Comparative computational modeling of the bat and human immune response to viral infection with the Comparative Biology Immune Agent Based Model

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Abstract

Given the impact of pandemics due to viruses of bat origin there is increasing interest in comparative investigation into the differences between bat and human immune responses. The practice of comparative biology can be enhanced by computational methods used for dynamic knowledge representation to visualize and interrogate the putative differences between the two systems. We present an agent-based model that encompasses and bridges the differences between bat and human responses to viral infection: the Comparative Biology Immune Agent-based Model, or CBIABM. The CBIABM examines differences in innate immune mechanisms between bats and humans, specifically regarding inflammasome activity and Type 1 Interferon dynamics, in terms of tolerance to viral infection. Simulation experiments with the CBIABM demonstrate the efficacy of bat-related features in conferring viral tolerance and also suggest a crucial role for endothelial inflammasome activity as a mechanism for bat systemic viral tolerance and affecting the severity of disease in human viral infections. We hope that this initial study will inspire additional comparative modeling projects to link, compare, and contrast immunological functions shared across different species, and in so doing, provide insight and aid in the preparation for future viral pandemics of zoonotic origin.

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Introduction:

The potential for zoonotic transfer of viruses from bat populations to humans is highly significant in terms of viral pandemics. Bats have been implicated as zoonotic reservoirs/precursors for Ebola [1], Middle East respiratory syndrome coronavirus (MERS-CoV) [2], severe acute respiratory syndrome coronavirus 1 (SARS-CoV1) [2] and, most recently, severe acute respiratory syndrome coronavirus 2 (SARS-CoV2) [3]. The public health impact of these pandemics has prompted a great deal of interest in examining specific aspects of bat physiology and immunology in order to gain insights into why bat-borne viruses might be particularly pathogenic when they adapt to cause human disease [2-5]. One of the unique aspects of bats among mammals is their ability to engage in active flight, and therefore there has been interest in examining the evolutionary adaptations that have arisen in bats in order to accommodate the increased metabolic demands associated with active flight, particularly with respect to the configuration of their immune systems [3-5]. Specifically, the increased metabolic demands associated with flight suggest the need to adapt to increases in oxidative stress and associated cellular damage [3-5], but at the potential cost of impairing their response to microbial infections. This in turn would suggest adaptations of other means of controlling infectious insults. The combination of these two seemingly required features, 1) increased resistance to cellular damage and oxidative stress and 2) parallel augmented anti-infection capabilities, has led to targeted investigation and characterization into two biological modules that address these features: 1) differences in bat inflammasome activation, and 2) constitutive production of Type 1 Interferons, a notable anti-viral mediator.

The inflammasome is an intracellular multi-protein complex that processes danger signals (either microbial projects or evidence of cellular damage) into a series of inflammatory response processes, including the production and release of pro-inflammatory cytokines (notably Interleukin-1 (IL1) and Interleukin-18 (IL18)), the induction of nuclear factor kappa-b (NF-kB), a transcription factor responsible for inducing a series of inflammation-related mediators, and promoting pyroptosis, a form of programmed cellular death that is itself an inflammation-promoting process [6-8]. As such, the inflammasome is a critical component of an organism's response to effectively deal with infection or tissue damage, but, if dysregulated, can contribute to the pathophysiological manifestation of a host of diseases [6-8]. Specifically, aberrant inflammasome activation has been invoked as a major source of disease severity in viruses of bat-origin, where the "cytokine storm" resulting from extensive systemic inflammation produces collateral tissue damage and organ dysfunction [6]. Alternatively, bats have been demonstrated to have significantly suppressed inflammasome activation and activity, perhaps because of their need to deal with periodic episodes of high metabolic stress that can produce the exact mediators that would lead to priming and activation of the inflammasome. These adaptations include resistance to inflammasome priming from extracellular danger signals, such as reactive oxygen species, pathogen/damage associated molecular patterns (P/DAMPs) and pro-inflammatory cytokines, and decreased transduction of subsequent inflammasome activation leading to the release of IL1/IL18 and induction of pyroptosis [3, 4].

In concert with decreased inflammasome activity bats have enhanced anti-viral capabilities in terms of their production of Type 1 Interferon (T1IFNs). T1IFNs are associated with intracellular compounds that inhibit viral replication and assembly, as well as serving an extracellular role in terms of recruiting immune cells, notably natural killer cells (NK cells) and antigen-presenting cells (macrophages and dendritic cells) to eliminate infected cells. In contrast to most mammals, where the production of T1IFNs is primarily initiated by evidence of infection, bats constitutively produce T1IFNs [3, 4]. This provides bat with an enhanced baseline level of antiviral capability, which, in

conjunction with their dampening of inflammatory reactivity, allows them to have improved tolerance to viral insults.

While there are other mechanisms for viral resistance in bats, the presence of features of disordered-inflammation manifesting in human disease represents a natural focus on the difference in inflammasome activity between humans and bats, and such investigation should take into account the anti-viral compensatory mechanisms of differential T1IFN behavior between humans and bats. The work represented in the above series of references demonstrates beneficial insights from the traditional approach to comparative biology, but we believe that this comparative process can be enhanced by dynamically representing the putative hypothesized mechanisms such that the consequences of those mechanisms can be seen. We have termed this use of computational modeling as *dynamic knowledge representation* [9, 10]. There are several benefits of this use of computational modeling:

1. It can be difficult to intuit the overall effects of a complex set of interactions, and therefore a dynamic representation of this knowledge can uncover unanticipated or paradoxical dynamic effects, particularly when positive and negative feedback are present [9].
2. Computational models of this type can be used for examining new hypotheses, be they components or interactions within the system itself, or putative interventions [9]. Examining the plausibility of such modifications can suggest new experiments or observations that might need to be performed.
3. These types of computational models can be used as experimental objects, where simulation experiments can be performed that evaluate the new hypotheses noted in #2. Since simulation experiments are not subject to the cost and logistical constraints that apply to wet-lab experiments, and can often be run at considerably greater scale (in terms of number of individuals examined), they can be a useful adjunct to pre-testing and design of subsequent real world experiments [9].
4. As computational embodiments of knowledge/hypothesis structures, these models can serve as "bridging" knowledge structures that can represent what is conserved from one individual or zoological context to another. Rather than relying on a list of components and features, a computational model for dynamic knowledge representation can encapsulate what is functionally "similar" from one species/organism/individual and note what the effect might be for what is explicitly "different." [11].

