Predicting the outcomes of treatment to eradicate the latent reservoir for HIV-1

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Predicting the outcomes of treatment to eradicate the latent reservoir for HIV-1

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Massive research efforts are now underway to develop a cure for HIV infection, allowing patients to discontinue lifelong combination antiretroviral therapy (AART). New latency-reversing agents (LRAs) may be able to purge the persistent reservoir of latent virus in resting memory CD4\textsuperscript{+} T cells, but the degree of reservoir reduction needed for cure remains unknown. Here we use a stochastic model of infection dynamics to estimate the efficacy of LRA needed to prevent viral rebound after AART interruption. We incorporate clinical data to estimate population-level parameter distributions and outcomes. Our findings suggest that ~2,000-fold reductions are required to permit a majority of patients to interrupt AART for 1 y without rebound and that rebound may occur suddenly after multiple years. Greater than 10,000-fold reductions may be required to prevent rebound altogether. Our results predict large variation in rebound times following LRA therapy, which will complicate clinical management. This model provides benchmarks for moving LRAs from the laboratory to the clinic and can aid in the design and interpretation of clinical trials. These results also apply to other interventions to reduce the latent reservoir and can explain the observed return of viremia after months of apparent cure in recent bone marrow transplant recipients and an immediately-treated neonate.

The latent reservoir (LR) for HIV-1 is a population of long-lived resting memory CD4\textsuperscript{+} T cells with integrated HIV-1 DNA (1). After establishment during acute infection (2), it increases to \(10^5\) to \(10^7\) cells and then remains stable. As only replicating virus is targeted by antiretroviral therapy (AART), latently infected cells persist even after years of effective treatment (3, 4). Cellular activation leads to virus production and, if treatment is interrupted, viremia rebounds within weeks (5). Several molecular pathways maintain latency, including epigenetic modifications, transcriptional interference from host genes, and the absence of activated transcription factors (6–9).

Major efforts are underway to identify pharmacologic agents that reverse latency by triggering the expression of HIV-1 genes in latently infected cells, with the hope that cell death from viral cytopathic effects or cytolytic immune responses follows, reducing the size of the LR (10, 11). Collectively called latency-reversing agents (LRAs), these drugs include histone deacetylase inhibitors (12–14), PKC activators (15–18), and the bromodomain inhibitor JQ1 (19–21). Although LRAs are the subject of intense research, it is unclear how much the LR must be reduced to enable patients to safely discontinue AART.

The feasibility of reservoir reduction as a method of HIV-1 cure is supported by case studies of stem cell transplantation (22, 23) and, more recently, early treatment initiation (24, 25), which have allowed patients to interrupt treatment for months or years without viral rebound. The dramatic reductions in reservoir size accompanying these strategies stand in stark contrast to the actions of current LRAs, which induce only a fraction of latent virus in vitro (26, 27) and have not produced a measurable decrease in LR size in vivo (12, 13, 28). It is unclear how patient outcomes depend on reservoir reduction between these extremes, nor even whether a reduction that falls short of those achieved with stem cell transplantation will bring any clinical benefit. LRA research needs to address the question: How low must we go?

In the absence of clinical data, mechanistic mathematical models can serve as a framework to predict results of novel interventions and plan clinical trials. When results do become available, the models can be tested and refined. Mathematical models have a long tradition of informing HIV-1 research and have been particularly useful in understanding HIV-1 treatment. Previous models have explained the multiphasic decay of viremia during ART (29), the initial seeding of the LR during acute infection (30), the limited inflow to the LR during treatment (31), the dynamics of viral blips (32), and the contributions of the LR to drug resistance (33). No model has yet been offered to describe the effect of LRAs. Here we present a novel modeling framework to predict the degree of reservoir reduction needed to prevent viral rebound following AART interruption. The model can be used to estimate the probability that cure is achieved, or, barring that outcome, to estimate the length of time following treatment interruption before viral rebound occurs (Fig. 1A).

