.5, df = 730.36, p
229 < 0.0001; Fig. 4d, 4e, 4g, 4h). The width of the tail (s.d. = 135 days) was such that 18.5%
230 of the 508 simulated epidemics that accumulated at least 100 cases still experienced
231 symptomatic individuals 730 days (two years) after the start of the epidemic (Fig. 4h).
232 When the convalescent period was extended from 3 months to 6 months, the projected
233 length of the epidemic increased to a mean of 1102 days (+/- 14.9), with 89.0% of the
234 489 sustained epidemics taking over two years to end (Fig. 4i). Importantly, there is

235 greater variance in the tail of the epidemic when sexual transmission is considered, and
236 this uncertainty grows with the length of the convalescent period (Fig. 4g, 4h, 4i).
237
238 **Discussion**
239 Our study shows that sexual transmission of Ebola virus from convalescent men could
240 have a profound effect on the duration of the epidemic in Sierra Leone. Using a
241 mathematical transmission model, we found that an average duration of the convalescent
242 period of 3 months, and a per sex act transmission probability of 0.1% could extend the
243 EVD epidemic in Sierra Leone by 123 days (95% CI: 110–137 days). Such a scenario
244 would be consistent with the occurrence of a small number of sexual transmission events
245 during the end-phase of the epidemic. So far, the reported cases of sexual transmission of
246 EVD remain rare [1,2]. Hence, the per sex act transmission probability of Ebola virus
247 from male convalescent survivors is unlikely to be higher than 0.1%, but might well be
248 below this value. Our sensitivity analysis indicates that the duration of the EVD epidemic
249 is heavily influenced by the period during which convalescent men can transmit sexually,
250 calling for a better understanding of the persistence and duration of infectivity of Ebola
251 virus RNA in convalescent patients.
252
253 To our knowledge, this is the first study using mathematical modeling to assess the
254 potential impact of sexual transmission of Ebola virus on the epidemic in West Africa.
255 We extended an accepted modeling framework that has been widely used to describe the
256 epidemic trajectories of EVD outbreaks and epidemics [12–14]. Our baseline model
257 provides a good description of the EVD epidemic in Sierra Leone and we performed

258 sensitivity analysis to account for the considerable uncertainty in key unknown
259 parameters regarding sexual transmission. Given that chance will play a crucial role in
260 sexual transmission of Ebola virus, we used stochastic simulations to explore the
261 expected variability in the tail of the epidemic. In the absence of a better understanding of
262 sexual transmission of EVD, mathematical modeling currently remains the only tool to
263 explore its potential impact on the epidemic trajectory.
264
265 Our study provides a preliminary picture of the potential epidemiological consequences
266 of sexual transmission of Ebola virus on the epidemic in West Africa. Consequently,
267 there are a number of limitations that should be considered when interpreting the results.
268 First, we limited our analysis to sexual transmission from convalescent men who remain
269 infectious through the presence of Ebola virus in their semen. However, our modeling
270 framework could be easily extended to account for transmission by other routes, e.g.,
271 through infectious vaginal secretions from female survivors. Second, we assumed a
272 homogeneously mixing population to describe both non-sexual and sexual transmission
273 of EVD. Spatial structure might play an important role in the spread of EVD [26] as close
274 contact with infected bodily fluids is typically required even for non-sexual transmission.
275 In particular, close contact limited to family or community members during the
276 convalescence period, often accompanied by decreased activity levels due to post-Ebola
277 sequelae, may help limit the chances of sexual transmission. Third, asymptomatic
278 infection may occur [27], and is predicted to lower epidemic projections due to increased
279 levels of immunity in the population [28]. Fourth, the model does not incorporate
280 potential heterogeneity in sexual behavior [15], and we assumed that all sexually active

