

Essay

On the evolutionary epidemiology of SARS-CoV-2

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There is no doubt that the novel coronavirus SARS-CoV-2 that causes COVID-19 is mutating and thus has the potential to adapt during the current pandemic. Whether this evolution will lead to changes in the transmission, the duration, or the severity of the disease is not clear. This has led to considerable scientific and media debate, from raising alarms about evolutionary change to dismissing it. Here we review what little is currently known about the evolution of SARS-CoV-2 and extend existing evolutionary theory to consider how selection might be acting upon the virus during the COVID-19 pandemic. Although there is currently no definitive evidence that SARS-CoV-2 is undergoing further adaptation, continued evidence-based analysis of evolutionary change is important so that public health measures can be adjusted in response to substantive changes in the infectivity or severity of COVID-19.

Zoonotic pathogens, which have jumped from animal to human hosts, can result in enormous public health challenges because so little is known about the pathogen during the initial stages of an outbreak. The most important public health intervention for such pathogens is therefore to suppress transmission as much as possible. The current COVID-19 pandemic, caused by the SARS-CoV-2 coronavirus, provides a stark example. Wide-scale shifts in human social networks, from restrictions on travel to lockdowns of entire cities or countries, have been critical for slowing the pandemic and reducing the number of deaths.

Because zoonotic pathogens are often poorly adapted following a host shift, it is also natural to ask how they will evolve in response to their novel human host and to medical and public health interventions. Examples where some evidence exists for adaptation following host shifts include myxoma virus in rabbits and avian flu, Ebola, and Zika virus in humans [1]. With SARS-CoV-2, we might also expect further adaptation to its human host. For example, although SARS-CoV-2 is already able to bind the ACE2 receptors critical for entry into human cells, computational models and data have identified additional mutations that might further strengthen binding affinity [2].

In this essay, we explore the evolutionary potential for SARS-CoV-2, guided by available data and evolutionary models. At present, there is a lack of compelling evidence that any existing variants impact the progression, severity, or transmission of COVID-19 in an adaptive manner. Models, however, indicate that natural selection can be strong and act on diverse aspects of SARS-CoV-2 as it spreads in its new human host. We argue for developing better strategies to detect, verify, and respond to evolutionary changes in the virus that have important effects on human health and disease spread. Doing so will enhance the set of tools at our disposal for implementing effective public health measures.

Current empirical evidence SARS-CoV-2 emergence

The growth of the human population has led to an increasing number of human-wildlife interactions, facilitating the movement of pathogens from animal hosts to humans (zoonoses) [3]. Viral spillover to a new species requires either pre-adaptation or rapid evolution of the proteins that dock and allow entry into new host cells. For SARS-CoV-2, six amino acids in the receptor-binding domain of the spike protein are critical for binding the host target receptor ACE2 and allowing infection in humans [4]. These critical spike protein residues are not all present in the most closely related coronavirus