Results

Determination of Key Viral Dynamic Parameters Governing Patient Outcomes. We use a stochastic model of HIV-1 reservoir dynamics and rebound that, in its simplest form, tracks two cell types: productively infected activated CD4\textsuperscript{+} T cells and latently infected resting CD4\textsuperscript{+} T cells (Fig. 1B). A latently infected cell can either activate or die, each with a particular rate constant. An actively infected cell can produce virions, resulting in the

Significance

HIV infection cannot be cured by current antiretroviral drugs, due to the presence of long-lived latently infected cells. New antilatency drugs are being tested in clinical trials, but major unknowns remain. It is unclear how much latent virus must be eliminated for a cure, which remains difficult to answer empirically due to few case studies and limited sensitivity of viral reservoir assays. In this paper, we introduce a mathematical model of HIV dynamics to calculate the likelihood and timing of viral rebound following antilatency treatment. We derive predictions for the required efficacy of antilatency drugs, and demonstrate that rebound times may be highly variable and occur after years of remission. These results will aid in designing and interpreting HIV cure studies.
and the ratio of post-LRA to pre-LRA reservoir A greatly exceeds e of the LR that remains following treatment interruption (a function of δ, A, P_{E0}, r, and efficacy q). Of note, the initial size of the reservoir itself is not included among these parameters: although it factors into both A (the product of the pre-LRA reservoir size and the per-cell activation rate), and q (the ratio of post-LRA to pre-LRA reservoir size), it does not independently influence outcomes. Both of these formulas provide an excellent match to the explicit simulation of the model (Fig. 2). The key assumption required for the analysis is that r greatly exceeds δ; because viral doubling times during rebound are measured on the order of a few days, whereas LR decay is measured on the order of many months or years, this assumption is expected to hold. Likelihood-based inference can therefore proceed by efficient computation of rebound probabilities (using [88]), rather than by time-consuming stochastic simulation.

Outcomes depend only on the four parameters above even in more complex models of viral dynamics, including other features of T-cell biology and the HIV lifecycle (SI Materials and Methods). Alternate models studied include explicit tracking of free virus with varying burst sizes, an eclipse phase during which an infected cell produces no virus, proliferation of cells upon reactivation, maintenance of the LR by homeostatic proliferation, and either a constant or Poisson-distributed number of infected cells produced by each cell (Figs. S2–S7). If proliferation of latently infected cells is subject to high variability, e.g., by bursts of proliferation, then rebound time and cure probability increase slightly beyond the predictions of the basic model (Figs. S6 and S7). No other modification to the model altered outcomes. Outcomes of LRA therapy therefore are likely to be insensitive to details of the viral lifecycle; accordingly, few parameters must be estimated to predict outcomes.

### Predicted Prospects for Eradicating Infection or Delaying Time to Rebound

Using best estimates of parameters derived from previously reported data (Table 1), we can explore the likely outcomes of interventions that reduce the LR. The best outcome of LRA therapy, short of complete and immediate eradication, is that so few latently infected cells survive that none reactivate and start a resurgent infection during the patient’s lifespan. In this case, LRA has essentially cleared the infection and cure is achieved. We simulated the model to predict the relationship between LRA efficacy and clearance (Fig. 2A). We find that the LR must be reduced 10,000-fold before half of patients are predicted to clear the infection.

If LRA therapy fails to clear the infection, the next-best outcome is extension of the time until rebound, defined as plasma HIV-1 RNA ≥ 200 copies per mL. We computed the relationship between LRA efficacy and median time until rebound among patients who do not clear the infection (Fig. 2B). Roughly a 2,000-fold reduction in LR size is needed for median rebound times of 1 y. Only modest (about 2-fold) increases in median rebound time are predicted for up to 100-fold reductions in LR size. In this range, the rebound time is independent of latent cell lifespan (decay rate δ) and is driven mainly by the reactivation rate (A) and the infection growth rate (r). The curve inflects upward (on a log scale) at ~100-fold reduction and eventually reaches a ceiling as...
clearance of the infection becomes the dominant outcome. The upward inflection results from a change in the forces governing viral dynamics. If the reservoir is large (little reduction), then cells activate frequently, and the dominant component of rebound time is the time that it takes for virus from the many available activated cells to grow exponentially to rebound levels; the system is in a growth-limited regime. If the reservoir is small (large reduction), the dominant component is instead the expected waiting time until activation of the first cell fated to establish a rebounding lineage; the system is in an activation-limited regime. Because waiting time is roughly exponentially distributed, times to rebound in this regime can vary widely among patients on the same therapy, even with identical values of the underlying parameters.