281 male survivors have the same average numbers of sex acts per month. The assumed
282 frequency of sex acts (8.3 sex acts per month) came from a study of heterosexual couples
283 in sub-Saharan Africa [29], and is on the high end of estimates gathered from studies of
284 other populations (e.g., [29–31], but see the wide range in individual frequencies in [32]);
285 the sexual activity of convalescent Sierra-Leonean EVD survivors has not been reported.
286 Fifth, EVD is known to exhibit superspreading characteristics [33,34], and we did not
287 include this in our model. Superspreading events could lead to explosive regrowth of the
288 epidemic after the occurrence of a new case through sexual transmission [33]. On the
289 other hand, 72% of infected individuals in transmission chains in Guinea did not generate
290 further cases [33], suggesting that some cases of sexual transmission of EVD might not
291 be detected at all. Sixth, we assumed a single compartment for convalescent survivors
292 with an exponentially distributed period of convalescence. Recent data indicates that the
293 time during which convalescent men remain positive for Ebola virus RNA could be better
294 described by a unimodal distribution [1]. Seventh, it remains to be determined whether
295 the virus found in semen of male convalescent survivors is replication competent, and the
296 time window during which these men remain infectious could be shorter than the duration
297 they remain positive for Ebola virus RNA. Finally, like other negative-sense single-
298 stranded RNA ((-)ssRNA) viruses [35], the species currently circulating in West Africa
299 has been estimated to have high substitution rates [36–38]. This rapid evolution detected
300 throughout the current outbreak zone suggests that within- or between-host adaptation of
301 the virus leading to pro-longed persistence in the seminal fluids is possible.
302

303 Awareness of the potential for sexual transmission has led to WHO issuing
304 recommendations that ask convalescent men to abstain from sexual activity as much as
305 possible and to use condoms for up to 6 months after the onset of symptoms [39].
306 Condom use and social awareness of the risks of sexual transmission during
307 convalescence should have an impact on the per sex act transmission probability (η) and
308 the frequency of sex acts (q), respectively. Our results show that condom use should
309 reduce the number of sporadic sexual transmission events during the tail of the epidemic
310 and after discharge of all remaining symptomatic individuals. However, the time during
311 which the public health community must stay vigilant is not reduced because these
312 interventions will not affect the time during which convalescent survivors can shed
313 infectious virus ($1/\alpha$). This is especially poignant since adherence to these
314 recommendations will never be 100%. Better knowledge about the rate at which
315 convalescent survivors recover completely and shed no further replicating Ebola virus
316 from their body is thus urgently needed to plan continued surveillance efforts.
317
318 The EVD epidemic in Sierra Leone was declared to be over on 7 November 2015 [40].
319 Our modeling results show that sporadic events of sexual transmission of Ebola virus –
320 potentially leading to small transmission clusters – could continue to occur in the months
321 to come. Sexual transmission of EVD is likely to be rare, but recent events such as the
322 suspected infection of a 16-year-old girl through sexual transmission in Makeni, Sierra
323 Leone, during September 2015 exemplify the continued risks [41]. In addition, the
324 considerable uncertainty around the infectivity of convalescent men who test positive for
325 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 [42–44]. 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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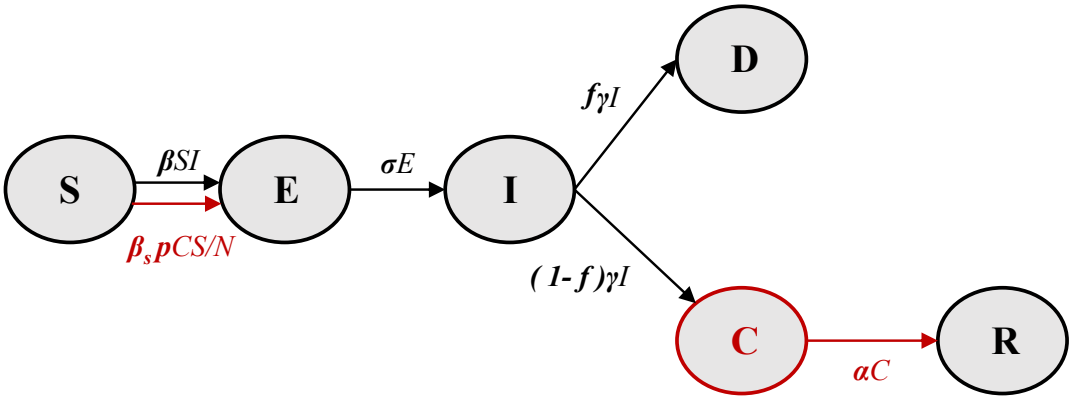
486