We note that this type of mathematical/computational modeling can be considered distinct from mathematical projects that focus on abstracting biological processes to a minimally sufficient and analytically tractable set of interactions (this includes compartment-based Susceptible-Infected-Exposed-Resistance (SIER) models of in-host viral dynamics [12]). While those approaches have their considerable benefits in terms of potentially providing fundamental insights into various biological processes and are more readily calibrated to existing data, they are intrinsically limited in their ability to capture the richness of biological interactions needed to generate the heterogeneous range of behaviors and phenotypes present in the real world. Although all computational models employ some degree of necessary abstraction (e.g. it is not possible to incorporate every possible aspect of knowledge into a model), we assert that there are investigatory benefits for constructing and using complex computational representations of biological knowledge, if for no other reason that such models embody what biological researchers consider important enough to expend their energies investigating.

Towards this end, we present an agent-based model of the innate immune response that encompasses and bridges the differences between bat and human response to viral infection; we term this model the Comparative Biology Immune Agent-based Model, or CBIABM. To our knowledge this is the

first dynamic mechanism-based computational model that seeks to directly compare bat and human immune mechanisms and the consequences of those mechanistic differences, namely inflammasome activity and differences in T1IFN dynamics, in terms of manifesting disease.

Methods:

Overview and Abstraction Level

The CBIABM is an agent-based model (ABM). Agent-based modeling is a discrete-event, rule-based, spatially-explicit, computational modeling method that represents dynamical systems as populations of stochastically interacting, rule-based components, termed *agents [13].* The structure of ABMs is well-suited to representing multi-cellular biological systems, with cell types represented by classes of agents, where the cellular agents are governed by rules extracted from basic science literature regarding the causal mechanisms (that arise from natural laws) that govern cellular behavior. As such, agent-based modeling has become widely used in computational biology for examining a wide range of biomedical processes, such as sepsis [14-16], infectious disease [17], wound healing [18, 19], vascular biology [20] and cancer (for an overview see [21]). Specifically, we contend that ABMs are well suited for the task of dynamic knowledge representation, with the added benefit of modularity in terms of agent-classes and hierarchical aggregation (i.e. ABMs of specific tissues can be combined to represent more complex organ structures) [9].

As noted previously, selection of level of abstraction is a key component of model development and should be guided by the intended purpose of the model. For the CBIABM, the intent is to evaluate the functional consequences of differing responsiveness several functional modules in the immune response to viral infection between humans and bats. The functional modules involved are not represented with high-levels of molecular detail but rather treated as aggregated input-output processes; thus, we avoid the need to incorporate specific molecular kinetic rate constants and instead focus on being able to represent the general time courses of the outputs of these processes. For example, we recognize that the inflammasome is a complex aggregation of various proteins, signaling molecules and transcription factors, however, functionally, these details can be reduced to representing a set of cellular inputs that trigger priming and activation of this complex, and a series of defined cellular behaviors that result from its activation.

Similarly, for the current set of simulation experiments on the CBIABM we do not represent a specific type of virus; the intent is to evaluate the differing immune configurations between bats and humans in a relatively virus-agnostic fashion. Therefore, the abstracted virus has a percentage ability to invade a cell, a specified replication rate, viral release modeled as a general exocyotosis function; all these functions have the potential to be informed and calibrated to specific virus types for future project, but for this initial study we model them generically. This type of structure also allows for the future implementation of more detailed viral properties, such as receptor-specific binding, apoptosis inhibition and other immune evading capabilities.

Also, given the goal of examining the immune differences between bats and humans we focus on the innate aspects of the immune response in the current development of the CBIABM, as the high-metabolic rate in bats has been identified as a main driver for this difference, and the ability to deal with intrinsic cellular damage and byproducts of increased oxidative/metabolic stress are primarily carried out by the innate immune response [3, 4]. While we recognize the importance of adaptive immunity in human disease, particularly in terms of the development of cytokine storm, in terms of comparing the role of the inflammasome and baseline anti-viral capabilities we make the modeling decision that focusing on the innate response is sufficient for this initial examination of the transition from bat viral tolerance to human viral pathophysiology.

Model Implementation:

The CBIABM is implemented in Netlogo [22], a freeware software package used for a range of agent-based modeling tasks ranging from K-12 Education to modeling of complex real-world systems. One of the primary benefits of Netlogo is that the models are written in a fairly read-able coding language; as such the entire CBIABM (with internal documentation) can be downloaded as a Netlogo executable file from http://www.github.com/An-Cockrell/Comparative-Biology-Immune-ABM. The topology of the CBIABM is a two-dimensional square grid composed of 51 x 51 "patches" (to use Netlogo terminology) where the edges wrap to form a torus. Each patch represents a spatial container for extracellular entities (mediators, extracellular viral particles) and cellular agents that can occupy that area of space. The CBIABM runs in a step-wise fashion during which all the functions of the model are executed, where each step represents approximately 10 minutes of real-world time; the parameters and rules for the CBIABM are thus fitted to generate behaviors in realistic time courses based on this step interval. Note that the "virus" reflected in this current version of the CBIABM is a generic virus and not calibrated to any particular species; however, the modular rule and parameter structure of the CBIABM is such that specific types of viruses can and will be implemented in the future. Each simulation run represents an infected simulated patient. The high-level sequence of events are as follows:

1. The simulation is initialized.
2. A specified amount of extracellular virus is placed in a random pattern onto the epithelial cell grid.
3. The rules for the cells are executed. The implementation of Netlogo shuffles the order of execution within each class of agent but runs each class of agents in a specified sequence. Once the specified set of instructions for each step are completed the process starts again until the stopping conditions are met.
4. The total time course simulated is 14 days.

There are stochastic processes incorporated into the rules of the CBIABM: 1) they manifest in the initial distribution of cells and extracellular virus, 2) to provide some noise in terms of the rate of viral infection and replication, and 3) to provide noise for incorporated thresholds for cellular rules related to activation status of the cells. These stochastic components result in each run being unique and distinct, mimicking the heterogeneity seen across a population of organisms, be they bat or human. Therefore, the evaluation of the output of the CBIABM is done at the population level, with evaluation metrics reported as a distribution of a particular model output across a population of simulation runs. The primary output metric used is "%system-health", which represents the health of the system as the percentage of healthy epithelial cells among the total possible number of 2601 (51 grid spaces x 51 grid spaces). Note that this output metric does not distinguish between epi-cell agents that eliminated by apoptosis or necrosis; the supposition is that the viability of a tissue is a function of the number of healthy cells present. This view of tissue damage/health also assumes that the different tissue level consequences of the various forms of cellular death: apoptosis, pyroptosis and necrosis, are due to their relative ability to induce and propagate inflammation, which reduces the total number of healthy epithelial cells (as opposed to a view that cells that die via necrosis are somehow "more dead" than those that die by apoptosis).