Survival curves, plotting the fraction of simulated patients maintaining virologic suppression over time, demonstrate the extreme interpatient variability and long follow-up times required for LRA therapy (Fig. 2C). For less than 100-fold reductions in LR size, simulated patients uniformly rebound within a few months because rebound dynamics are not in the activation-limited regime. If therapy decreases LR size 1,000-fold, then ~55% of patients are predicted to delay rebound for at least 6 mo. However, of these patients, 47% suffer rebound in the following 6 mo. Higher reservoir reductions lead to clearance in many patients. In others, rebound may still occur after years of apparent cure, posing a challenge for patient management.

Earlier work suggested a shorter reservoir half-life of 6 mo (35), indicating that dramatic decreases in LR size would occur after 5 y or more of suppressive ART even in the absence of LRA therapy. We consider the prospects for HIV eradication or long treatment interruptions with this faster decay rate. In this optimistic scenario, only 1,500-fold reductions are needed for half of patients to clear the LR, and rebound becomes highly unlikely after a few years. Alternatively, in a worst-case scenario where latent cell death is perfectly balanced by homeostatic proliferation such that the reservoir does not decay at all (δ = 0), much higher efficacies are needed to achieve beneficial patient outcomes (Fig. 3).

Setting Treatment Goals with Uncertainty Considerations. We conducted a full uncertainty analysis of the model, by simultaneously varying all parameters over their entire ranges (Table 1 and Fig. S1). For each simulated patient, values for the three parameters δ, A, and r were sampled independently from their respective distributions, whereas P_est was sampled from a conditional distribution that depends on r (Materials and Methods). Results for this simulated cohort are similar to those for the point estimates, with greater interpatient variation in outcomes (Fig. 3A). This variation makes the survival curves less steep: Cure is slightly more likely at low efficacy, but slightly less likely at high efficacy. As expected from Eq. 1, cure is more likely for patients with lower A or P_est values and higher δ values. If therapy provides only 10 to 100-fold LR reductions, a subset of patients may delay rebound for several months.

Using these cohort-level predictions, we can set efficacy goals for the reservoir reduction needed to achieve a particular likelihood of a desired patient outcome. Fig. 4 provides target LRA efficacies for which 50% of patients are predicted to remain rebound-free for a specified interruption time. Reductions of under 10-fold afford patients only a few weeks to a month off treatment without rebound. For 1-y interruptions, a 1,000–3,000-fold reduction is needed. To achieve the goal of eradication (cure) a 4-log reduction is required. This value increases to 4.8 logs to cure 75% of patients, and to 5.8 logs for 95% of patients.

Model Applications and Comparison with Data. The current ability to test the model against clinical data is limited both by the dynamic range of assays measuring LR size and by the low efficacy of investigational LRA treatments. However, we can compare our predictions to results observed for non-LRA-based interventions that lead to smaller LR size and prolonged treatment interruptions (Fig. 4). A 2010 study of early ART initiators who eventually underwent treatment interruption found a single patient with LR size ~1,500-fold lower than a typical patient (0.0064 infectious units per million resting CD4+ T cells versus an average of one per million) in whom rebound was delayed until 50 d off treatment (36). The well-known “Berlin patient” (22) has remained off treatment following a stem cell transplant since 2008, and a comprehensive analysis of his viral reservoirs found HIV DNA levels at least 7,500-fold lower than typical patients in the most sensitive assay (37). The two recently reported “Boston patients” also interrupted treatment, following transplants causing at least a 3 to 4 log decrease in viral reservoirs (23); they have since both rebounded, at ~3 and 6 mo postinterruption. In the case of the “Mississippi baby”, infection was discovered and treated within 30 h of birth, and ART continued until interruption at around 18 mo. Virus remained undetectable for 27 mo, when viral rebound occurred, assuming the accuracy of widely reported claims (e.g., ref. 38). At the time of treatment cessation, the LR size was likely at least 300-fold lower than that of a typical adult [based on less than 0.017 infectious units per million resting CD4+ T cells at age 30 mo (39), and scaled on a weight basis relative to adults]. These few available cases demonstrate that our model is not inconsistent