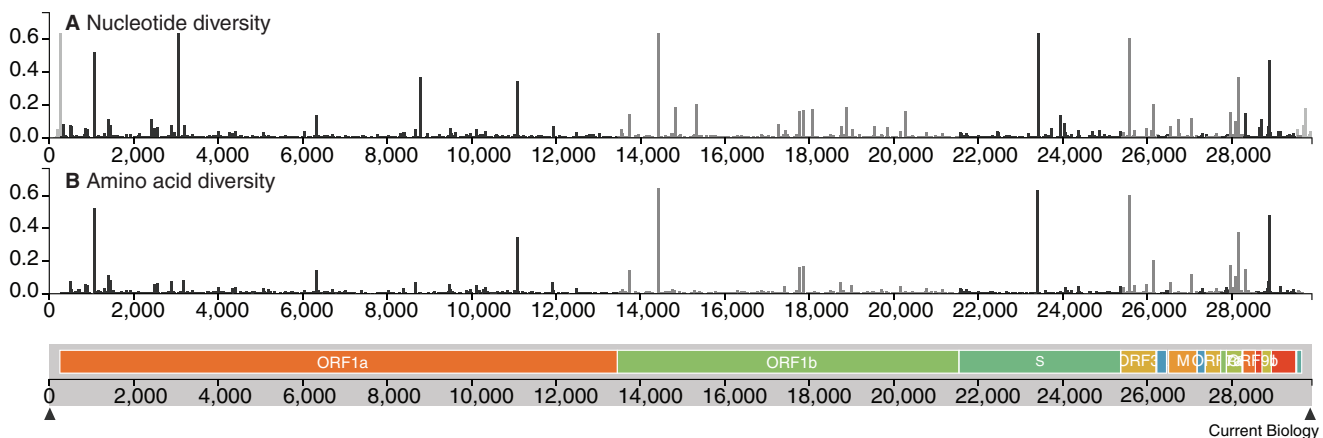


Figure 1. Variability among SARS-CoV-2 genomes.

Genetic diversity segregating among SARS-CoV-2 genomes (from Nextstrain [8]). Horizontal axis is genomic location and vertical axis is entropy, an information-based measure that highlights sites exhibiting the most genetic variation: (A) at the nucleotide level, (B) at the amino acid level.



Box 1. Searching for adaptive mutations in SARS-CoV-2.

Within weeks after the initial reports emerging from Wuhan, China, of a new respiratory illness in December 2019, scientists had already started searching for signatures of adaptation to humans within the genomes of SARS-CoV-2. One of the earliest studies to appear identified two strains of SARS-CoV-2 circulating in Wuhan (strains ‘L’ and ‘S’) and suggested that they had functional consequences, with the former being more ‘aggressive’ [5]. This claim was widely picked up in the media and led to considerable speculation that evolutionary change could result in COVID-19 becoming more severe. However, this inference was based solely on the frequencies of the two variants, and the stochastic occurrence of mutations on the basal branches of a star-like phylogeny for a spreading disease can fully account for the frequency data [10]. The original authors have since acknowledged this more parsimonious explanation [5].

Similarly, a recent study [37] found that the non-synonymous mutation D614G in the spike gene (see peak in ‘S’ in Figure 1B) has been increasing in frequency in multiple countries. This pattern is expected if the mutation is selectively advantageous, but it can also be explained by purely neutral sampling processes. Even without selection, a parallel increase in the frequency of a mutation across multiple countries is expected if new disease outbreaks are first seeded by travelers from a geographic location with a low mutant frequency (for example, China) followed by travelers from a location where the mutation is (by chance) at a high frequency (such as Italy). It is important to assess the plausibility of such neutral explanations before drawing any conclusions. Korber *et al.* [37] also looked for corroborating evidence of selection in both hospitalization rates and viral load, but only the latter was associated with genotype and, even then, factors like days since symptom onset (a major determinant of viral load [21]) were not controlled and may have changed over time as testing became more available. Several groups are currently investigating the impact of D614G on SARS-CoV-2, at both the functional and epidemiological levels, and this will shed light on the selective importance of this mutation.

Another genetic change that has received media attention involves a 382 nucleotide deletion in ORF8 found in multiple COVID-19 patients in Singapore. Although no direct evidence exists that this deletion was positively selected, similar deletions have been found in other coronaviruses, including SARS variants that arose during the 2003–2004 outbreak [38]. Experiments in cell culture demonstrated that one of these earlier SARS deletions reduced the rate of viral replication [39]. The repeated appearance of such deletions is intriguing, but direct evidence is needed to link such deletions to disease outcomes and/or transmission rates.

Finally, [40] used sister clade comparisons to examine whether any of 31 specific mutations identified in the SARS-CoV-2 genome, including the D614G mutation mentioned above, are associated with an increased transmission rate. Their results show that most mutations are found in clades that, if anything, are associated with reduced transmission, concluding that there is no evidence for positively selected alleles. However, sister clade comparisons lack power and are biased against finding derived characters that boost the growth of a lineage.

Definitive conclusions await further monitoring and testing, accounting for the null expectations with a rapidly expanding zoonotic disease.

identified to date, RaTG13, sampled from the horseshoe bat, *Rhinolophus affinis* (RaTG13 and SARS-CoV-2 are 96% similar at the nucleotide level), but they are found in coronavirus sampled from pangolin [4]. The SARS-CoV-2 genome shows no evidence of recent recombination, arguing against a recombinant origin involving pangolin [5,6]. Given the

poor sampling of coronaviruses from wildlife and the wide range of animals with similar ACE2 receptors (including pigs, ferrets, cats, and non-human primates [2]), it is likely that we simply have not identified the most closely related animal source [4], making it impossible to know what evolutionary changes happened immediately prior to or during the transition to humans.