The CBIABM represents the following cell types:

1. Epithelial cells. These are generic epithelial cells that represent the cells initially exposed and susceptible to viral infection. One epithelial cell agent occupies a single grid space for a total of 2601 possible healthy epithelial cells in the system and they do not move. The

total health of the system is reflected by the percentage of healthy epithelial cells out of 2601, the variable called "%System-Health". The epithelial cell agents have the following variables and functions:

a. Susceptibility to infection: this variable represents how readily the epithelial cell can be infected by extracellular virus and abstracts its expression of potential receptors that can be targeted by various viruses.
b. Susceptibility to reactive oxygen species/cytotoxic compounds: this variable represents how much damage the epithelial cell can sustain before it undergoes necrosis, a pro-inflammatory form of death that results in the production of additional danger signals (P/DAMPs).
c. Byproduct of metabolism: this variable represents the amount of oxidative byproducts produced from baseline metabolism and are sensed as P/DAMPs. This value is increased 10-fold between bat and human, representing dampened sensing by bats [3].
d. Total cell membrane: this variable represents how much cell membrane the cell has that can be consumed by viral exocytosis before the cell dies by necrosis (pro-inflammatory death) and release of danger signals (P/DAMPS).
e. Apoptosis: This function is initiated by sensing of viral infection and represents programmed cell death to shorten the time (and therefore total amount) of viral production by an infected epithelial cell. This function is also accelerated by interactions with NK cells as a representation of NK cells' anti-viral effect. As a result of apoptosis almost no epithelial cells progress to membrane consumption death (1c above), though may be altered in future versions where for simulations of viruses known to interrupt apoptosis. Notably cells that die by apoptosis do not propagate inflammation.
f. Production of Type 1 Interferons (T1IFN): primary inflammatory and anti-viral mediator produced by infected epithelial cells in humans and at baseline in bats.
g. Regeneration: this is an abstracted healing function that allows regrowth of new epithelial cells into empty patches from where dead epithelial cells (either apoptotic or necrosed) have been cleared by phagocytosis. This process is simulated to take 3 days.

2. Natural Killer cells (NK cells): These are mobile immune cells that are a major component of innate antiviral activity. The migrate towards infected epithelial cells and accelerate their apoptosis. Their functions and properties include:

    a. Chemotaxis to T1IFN
    b. Production of Interferon-gamma (IFNg) in the presence of T1IFNs, Interleukin-12 (IL-12) and Interleukin-18 (IL-18).
    c. Accelerate apoptosis in infected epithelial cells via an abstraction of perforin and granzyme function.

3. Macrophages: These are mobile immune cells that respond to signals produced by infected epithelial cells and immune cells. These cells are central regulators of the innate immune response; they also phagocytose extracellular virus and cellular debris from dead epithelial cells, clearing space for new epithelial cells to regenerated into. Their functions and variables include:

    a. Chemotaxis to T1IFNs and P/DAMPS

b. Have a differential activation level representing the ability to perform pro-inflammatory functions (M1 Phenotype) or anti-inflammatory functions (M2 Phenotype). The activation level is determined by a balance between pro-inflammatory signals: T1IFN, P/DAMPs, IFNg and Interleukin-1 (IL1) versus anti-inflammatory signals: Interleukin-10 (IL-10).

    i. M1 Macrophages produce Interleukin-8 (IL-8) and Il-12, and if their inflammasome is activated, Tumor Necrosis Factor (TNF), Interleukin-6 (IL-6), IL10 and IL-1 and IL-18.
    ii. M2 Macrophages produce IL-10.

c. Have an abstracted inflammasome that becomes activated through two steps:

    i. Priming: Occurs when exposed to P/DAMPs or TNF.
    ii. Activation: If already primed, if sufficient extracellular virus is phagocytosed, this triggers the production of precursors for IL-1 and IL-18, allows M1 production of TNF, IL-6 and IL-10 and initiates the pyroptosis pathway.

Both priming and activation have defined thresholds; these are set at different levels between humans (lower) and bats (higher).

d. Can undergo pyroptosis: as discussed above, pyroptosis is an inflammogenic form of cell death. The precursors to IL-1 and IL-18 are released as active cytokines upon pyroptosis, as well as the production of P/DAMPs representing the release of extracellular DNA at cell death. Pyroptosis occurs ~ 2 hours after inflammasome activation [8, 23-25].
e. Perform phagocytosis: this is the endocytosis of extracellular viruses and cellular debris, clearing away damaged cells in order to allow for epithelial regrowth. However, it is recognized that there is a limit to the amount of material a macrophage can phagocytose, therefore there is a variable that determines the upper limit of this amount: when this limit is reached the macrophage is considered "exhausted" and is unable to clear any more material [26].

4. Dendritic Cells: These are antigen presenting cells that have similar functions to macrophages but are a key component in the transition from innate to adaptive immunity: they are primarily responsible for presenting antigen to naïve T-cell subtypes and inducing antigen-specific differentiation of various T-cell subtypes. However, in the current version of the CBIABM their role in inducing adaptive immunity is not represented, and rather they serve primarily to chemotax in response to T1IFN and produce IL-12 and IFNg.

5. Endothelium: The majority of the initial viral response is considered to take place in the epithelial tissue at risk, though the vascular supply to that tissue means that there is close proximity with the endothelial cells lining those vessels. The activation of the endothelium is a key step in the transition from what would otherwise be an inflammatory process restricted in local tissue to an expansion towards systemic effects. As such, endothelial activation is a critical tipping point that affects the manifestation of disease [27]. The inflammatory role of the endothelium is represented in the CBIABM by projecting a layer of endothelial cells "on top of" each epithelial cell, and having those cells being able to be activated by signals generated on the patch on which it sits. Endothelial cells are activated

by a combination of inflammatory signals: IL1 and TNF. This activation involves the function of the endothelial inflammasome, which in humans activates a series of signaling and adhesion functions that eventually lead to the recruitment of polymorphnuclear neutrophils (PMNs) from the blood stream to the area of inflammation. We *hypothesize* that similar to their immune cell inflammasomes bats have a reduced degree of responsiveness in their endothelial inflammasomes; this decreased function is reflected in the different values assigned to the endothelial-activation threshold between human and bat simulations. In addition to the simulated induction of adhesion molecules, activated endothelium produces platelet activating factor (PAF), which is a chemotaxis signal for polymorphonuclear neutrophils (PMNs) [28].