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

Parameter		Value (Range)	Comments and References
Basic reproductive number	$R_{0,N}$	2.02 (1.26 – 2.53)	Non-sexual transmission only [45] Range explores estimates from [13] and [46]
Date of onset of symptoms in index case		April 6, 2014	WHO epidemic day 92, epidemic week 14 [47]
Rate at which transmission rate decays	k	0.01 d^{-1}	Results in a good description of the EVD epidemic in Sierra Leone
Time at which transmission rate starts to decay	τ	90 d	We assume that control measures were not effectively deployed country-wide until three months following the first detected case ($R_{0,N}$ estimates began to fall in August 2014 [45]).
Initial population size	N_0	6.316×10^6	Based on 2014 estimate [48]
Incubation period	$1/\sigma$	9.31 d	[14]
Case fatality rate	f	0.69	[45]
Infectious period	$1/\gamma$	7.41 d	[14]
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 [49]
Frequency of sex acts	q	0.272 d^{-1} (0.136 – 0.544)	8.27 coital acts per month [29]
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 [45].
Rate at which convalescent survivors recover completely	α	1/83.84 d^{-1} (1/168 – 1/42)	3 months after onset of symptoms [4,39] and assuming an infectious period of 7.41 days

490

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 [12–14]. The red elements (convalescent individuals and additional transmission term) were added to account for sexual transmission.



496 **Figure 2. Effect of convalescent period on EVD epidemics.** The average duration of
497 the convalescent period ($1/\alpha$) is varied between 3 and 9 months. (a, b): Epidemic
498 trajectories in presence (broken lines) and absence of sexual transmission (solid lines).
499 Vertical lines mark the day of last symptomatic case. (c) Daily incidence of sexual
500 transmission. (d) Cumulative number of sexual transmission events. Note that the vertical
501 axes vary across panels.