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Estimation method</th>
<th>Ref(s.)</th>
<th>Best estimate</th>
<th>Distribution*</th>
</tr>
</thead>
<tbody>
<tr>
<td>LR decay rate</td>
<td>δ</td>
<td>Long-term ART, δ = ln(2)/t½2</td>
<td>(6, 7)</td>
<td>5.2 × 10⁻⁴ d⁻¹</td>
<td>δ ~ N(5.2, 6) × 10⁻⁴ d⁻¹</td>
</tr>
<tr>
<td>LR exit rate</td>
<td>A</td>
<td>Viral rebound after ART interruption</td>
<td>(8, 69)</td>
<td>57 cells per day</td>
<td>log₁₀(A) ~ N(1.76, 1.0)</td>
</tr>
<tr>
<td>Growth rate</td>
<td>r</td>
<td></td>
<td></td>
<td>0.4 d⁻¹</td>
<td>log₁₀(r) ~ N(−0.40, 0.19)</td>
</tr>
<tr>
<td>Establishment prob.</td>
<td>F_est</td>
<td>Population genetic modeling</td>
<td>(71, 72)</td>
<td>0.069</td>
<td>Composite distribution</td>
</tr>
</tbody>
</table>

*Notation X ~ N(μ, σ) means that X is a random variable drawn from a normal distribution with mean μ and SD σ.

Fig. 2. Clearance probabilities and rebound times following LRA therapy predicted from the model using point estimates for the parameters (Table 1). LRA log-efficacy is the number of orders of magnitude by which the LR size is reduced following LRA therapy, −log₁₀(q). (A) Probability that the LR is cleared by LRA. Clearance occurs if all cells in the LR die before a reactivating lineage leads to viral rebound. (B) Median viral rebound times (logarithmic scale) among patients who do not clear the infection. (C) Survival curves (Kaplan–Meier plots) show the percentage of patients who have not yet experienced viral rebound, plotted as a function of the time (logarithmic scale) after treatment interruption. Solid lines represent simulations, and circles represent approximations from the branching process calculation. All simulations included 10⁶ to 10⁹ patients.
with current knowledge. When survival curves for larger cohorts become available, Bayesian methods can be used to update estimates in Table 1 and reduce uncertainty of future predictions.

Discussion
Our model is, to our knowledge, the first to quantify the required efficacy of LRA s for HIV-1 and set goals for therapy. For a wide range of parameters, we find that therapies must reduce the LR by at least 2 orders of magnitude to meaningfully increase time to rebound after ART interruption (upward infection in Figs. 2B and 3A, II; B, II; C, II), and that reductions of approximately 4 orders of magnitude are needed for half of patients to clear the infection (Figs. 3 A, I; B, I; C, I; and 4). Standard deviations in rebound times of many months are expected, owing to substantial variation in reactivation times after effective LRA therapy brings the infection to an activation-limited regime. Though the efficacy required for these beneficial outcomes likely exceeds the reach of current drugs, our results permit some optimism: We show for the first time, to our knowledge, that reactivation of all cells in the reservoir is not necessary for cessation of ART. This is because some cells in the LR will die before reactivating or, following activation, will fail to produce a chain of infections leading to rebound. On a more cautionary note, the wide distribution in reactivation times necessitates careful monitoring of patients, as rebound may occur even after long periods of viral suppression.

Even without any reservoir reduction, variation in infection parameters and chance activation together predict delays in rebound of at least 2 mo in a small minority of patients (Figs. 3A-C, III and 4), consistent with ART interruption trials such as SPARTAC (40). More detailed (and possibly more speculative) models including immune responses may be needed to explain multiply posttreatment control, such as seen in the VISCONTI cohort (24).

Our analysis characterizing the required efficacy of LRA therapy does not rely on the specific mechanism of action of these drugs, only the amount by which they reduce the reservoir. We have assumed that, after ART/LRA therapy ends, cell activation and death rates return to baseline. We have also assumed that the reservoir is a homogeneous population with constant activation and death rates. The presence of reservoir compartments with different levels of LRA penetration does not alter our results, as they are stated in terms of total reservoir reduction. If, however, these compartments vary in activation or death rates (41), or if dynamics of activated cells depend on their source compartment, then our model may need to be modified. Moreover, if spatial population structure affects viral replication, viral dynamics above the detection limit (from which we estimated parameters $\delta$ and $\lambda$) may not correspond straightforwardly to the infection/death rates in early infection, due to local limitations in target cell density (42). Spatial restrictions on viral transmission may be particularly important in densely packed lymphoid tissue (43). Without a clear understanding of multiple compartments constituting the LR, we have considered the simplest scenario which may fit future LRA therapy outcomes.