Genetic variation in SARS-CoV-2

Clues to the history of a disease can be obtained from its phylogenetic tree. Within humans, SARS-CoV-2 displays a star-like phylogeny with many long-tip branches [7], as expected in a growing population. Based on genomic sampling over time, the substitution rate is estimated to be 0.00084 per site per year (www.nextstrain.org [8]; 16 May 2020), 2- to 6-fold lower than the substitution rate for influenza (0.004–0.005 substitutions/site/year for influenza A and 0.002 substitutions/site/year for influenza B in the haemagglutinin gene [9]). Across its ~30,000-basepair genome (Figure 1), SARS-CoV-2 thus undergoes roughly one genetic change every other week.

Genomic tracking tools like Nextstrain [8] allow us to analyze genetic variants very rapidly, as soon as their sequences become available during an outbreak. Figure 1 illustrates the nucleotide variation among the 5,380 genomes available on May 16, 2020 (Figure 1A). Several of these are nonsynonymous and thereby alter the amino acid composition of viral proteins (Figure 1B).

Although Figure 1 reveals substantial genetic variation in SARS-CoV-2, it is unclear if these changes have any functional significance. Many are likely neutral or slightly deleterious to the virus [5,10], having risen in frequency by chance when carried to new susceptible hosts. Mutations with no functional significance readily fluctuate in abundance, acting like genomic fingerprints that can be used to track viral geographic spread and to reconstruct epidemiological dynamics (for example, see May 8, 2020 Situation Report on international spread from Nextstrain). In the long run, deleterious mutations are expected to be eliminated, as seen in genetic comparisons between more distantly related coronavirus lineages [6]. However, even deleterious mutations can rise in abundance during an epidemic as long as their effective reproduction number remains larger than one.

More controversial is whether any of the nonsynonymous variants circulating in humans increases viral fitness. Box 1

describes four of the most prominent studies about suspected adaptive SARS-CoV-2 mutations and the reasons for caution.

Natural selection on SARS-CoV-2

Even though the adaptive significance of genetic variants remains to be established, we can use evolutionary theory to gain insights about how natural selection might act on disease characteristics. Modeling SARS-CoV-2 is currently challenging because we lack crucial information. For example, the fraction of cases that are asymptomatic, the relative infectiousness of asymptomatic individuals, and how these vary with age are not yet well understood. We therefore first explore a general model, without specifying the exact parameter values. We then illustrate the dynamics using parameter values consistent with available data.

An extensive body of theory has been developed to understand the short- and long-term evolution of pathogens [11–15]. There are two types of pathogen traits whose evolution is usually distinguished: antigenic traits and disease life-history traits [15].

Antigenic evolution refers to the appearance and spread of viral genotypes that can escape existing immunity in the population [16]. For example, continued antigenic evolution is the reason why seasonal influenza vaccines must be periodically updated – the influenza virus eventually evolves so much that it escapes the immune response induced by the vaccine [17]. In the case of SARS-CoV-2, where no natural immunity previously existed [18] and no vaccine is yet in widespread use, natural selection for antigenic escape mutations will be very weak. Modeling protective immunity and escape mutations will, however, be an important step for future theory if SARS-CoV-2 becomes endemic to the human population.

Disease life-history evolution refers to the appearance and spread of genotypes that cause different disease characteristics [19]. For example, the transmission rate of the virus, the length of the asymptomatic period that it causes, and the mortality induced by the infection are