6. Polymorphonuclear neutrophils (PMNs): these are the primary circulating immune/white blood cells. They serve a central role in the response to bacterial infections, but in general their role in containing viral infections is less pronounced. However, they can be recruited to sites of viral infection if the endothelium in the region of the infection becomes activated and initiates the sequence of PMN adhesion and migration through the blood vessel walls into the tissue. The process of PMN adhesion and migration is abstracted in the CBIABM and is modeled to take about 6-12 hours from initial endothelial activation through the production of endothelial adhesion molecules, the adhesion of PMNs to those molecules through to the migration of PMNs into the tissue. Once in the tissue they will chemotax towards IL-8 and PAF, and subsequently undergo a respiratory burst that produces proteolytic and cytotoxic compounds that induce epithelial cell necrosis (a pro-inflammatory cell death) [29].

Mediators are generated based on rules by the cellular agents and are represented as variables present on each grid-space; therefore, the total amount of a particular mediator is the sum of all the individual values for each patch. Mediators diffuse from patch-to-patch using the Netlogo "diffuse" function, where a defined percentage of the variable is evenly distributed to the surrounding 8 patches. Mediators are reduced by three processes:

1. They are consumed by binding to receptors on the cellular agents.
2. There is a percentage degradation of the value of each mediator per step.
3. There is an arbitrary lower threshold of the value of each mediator at which point the value is set to 0.

The mediators included in the CBIABM, their represented functions and associate references can be seen in Table 1:

Mediator	Modeled Function and References
Pathogen/Damage Associated Molecular Patterns (P/DAMPS)	Produced when cells die by some other means than apoptosis (pyroptosis or necrosis) [24, 25]
Reactive Oxygen Species (ROS)	Produced as a byproduct of cellular respiration and during PMN respiratory burst [29]
Platelet Activating Factor (PAF)	Made by activated endothelial cells, functions as chemotaxis and adhesion activation signal for PMNs [28, 29]
Tumor Necrosis Factor (TNF)	Produced by pro-inflammatory macrophages and PMNs, functions to activate the inflammasome in macrophages,

	activates endothelium, chemotactic compound for PMNs [6-8, 29]
Interleukin-1 (IL-1)	Produced by inflammasome priming and activation in macrophages, released at pyroptosis and produced by PMNs, functions to activate endothelium and shift macrophages to M1/proinflammatory phenotype [3, 4, 6, 7, 30]
Interleukin-18 (IL-18)	Produced by infected epithelial cells and as part of inflammasome priming and activation in macrophages, released at pyroptosis by macrophages, function is to facilitate NK cells to produce IFNg [3, 4, 6-8, 31]
Interleukin-6 (IL-6)	Produced by pro-inflammatory/M1 macrophages, dendritic cells and infected epithelial cells, function to down-regulate subsequent TNF and IL1 production by macrophages [32, 33]
Interleukin-8 (IL-8)	Produced by pro-inflammatory/M1 macrophages, functions as chemotactic compound for PMNs [29]
Interleukin-10 (IL-10)	Produced by both pro- and anti-inflammatory macrophages (M1 and M2), function is to shift balance of macrophages from pro-inflammatory M1 to anti-inflammatory M2 [34, 35]
Interleukin-12 (IL-12)	Produced by dendritic cells and pro-inflammatory M1 macrophages, function to facilitate NK cell production of IFNg [36, 37]
Type 1 Interferons (T1IFN)	Produced by infected epithelial cells and NK cells, functions as chemotactic compound for NK cells and macrophages, facilitates production of IFNg by NK cells, has antiviral effect by reducing viral replication in infected epithelial cells, constitutively produced in bats, only induced in humans, enhances apoptosis in response to viral infection [3, 4, 38-40]
Interferon-gamma (IFNg)	Produced by NK cells, pro-inflammatory M1 macrophages, dendritic cells, functions to shift towards pro-inflammatory/M! macrophages, activate NK cells [39, 41, 42]

Initialization of the CBIABM involves generating epithelial-cell agents that populate each grid space of the 51 x 51 square grid. Set populations of NK-cells, Dendritic Cells and Macrophages are randomly distributed across the space. A viral inoculum is applied by setting the value for extracellular-virus to 100 +/- Random 20 (to introduce noise) for a random number of grid-spaces equal to the Initial Inoculum variable; this is the variable that represents the perturbation to the system. During simulation runs the cells and mediators listed above will interact with each other based on there programmed rules but acting upon different local conditions arising from the heterogeneous spatial distributions of the initial conditions (i.e. inflammatory cell and extracellular virus locations). Figure 1 depicts the set of interactions between the various cellular agent types, the simulated mediators (production and effects), and functions represented by the model rules. As noted previously, the entire CBIABM version that was used to generate the data for this paper is available for download at http://www.github.com/An-Cockrell/Comparative-Biology-Immune-

ABM ; this includes descriptions of the specific parameters used for the simulation experiments described below.