Throughout this paper, we assume that combination ART is sufficiently effective so that viral replication alone cannot sustain the infection after all latent virus is cleared. Studies of treatment intensification (44, 45), viral evolution during ART (46, 47), and in vitro antiviral efficacy (48, 49) all support this assumption. Moreover, HIV persistence is widely believed to result solely from the long lifespan or proliferative ability of latently infected cells (3, 50). If this assumption is violated, e.g., by the presence of latent drug-protected compartments (43, 51, 52), then any curative strategy predicated solely on latency reversal would be futile.

Our model also highlights the importance of measuring specific parameters describing latency and infection dynamics. Despite the field’s focus on measuring LR size with increasing accuracy (53), our results suggest that the rate at which latently infected cells activate, and the fraction of these that are expected to establish a rebounding infection, are more predictive of LRA outcomes. Among all parameters that determine outcome, the establishment probability is least understood, as it cannot be measured from viral load dynamics above the limit of detection. Simply because an integrated provirus is replication competent and transcriptionally active does not mean that it will initiate a growing infection: As with all population dynamics, chance events dominate early stages of infection growth (34, 54). HIV-1 transcription is itself a stochastic process, governed by fluctuating concentrations of early gene products (55). Sensitive assays of viral outgrowth may pave the way toward understanding the importance of these chance events to early infection; for instance, fluorescent imaging studies of adenovirus have shown that a large majority of in vitro infections seeded by single productively infected cells die out early, before rapid growth and plaque formation can occur (54). Keeping other parameters constant, assuming a worst-case (highest) value for the establishment probability raises the reservoir reductions required for cure or a desired extended rebound time by 0.8 logs. Regardless of the exact probability, the stochastic nature of HIV-1 activation and infection dynamics implies that even similarly situated patients may experience divergent responses to LRA.

The model can also advise aspects of trial design for LRAs. Survival curves computed from [S8] can be used to predict the probability that a patient is cured, given that they have been off treatment for 40 days. In most situations, the LR is cleared by at least 2 orders of magnitude to meaningfully increase time to rebound. LRA log-efficacy is the number of orders of magnitude by which the LR size is reduced following LRA therapy, $-\log_{10}(q)$. (I) Probability that the LR is cleared by LRA. Clearance occurs if all cells in the LR die before a reactivating lineage leads to viral rebound. (II) Median viral rebound times (logarithmic scale) among patients who do not clear the infection. (III) Survival curves (Kaplan–Meier plots) show the percentage of patients who have not yet experienced viral rebound, plotted as a function of the time (logarithmic scale) after treatment interruption. All simulations included $10^3$ to $10^5$ patients.

Fig. 3. Predicted LRA therapy outcomes, accounting for uncertainty in patient parameter values. (A) Full uncertainty analysis where all viral dynamics parameters are sampled for each patient from the distributions provided in Table 1. (B) A best-case scenario where the reservoir half-life is only 6 mo ($\delta = 3.8 \times 10^{-3} \text{ d}^{-1}$). All patients have the same underlying viral dynamics parameters, otherwise given by the point estimates in Table 1. (C) A worst-case scenario where the reservoir does not decay because cell death is balanced by homeostatic proliferation ($\delta = 0$). (I) Probability that the LR is cleared by LRA. Clearance occurs if all cells in the LR die before a reactivating lineage leads to viral rebound. (II) Median viral rebound times (logarithmic scale) among patients who do not clear the infection. (III) Survival curves (Kaplan–Meier plots) show the percentage of patients who have not yet experienced viral rebound, plotted as a function of the time (logarithmic scale) after treatment interruption. All simulations included $10^3$ to $10^5$ patients.
In this notation, \( Y \) and \( Z \) represent individual actively or latently infected cells, respectively, \( \Theta \) represents no cells, and the arrows represent one type of cell becoming the other type. A latently infected cell can either activate (at rate \( a \)) or die (at rate \( d_a \)). An actively infected cell can either die (at rate \( d_r \)) or produce a collection of virions (at rate \( b \)) that results in the infection of \( c \) other cells, where \( c \) is a Poisson-distributed random variable with parameter \( \delta \). After an infection event, the original cell dies.