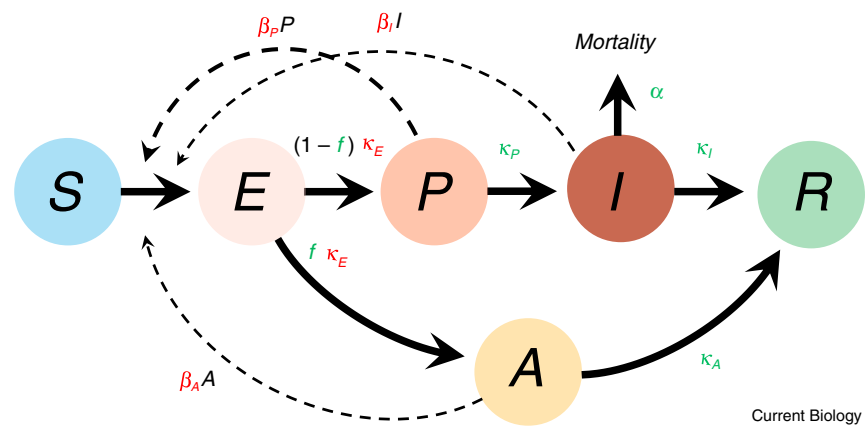


Figure 2. Epidemiological model for COVID-19.

Susceptible individuals, S , enter the exposed class, E , upon infection after contact with infected individuals (as indicated by dashed curves, with transmission rates β_j). A proportion of new infections, f , remain asymptomatic, A , whereas the remainder become pre-symptomatic, P . The latter eventually progress to the symptomatic stage, I , and die from the disease at rate α (referred to as ‘virulence’). All other individuals eventually recover, R , and are assumed to be immune. Transition rates between disease classes are denoted by κ_j . As shown in the Supplemental Information, selection acting on these traits favors increased transmission and a briefer interval between exposure and infectiousness (red parameters are selected to increase). Selection also favors mutations that keep individuals in the infectious stage longer (green parameters are selected to decrease), including reduced virulence. As long as pre-symptomatic and symptomatic individuals are the major source of new infections, selection also favors a reduction in the proportion of asymptomatic individuals (f).

all disease life-history traits. As will be shown, these traits can be under strong selection, even for emergent diseases that are spreading rapidly in immunologically naive populations.

Modeling epidemiology

To make predictions about the evolution of pathogens, we must consider the potentially complex interaction between epidemiological and evolutionary dynamics. An important starting point is therefore to develop an appropriate model for the epidemiology of SARS-CoV-2.

Data from multiple countries suggest that the median duration of time between infection and the onset of symptoms (that is, the incubation period) is approximately 5 days [20]. Also, infectiousness has been inferred to start ~2.5 days before symptom onset, with high transmission prior to the onset of symptoms [21]. Viral loads then drop after symptom onset, halving within ~2–4 days [21]. Together these results suggest that there is both an exposed but non-infectious stage and a pre-symptomatic stage that is highly infectious. Once infected, individuals either recover with

relatively little medical intervention, or they progress to more severe disease and suffer a higher mortality rate. The overall case fatality for symptomatic individuals is estimated to be 1–2% [22], and the mean length of time from symptoms until death is approximately 18 days [23]. Finally, some infected individuals remain asymptomatic throughout the course of infection. Based on a systematic review, Buitrago-Garcia *et al.* estimate that 29% of cases remain asymptomatic (95% CI: 23–37%) but note that this may be an overestimate due to publication biases and the requirement for at least one asymptomatic individual in many of the studies [24]. Regarding the source of new infections, their review suggests that pre-symptomatic cases account for about 40–60% of new infections, with <10% from asymptomatic individuals and the remainder from individuals who have developed symptoms [24]. As they highlight, these numbers remain highly uncertain. Figure 2 captures these key qualitative features of COVID-19, as we understand it, and can be used to examine the epidemiology and