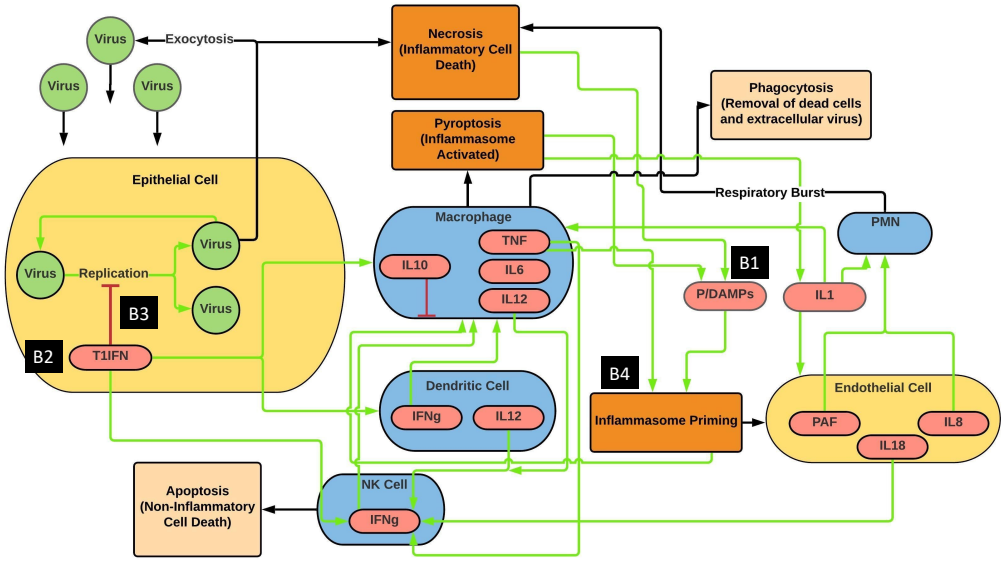

Figure 1. Schematic of the main cell types, mediators, interactions, and functions represented in the CBIABM. Green arrows represent positive or stimulatory interactions, red connectors represent negative or inhibitory interactions. Note that the primary means of suppressing viral infection is through the death of infected epithelial cells, either by apoptosis or necrosis; both pathways lead to decreased numbers of healthy epithelial cells (%System-Health). Also note that the differences in bat and human parameterization are seen at: B1 = increased P/DAMPS due to increased metabolism, B2 = baseline production of Type 1 Interferons (T1IFN), B3 = enhanced antiviral effect of T1IFNs and B4 = decreased inflammasome activity. T1IFN = Type 1 Interferons, P/DAMPS = Pathogen/Damage Associated Molecular Patterns, PAF = Platelet Activating Factor, IL1 = Interleukin 1, IL2 = Interleukin 2, IL6 = Interleukin 6, IL10 = Interleukin 10, IL12 = Interleukin 12, TNF = Tumor Necrosis Factor, IFNg = Interferon-gamma, PMN = polymorphonuclear neutrophil, NK cell = Natural Killer Cell.

Simulation Experiments:

Given the goal of examining fundamental differences between bat and human responses to a viral infection (e.g. not resistance to specific viruses), parameters related to viral invasiveness and viral replication rate were kept constant between simulations in the bat and the human. This choice was made to remove virus-specific properties, such as exploitation of specific cellular receptors as a means of producing differential virulence, as this would confound the evaluation of more general and conserved differences between bats and humans. The time course for the viral replication was set to generate peaking or at least plateauing mediator levels between 3-7 days simulated time, corresponding to an onset of symptoms ~3-7 days after inoculation. We make the modeling assumption that the basic interaction map (seen in Figure 1) is conserved between bats and humans, albeit with the notable differences listed here:

1. Higher baseline production of P/DAMPS to simulate the enhanced metabolic rate in bats.

2. Baseline production of Type 1 Interferons
3. Enhanced intracellular anti-viral effect of Type 1 Interferons
4. Reduced Inflammasome Priming and Activation

Our goal is to evaluate a minimally sufficient set of differences that have received emphasis in the comparative immunology between bats and humans [3, 4]; future expansion of the CBIABM can incorporate additional differences between the species.

The initial calibration of model parameters involved hand-fitting to expected general time-courses of viremia, viral eradication, initiation of inflammatory responses and general trajectories of cytokine time courses with the modeling assumption that symptoms arising from pro-inflammatory cytokines would manifest ~ 3-7 days post-inoculation. We note that as the CBIABM is focused on properties of innate immunity and does not include expansion of the immune response to T-cell functions and other aspects of the adaptive response, it is incorrect to try and fit mediator trajectories to clinical time points much beyond 10 - 14 days (the time-period before cytotoxic T-cell populations peak and is associated with potential cytokine storm [43]). However, since the induction of T-cell responses is itself a function of the ability to either contain or propagate initial inflammatory signals and/or contain the degree of viral replication, we believe that the conclusions we can draw about the differential tolerance between bat and human immune properties are valid.

Following calibration simulation experiments were carried out for both human-parameterizations and bat-parameterizations. The first set of experiments were a sweep of the initial viral inoculum from a value of 25 to 150 (arbitrary units) in increments of 25 and evaluating CBIABM behavior and outcome after 14 simulated days (n = 1000 stochastic replicates per initial inoculum value). These simulations were used to establish dose-dependent population outcome curves reflecting end-state %System-Health.

During the course of development of the CBIABM we noted that when the models only reflected behaviors within the epithelial tissue there did not appear to be as significant differences between the bat and human simulations as suggested by the literature in terms of total end %SystemHealth, despite incorporation of the differences note previously [2-4]. Of particular interest was that the impaired inflammasome activation and increased antiviral effect of Type 1 Interferons in the bat-parameterization of the CBIABM appeared to be offset by the enhanced eradication of infected epi-cells in the human-parameterization of the CBIABM in terms of the total number of dead epi-cell agents generated. This could be explained by the fact that the primary means of controlling viral infections is through the eradication of infected cells, and that both the primarily apoptotic mechanisms in the bat and the inflammasome-affected processes in the human reached had similar efficacy in depleting the infected epithelial population. It was only when the process of endothelial activation was added, which is related to inflammasome activation and for which we assumed would similarly be reduced in bats, that noticeable differences in bat resistance to viral load became evident. In order to characterize this effect, a parameter sweep was run across progressing thresholds of endothelial-activation (from the human level = 5 to the bat level = 10; all arbitrary units) in the human-parameterization of the CBIABM, using the highest tested viral initial inoculum (= 150) to visualize the greatest effect.

Finally, one of the proposed mechanisms for zoonotic transfer from bat populations to humans is viral spillover as a result of increased stress in bat populations (either due to environmental changes or the introduction of other types of infections, such as white nose syndrome [5]). We simulated this effect by varying the parameter value of metabolic stress ("Metabolic-byproduct") in the bat

parameterization of the CBIABM and evaluated trends in population %System-Health (n = 1000 stochastic replicates per initial condition) associated with those changes.

Results:

Initial calibration of the CBIABM was able to generate plausible behaviors: viral dynamics that resulted in peaks at 3-7 days, elevated mediators at 3-7 days consistent with development of symptoms attributable to the presence of those mediators. Time course data for 10 stochastic replicates at simluated moderate (Initial Inoculum = 75) and severe (Initial Inoculum = 150) infection can be seen in Figure 2. Note again that the lack of T-cells in the current version of the CBIABM results in the absence of their contribution in terms of generating inflammation-related mediators in the >7 day period of simulated time.