Each event occurs independently within a large, constant target cell population. As the model does not include limitations on viral growth, it describes only the initial stages of viral rebound. Because clinical rebound thresholds (plasma HIV RNA >50–200 copies per mL) are well below typical set points (10^4 to 10^7 copies per mL), this model suffices to analyze rebound following LRA therapy and ART interruption. We do not explicitly track free virus, but assume it to be proportional to the number of infected cells. This assumption is valid because rates governing production and clearance of free virus greatly exceed other rates, allowing a separation of time scales. As we are not interested in blips or other intraday viral dynamics, this assumption does not influence our results. A method for calculating the proportionality between free virus and infected cells is provided in SI Materials and Methods.

The growth rate of the infection is \( r = bi/(1 - d) \). The total death rate of infected cells is \( d_r = b + d \), and the basic reproductive ratio (mean offspring size for a single infected cell) is \( R_0 = bi/(b + d) \). The establishment probability \( PE_0 \) is the solution to \( R_0(1 - e^{-PE_0}) - PE_0 = 0 \). The total LR decay rate in the absence of viral replication is \( \delta - \delta_c \). If there are \( Z \) cells in the LR, then the number of cells reactivating per day is \( A = 2 \delta_c Z \).

Analysis of the model to determine the four key parameters \( (\delta, \lambda, r, PE_0) \) and rapidly compute survival curves is provided in SI Materials and Methods. A script for computation of survival curves is also provided at www.danielrosenbloom.com/reboundtimes.

**Parameter Estimation.** The half-life of latently infected cells has been estimated to be approximately \( t_{1/2} = 44 \) mo (3, 4). The resulting value of \( \delta = \ln(2)/t_{1/2} = 0.14 \) is well above estimates for active cells. The recruitment rate of latent cells from the reservoir is \( \lambda = 10^{-5} \) mo^−1, whereas the time to rebound is \( \tau = 10^6 \) mo. For each \( \lambda \) value we perform 10^6 to 10^8 simulations.

**Simulation of the Model.** We use the Gillespie algorithm to track the number of latently and actively infected cells in a continuous time stochastic process. The initial number of latent cells is \( Z(0) = \text{Binomial}(N_{RL0},q) \), where \( N_{RL0} \) is pretreatment LR size and \( q \) is efficacy of LRA treatment (fraction of cells remaining). The initial number of actively infected cells \( Y(0) \) is then chosen from a Poisson distribution with parameter \( \lambda Z(0)/d_r \) (corresponding to the immigration–death equilibrium of the branching process). The simulation proceeds until the number of actively infected cells reaches the threshold for clinical detection given by a viral load of 200 copies per mL (equivalent to \( Y = 3 \times 10^4 \) cells total) or until no active or latent cells remain. Because stochastic effects are important only for small \( Y \), we switch to faster deterministic numerical integration when \( Y \) reaches a level where extinction probability is very low (<10^-5). For each \( q \) value we perform 10^4 to 10^6 simulations.

Simulations are seeded with values of the key parameters \( (\delta, \lambda, r, PE_0) \), which may be either the point estimates or random numbers sampled from the distributions in Table 1. We then back out values of model-specific parameters consistent with the sampled key parameters. In general, we use a pretherapy LR size of \( N_{RL0} = 10^6 \) cells to get a \( A = 0 \). We then have \( d_r = \delta − a \). As detailed in SI Materials and Methods, sampling \( PE_0 \) requires first

**Materials and Methods**

**Basic Stochastic Model.** The basic model of reservoir dynamics and rebound tracks two cell types: productively infected activated CD4+ T cells and latently infected resting CD4+ T cells. The model can be described formally as a two-type branching process, in which four types of events can occur (Fig. 1):
sampling the variance-mean ratio of the viral offspring distribution ($\lambda$). Then using $r$ and $\lambda$ along with $d_1 - d + b = 1 - d_1$, we can obtain $i$, $b$, and $\rho$. Consistent with our generating function analysis, we find that the specific values assumed for $N_{\text{lat}}$ and $d_1$ do not influence the results. For simulating other models, any other parameter assumptions are listed in the corresponding SI figure legends.

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