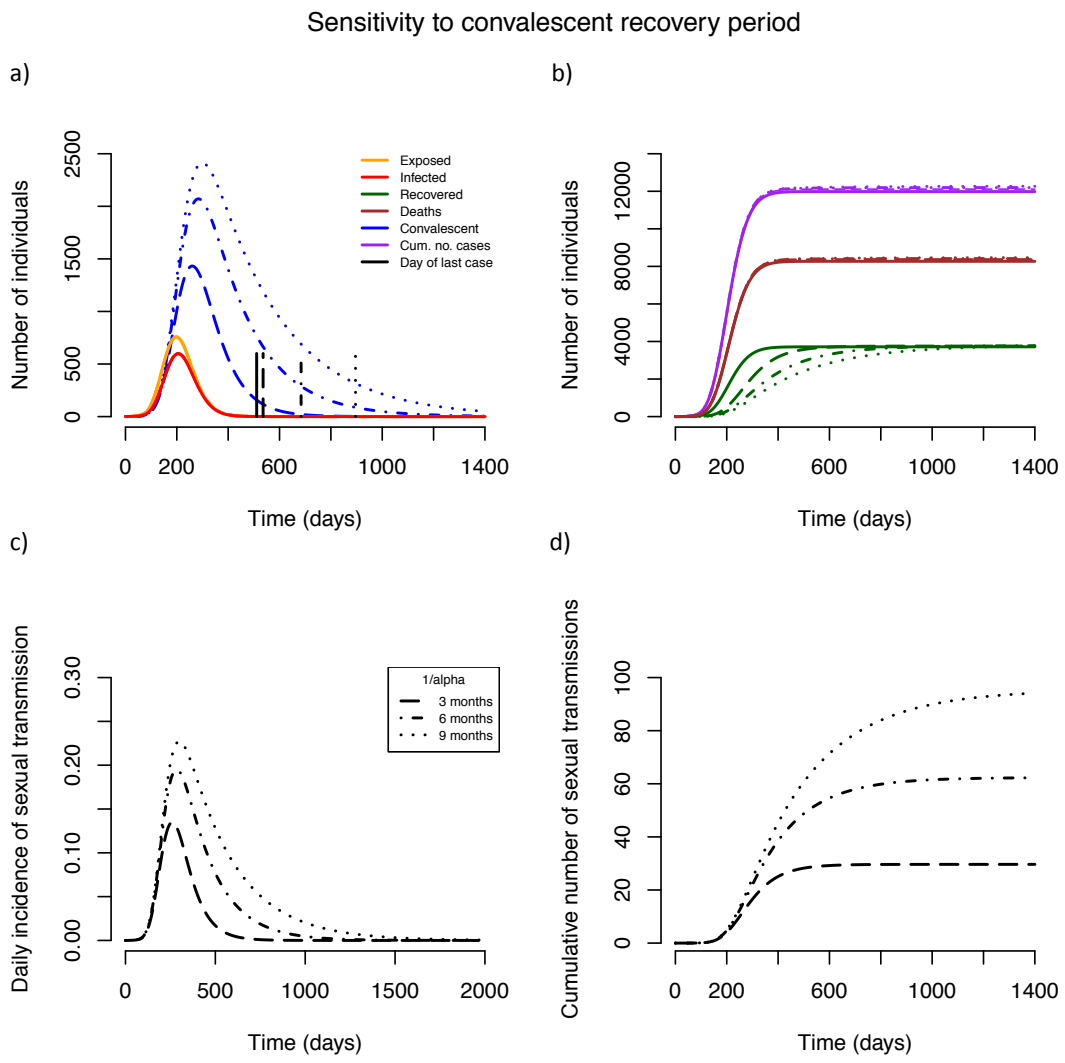


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Figure 3. Effect of per sex act transmission probability on EVD epidemics. The per sex act transmission probability (η) is varied between 0.05% and 0.2%. (a, b): Epidemic trajectories in presence (broken lines) and absence of sexual transmission (solid 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.