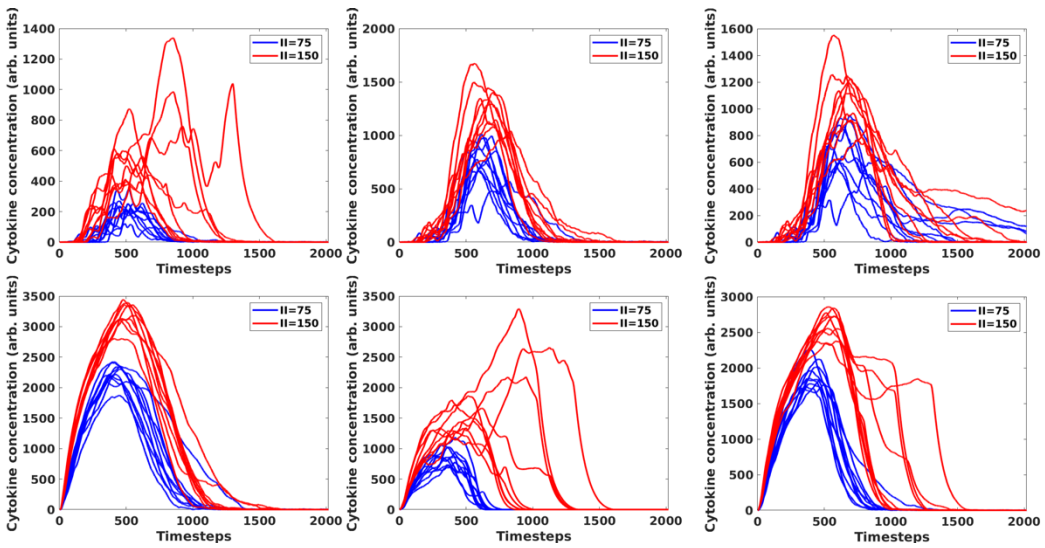

Figure 2. Representative mediator trajectories produced by the human parameterization of the CBIABM with 10 stochastic replicates at Moderate Disease Severity (Initial Inoculum = 75 shown in Blue) and Severe Disease Severity (Initial Inoculum = 150 shown in Red). Each panel shows a mediator incorporated in the CBIABM, starting clockwise from top left: Interleukin-1 (IL1), Tumor Necrosis Factor (TNF), Interleukin-10 (IL10), Interleukin-8 (IL8), Interferon-gamma (IFNg) and Interleukin-12 (IL12). Note Y-axes are at different scales; the absolute values of the simulated mediator levels are meaningless. Given representation of a generic virus these plots all demonstrate plausible trajectories corresponding to assumed onset of symptoms at ~3 days (= Timestep 432), with expected higher values and generally increased durations with greater disease severity. These simulations also demonstrate the effect of stochastic processes in variation in the trajectories, consistent with the heterogeneity present within a clinical population.

The sweep of viral initial inoculum is seen in Figure 3A-B. Figure 3A depicts the comparison between the human-parameterization and the bat-parameterization of the CBIABM. There is an expected dose-dependent relationship between the Initial Inoculum and the degree of reduced %System-Health. There is considerably greater degree of impaired %System-Health seen in the human-parameterizations such that bat-parameterizations show minimal tissue damage (surrogate for manifestation of disease and disease severity) for levels of Initial Inoculum that produce considerably reduced #System-Health in the human-parameterizations. The resistance of the bat-

parameterizations is so marked that the dose-dependent differences to the varied initial inoculum can only be appreciated in the log-scaled magnified view seen in Figure 3B.

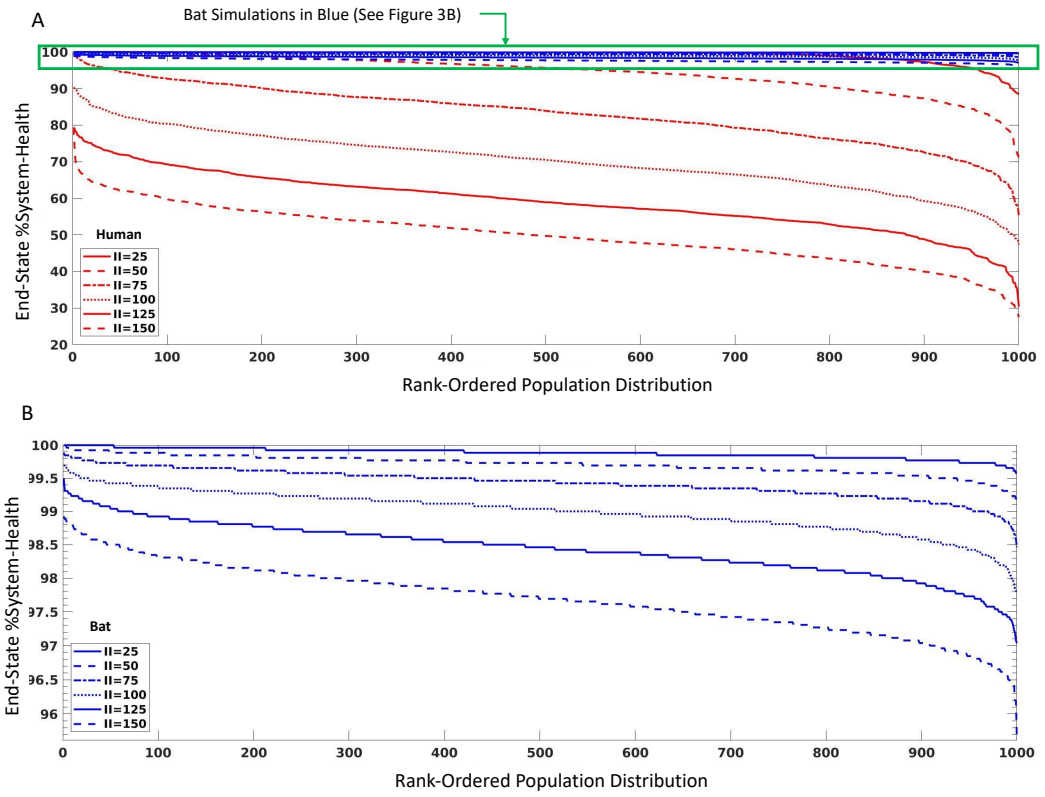

Figure 3A-B. Sweeps of Virus Initial Inoculum for Bat and Human Parameterizations with 1000 stochastic replicates per condition. Panel A shows both Bat (Blue) and Human (Red) Rank-Ordered Population Distributions at Initial Inoculums from 25 to 150 in 25 increments. The Rank-Ordered Population Distributions reflect the stochastic replicates ranked by their end #System-Health; while these lines are technically 1000 individual columns, for visualization purposes they are shown as curves. The decreasing curves seen with increasing Initial Inoculum is consistent with a dose-dependent worsening of outcomes across a population of runs. Note that the bat-parameterizations essentially demonstrate no disease severity (in terms of reduced %System-Health) for corresponding Initial Inoculums that generate significantly reduced %System-Health in human-parameterizations. Panel B is a log-scale magnification of the results for the bat parameterizations, which shows a similar dose-dependency but with considerably reduced tissue damage.