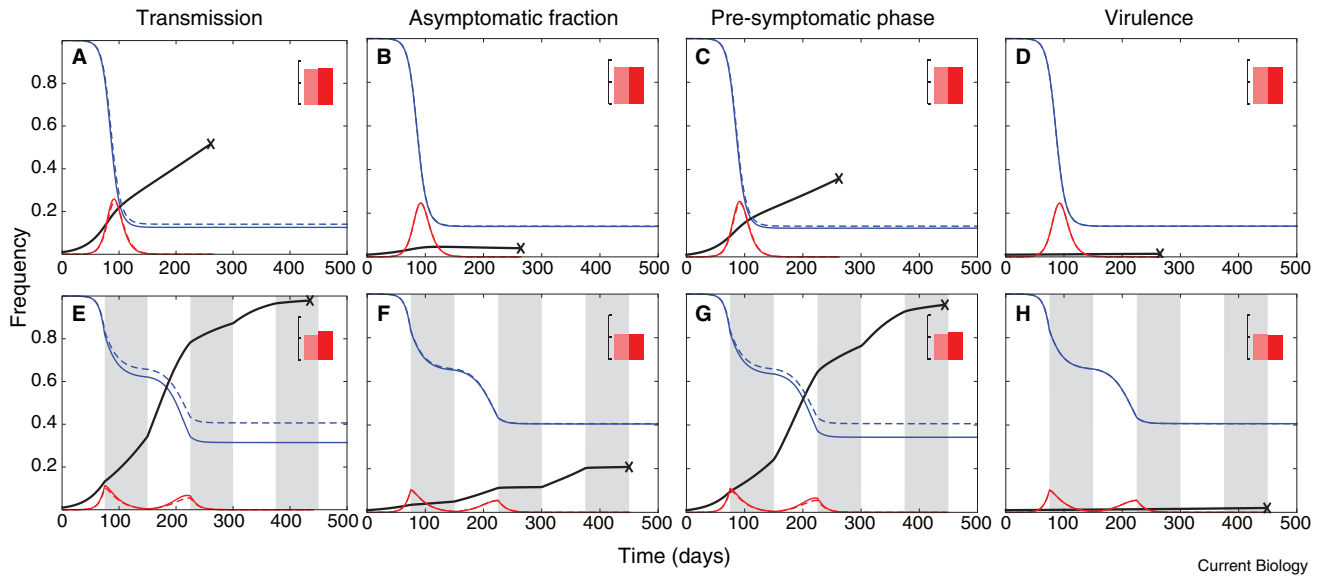


Figure 3. Simulations of SARS-CoV-2 evolution without pleiotropy.

Evolutionary and epidemiological dynamics of a mutation that only affects a single trait, either in the absence (top panels) or presence (bottom) of periodic social distancing. Parameters of the resident virus (r) are chosen to be roughly consistent with available data: $\beta'_s = 3\beta'_i = 10\beta'_a = 1$, $\kappa'_e = 0.25$, $\kappa'_s = 1$, $\kappa'_i = 0.2$, $\kappa'_a = 0.11$, $f' = 0.2$, and $\alpha' = 0.005$. This yields a basic reproduction number $R'_0 \approx 2.3$. A mutant allele increases transmission in panels (A) and (E) (all transmission rates multiplied by 1.2), decreases the fraction of asymptomatic cases in panels (B) and (F) ($f^m = 0.1$), progresses more slowly through the pre-symptomatic stage in panels (C) and (G) ($\kappa_p^m = 0.67$), and decreases virulence in panels (D) and (H) ($\alpha^m = 0$). In the latter case, mutants that reduce mortality do spread, but selection is very weak and the effects are hardly visible. Grey regions indicate periods of effective social distancing (all transmission rates are reduced by 60%). Curves show the numbers of infected (red) and susceptible individuals (blue), measured as a fraction of the initial number of susceptibles, as well as the frequency of the mutation (black). Solid curves are with evolution (dashed are without evolution, for reference). Inset bar chart shows cumulative deaths, with ticks at 1% intervals (pink, without evolution; red, with evolution).

evolution of SARS-CoV-2 across a range of plausible parameters (see Supplemental Information for details).

In Figure 3, we illustrate the epidemiological dynamics without evolution (dashed curves), using example parameter values. Without public health interventions (top panels) the rapid spread of SARS-CoV-2 generates a high prevalence of infections (red curves) followed by herd immunity, halting the local epidemic ('X'). In the bottom panels, we include periods of social distancing (grey regions), during which all transmission rates are reduced by 60%. Social distancing 'flattens the curve', prolonging the duration of the epidemic and reducing peak health-care demand. Even without accounting for the excess mortality that would result if hospitals became overwhelmed, social distancing also reduces the total number of deaths (compare inset bar heights in top and bottom panels). The reason is subtle. By reducing the height of the epidemic, public health measures reduce the

number of infected individuals at the point in time when there no longer remain enough susceptible individuals to sustain the disease, even without social distancing, thereby lowering the number of subsequent infections and deaths. In addition, public health measures buy time for effective treatments and vaccines to be developed, which would lower mortality even further than shown in the bottom panels.