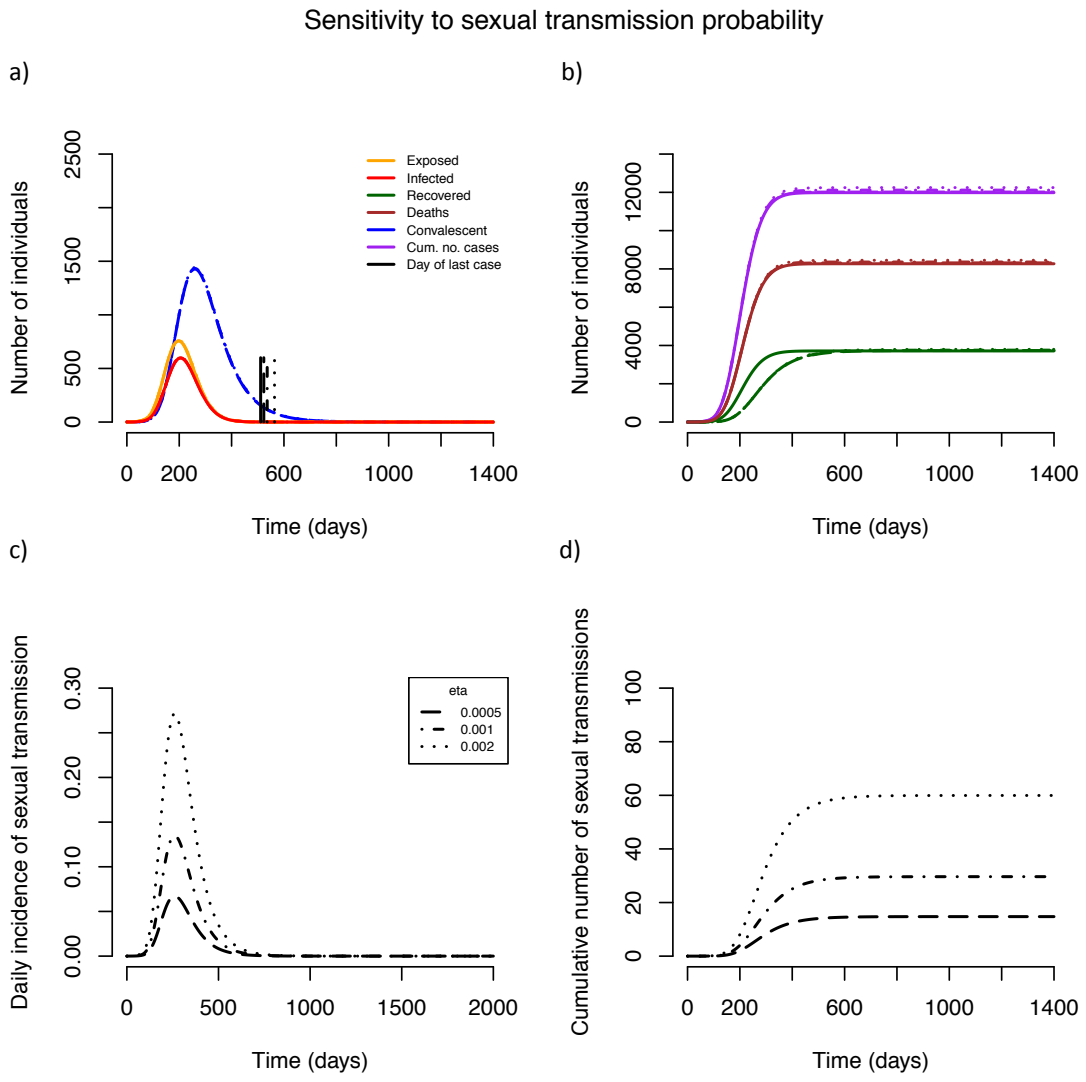
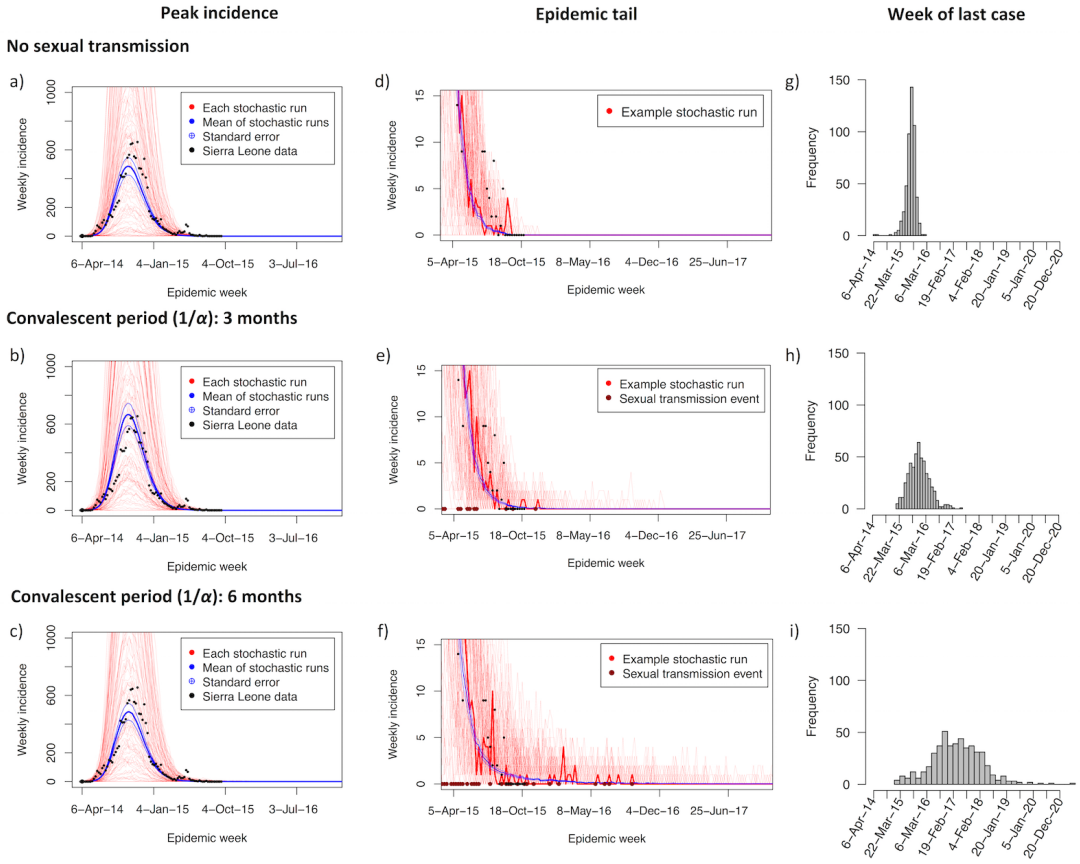
Figure 4. Impact of convalescent period on the tail of the EVD epidemic. Monte Carlo simulations of the weekly incidence of new cases (a, b, c) and the sporadic occurrence of sexual transmission events at the epidemic tail (d, e, f), assuming no sexual transmission (a, d), and sexual transmission with 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 [21]. 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.