The parameter sweep of the endothelial-activation threshold (a proxy for the ability to activate the endothelial inflammasome) can be seen in Figure 4; these simulations were all carried out with an Initial-Inoculum = 150 in order to depict the greatest impact of varying this parameter. Figure 4 demonstrates that progressively increasing the threshold for endothelial-activation towards levels seen in the bat (= 10) in otherwise human-parameterized versions of the CBIABM shows increased resistance to viruses. However, while the human-parameterized version with bat-level endothelial activation threshold is substantially more resistant, it still does not match the resistance level in the bat-parameterization. While this suggests that the other features of increased bat tolerance to viral infection do play a role in reducing the manifestation of disease in bats, the considerable reduction

in population disease severity seen only by reducing endothelial inflammasome activity points to it as a potential impactful mechanism for bat viral tolerance.

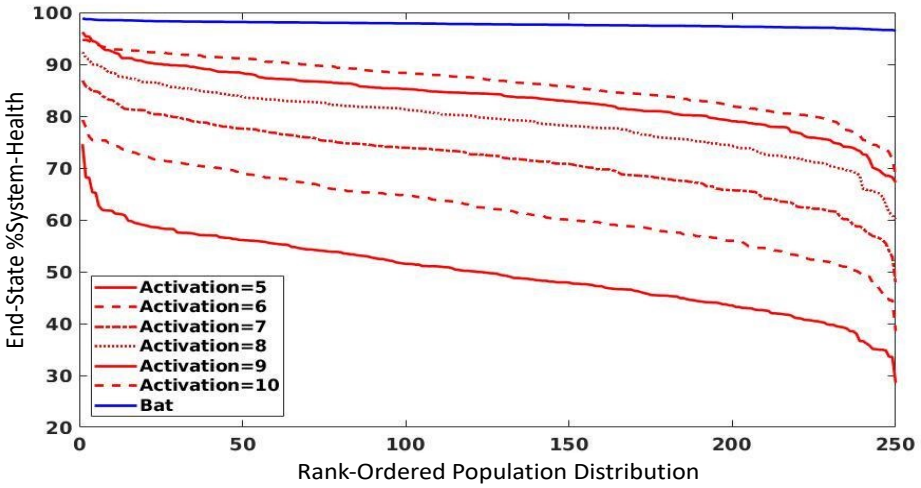

Figure 4. Parameter sweep if Endothelial-Activation threshold level from baseline human-parameterization (=5) to baseline bat-parameterization level (=10) with Initial-Inoculum = 150. Endothelial-Activation threshold reflects the ability to activate the endothelial inflammasome, with subsequent effects (adhesion activation and PAF production) that recruit circulating PMNs to the area of activation. There is a progressive reduction in the degree of tissue damage/disease severity across simulated populations (stochastic replicates n = 250) with increasing Endothelium-Activation thresholds (simulating decreasing endothelial inflammasome activation), though even when the Endothelium-Activation threshold is at the same level (=10) between the bat- and human-parameterizations, there is still an increased tolerance of the bat versions to viral insult.

The last set of simulation experiments are intended to investigate the potential stress-related causes of viral spill-over in bat populations, a presumed process involved in the zoonotic transfer that can lead to pandemics [5]. We translate the more general concept of "stress" into a representation in metabolic terms, and therefore represent increased stress level by increasing the Metabolic-Byproduct variable in the CBIABM. We performed a parameter sweep of this value, Metabolic-Byproduct, starting from the value in the baseline bat-parameterization (=2.0, itself a 10x increase over the human-parameterization) and increasing it by increments of 1; as with the parameter sweep for Endothelial-Activation all these simulations were run with an Initial-Inoculum = 150. The results of this parameter sweep can be seen in Figure 5, with progressively worse %System-Health population distributions with increasing values of Metabolic-Byproduct (e.g. increasing stress). We believe that increased manifestation of disease/disease severity for equivalent degrees of viral exposure would lead to increased viral shedding and lead to viral spillover and increase the chance for the viral spillover that could lead to zoonotic transfer.

Discussion

The recent viral pandemics involving Ebola, SARS, MERS, and, most recently and dramatically, SARS-COV2/COVID-19, has placed focus on bats as a zoonotic reservoir for viruses that are candidates to drive the next pandemic. In particular, the unique physiological adaptations for flight seen in bats has led to interest on the intersection of the ability of bats to deal with the metabolic consequences of flight and their noted viral tolerance, with resulting insights into how those adaptions have manifested in differences in their innate immune response and dampened

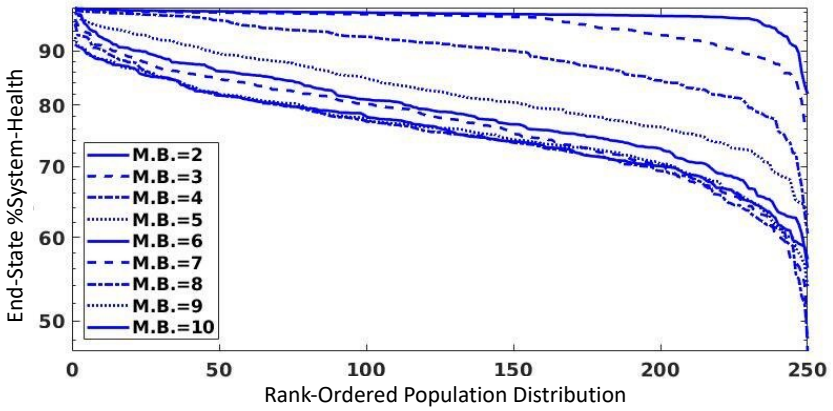

Figure 5. Parameter sweep of Metabolic-Byproduct (M.B.), a proxy variable for stress in the CBIABM. The value for M.B. in the baseline bat parameterization is itself a 10x increase of the same term in the human-parameterization, reflecting the increased metabolic stress from powered flight. Increasing M.B demonstrates a progressive worsening of the population distribution of %System-Health, which we consider a pre-condition for increase viral shedding. Interestingly, the decreasing %System-Health seen with increasing M.B appears to converge monotonically.

inflammatory response to cellular injury. This finding is of particular importance in understanding the potential pathophysiological manifestations should bat-borne viruses acquire the ability to infect human tissues, as there is compelling evidence that clinical disease severity in viral infections is heavily driven by the human host's inflammatory response (e.g. "cytokine storm") [6, 44-48]. This has led to a great deal of interest in studying particular molecular components (the inflammasome [6]) and cellular functions (pyroptosis [23]) that can lead to increased inflammation and more severedisease. While most recent work has understandably focused on COVID-19/SARS-COV2, the role of inflammation-induced collateral tissue damage is a shared feature of many viral infections [6, 44-48]. We pose that developing response capabilities to future pandemics should identify countermeasures focused on conserved mechanisms that drive viral disease severity. Such therapeutic countermeasures aimed at disease mitigation would fill a gap between public health non-pharmacological interventions (i.e. contact/transmission limiting strategies) and virus-specific modalities such as vaccines or new therapeutics that target virus-specific mechanism of infectivity; despite the impressive and unprecedented success and rapidity of COVID-19 vaccine development, it is difficult to imagine how such modalities could be made available is less than a year. More generic pandemic countermeasures would target shared mechanisms of viral pathophysiology, of which inflammation-propagating mechanisms represent a particularly attractive target for disease severity mitigation. Towards that end, we would also pose that understanding how viral tolerance evolved and manifests in bats can produce insights into how targeted therapeutic immunomodulation can mitigate the severity of viral infection.

We further contend that there is a potentially significant role for mathematical and computational modeling in the execution of comparative biology. Currently, comparison from species to species is primarily descriptive; while there may be some intuitive impression about how such differences may manifest, there is a lack of formalized or explicit representations of those impressions that can allow for rigorous interrogation of what are admittedly highly complex systems. Detailed mechanism-based computational models can serve as explicit representations of specific hypotheses that can then be executed (as with any other experimental object) and subjected to simulation experiments where their behavior can be evaluated [11]. While there has been interest in developing

mathematical models of bat in-host viral dynamics (see [12] for a recent review), to our knowledge the CBIABM is the first computational model that explicitly represents the molecular processes that distinguish between bat and human viral tolerance. With detailed models such as the CBIABM not only can imputed differences between species be explicitly represented there is also a concurrent explicit representation of what is conserved from one context (be it a species or an individual) to the next. This capability also addresses a critical gap in the practice of biology, because as with the descriptive nature of differences between organisms/species, what is similar between organisms/species is often informally assumed (e.g. the justification for using wet lab experimental models), but not rigorously and formally represented or evaluated.

The current version and associated experiments with the CBIABM represent how such a process might work. We make no claim that the CIABM is a comprehensive representation of either the bat or human immune system, nor even that it completely describes all the known features associated with bat viral tolerance. Rather, the CIABM is an explicit representation of a specific set of hypotheses related to a specific set of mechanisms proposed as being important in characterizing the difference between viral tolerance in bats and humans. As such, the CBIABM is not expected to be able to model a clinical disease course; it does not contain features, such as the adaptive immune system, that are known to play an important role in human disease, nor is it able to generate higher-order phenomena, such as vital signs or organ function, normally used to characterize disease. However, conversely, despite its abstraction the CBIABM is a complex model (see Figure 1) and does represent a fairly large list of known mechanisms identified through experimental biology. As such, the CBIABM can address questions about the role of those specific mechanisms it does incorporate, a capability that is not present in more "theoretical" mathematical models that abstract away such detail so they may be more analytically tractable.

One example of an insight gained from this type of complex modeling is the potential role of the endothelial inflammasome as both a feature that distinguishes between bat and human viral tolerance and as a potential therapeutic target in treating viral diseases. Most interest in the inflammasome has been understandably focused on its manifestation in immune cells; this is reasonable since immune cells are the cellular effectors of the immune/inflammatory response. However, our simulations with the CBIABM show that in order to reflect the differences between bat and human responses to viral infection it is insufficient to only focus on the immune cells. Comparison between bat and human parameterizations using only differences in immune cell inflammasome activity were able to generate some differences in viral tolerance, but not at the known differences between bat and human metabolic rates (x10 fold more in bats); see Figure 4. Alternatively, the endothelium is well recognized as playing a role in the acceleration of local tissue inflammation to systemic disease [27], but without a more "complicated" modeling context the impact of this feature on how bats maintain viral tolerance would not be appreciated. In our review of the literature we were not able to find any studies examining bat endothelial inflammasomes but given the ubiquity of inflammatory cell adhesion and trafficking, we make the assumption that such molecular endothelial-mediated mechanisms do exist and, given the reduced inflammatory cell inflammasome activity seen in bats, that such a reduced activity would also be present in the inflammasome in other cell types. At the very least, the results of these simulations represent a testable hypothesis should such experiments be ever carried out. In terms of potential therapeutic targets, while the endothelium in COVID-19 has received considerable attention, given that the receptor target for the SARS-COV2 spike protein is present in vascular tissue and given the clinically reported hypercoagulable complications (e.g. inappropriate clot formation) seen in COVID-19, most proposed therapies target the down-stream process of coagulation [49]. Alternatively, our comparative biology simulations suggest that a specific molecular mechanism/module, the endothelial inflammasome, could be a more general

functional reason for why local viral infections become systemic, and could potentially provide an area for investigating and developing more generalizable therapeutic agents.

We accept that there are limitations of the current version of the CBIABM. The CBIABM lacks representation of the adaptive immune response, which does not allow the CBIABM to replicate clinical disease dynamics and associate meditator time-series data. This in turn and limits the ability to use the CBIABM as a test platform for discovering new therapeutic control strategies, which is one of the most potentially impactful roles for complex mechanism-based simulation models [50-52]. We will also incorporate more sophisticated representations of "stress," such as the role of emergence from hibernation and the effect of co-infections on viral spillover. We further recognize that the current set of simulation experiments do not fully explore the different parameter combinations that might lead to the differences between viral tolerance phenotypes, with implications on the relative roles and contributions for cell-specific inflammasome activity and T1IFN anti-viral functions. To address this we will adapt the CBIABM to our developed pipeline for utilizing machine learning and artificial intelligence methods to refine model rule and parameter space while encompassing biological heterogeneity [53]. This approach, in concert with the modular structure of the CBIABM will also allow future developments that include the implementation of virus-specific properties and functions related to invasiveness, replication and countermeasures to anti-viral mechanisms, and the ability to represent differences in inflammasome suppression seen across various bat species [54].

In summary, we believe that there is considerable benefit in the comparative biology study of the differences between bats and humans with respect to viral tolerance, and that these investigations can provide invaluable insights that may help our preparations for the inevitable "next pandemic." We also believe that comparative computational models with sufficient complexity and representation of biological mechanisms, such as the CBIABM, can serve as important adjuncts to help inform and integrate more traditional experimental and investigatory methods and help our ability to develop biological countermeasures that could mitigate the health and societal impact of future pandemics.

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