Modeling evolution

We next use the model in Figure 2 to explore how SARS-CoV-2 might evolve by considering the fate of mutations that alter the viral life history traits (for example, transmission, disease progression, and/or virulence). Many functionally relevant mutations will be lost through stochasticity when they first arise, even if they are selectively advantageous. Indeed, the probability of a mutation escaping stochastic loss during the initial stages of an outbreak can be described by equation (S8) (in the Supplemental Information),

which depends on the mean, R_0 , and variance, σ^2 , in new infections caused by a single infected individual in a fully susceptible population (R_0 is sometimes called the 'reproduction number'). The spread of SARS-CoV-2 is highly variable, with some cases leading to many new infections and others to none. Assuming the mutant R_0 is similar to that of the wild-type R_0 (estimated to be ~ 2.5 [25]), the probability of escaping stochastic loss falls rapidly as heterogeneity in disease outcomes increases (for example, falling from 89% to 31% as the variance increases from 1 to 10 times the mean R_0). This result emphasizes the high degree of chance in the evolution of SARS-CoV-2.

In the Supplemental Information, we discuss the evolutionary dynamics of genotypes that avoid stochastic extinction. Figure 2 summarizes the resulting selection on each life history trait (derived analytically without specifying the parameter values, many of which remain uncertain). Of course, viral mutations can alter multiple traits simultaneously through

pleiotropy. For example, mutations that increase viral replication rate might affect transmission rate (the β s), the rate of disease progression (the κ s), the fraction of asymptomatic cases (f), and/or virulence (α). The summed effect of selection on all such traits governs the fate of the mutant, as described by equation (S6) in the Supplemental Information.

Some intuition for the general results derived in the Supplemental Information can be obtained by considering the special case where individuals with symptoms are immediately isolated and where asymptomatic individuals do not contribute to new infections (so that β_i and β_a are negligible). In this case (and assuming a very transient exposed class), evolutionary change is driven by selection on the pre-symptomatic class, as they are then the major source of new infections. We can then describe the dynamics of a mutation using a single equation for the change in q_p (the fraction of pre-symptomatic infections that harbour the new mutation):

$$dq_p/dt = sq_p(1-q_p) \quad (1a)$$

where $q_p(1-q_p)$ represents the 'genetic variation' and s the 'selection coefficient' given by:

$$s = S(1-f)\Delta\beta_p - S\beta_p \Delta f - \Delta\kappa_p \quad (1b)$$

(see Supplemental Information). Here, $\Delta\beta_p$ is the difference in pre-symptomatic transmission rate between the new mutation and wild-type, Δf is the difference in the fraction of asymptomatic individuals, and $\Delta\kappa_p$ is the difference in the rate at which pre-symptomatic individuals develop symptoms. Given that the 'genetic variance' in equation (1) is positive, the mutation will increase in frequency as long as its 'selection coefficient' is positive; that is, if it transmits better, leads to fewer asymptomatic cases, remains infectious longer, or some combination of the three.

We next use these results to examine the nature of selection acting on the life history traits of SARS-CoV-2. We start by considering selection acting on each life history trait on its own and then explore how mutations that affect multiple traits will evolve. Throughout, we use the full model, with selection described by equation

(S6) in the Supplemental Information, using the special case represented by equation (1) only to help explain the results. The accompanying *Mathematica* package provides all code and explores a range of parameters to confirm the robustness of the illustrated results (available from DRYAD: <https://doi.org/10.5061/dryad.5hqbzkh3g>).

Transmission rates

Selection favors genotypes that have a higher transmission rate, when considered as a trait on its own (no pleiotropy), with the strength of selection for increased transmissibility being proportional to the density of susceptible hosts, S . This result holds generally (equation S6) and can be seen most clearly in equation (1). This means that selection for genotypes that have a higher transmission rate will be strongest in dense populations with a large number of immunologically naive individuals [11,13,14], a prediction that has been verified experimentally in other systems [26,27].

Public health interventions, like social distancing, will typically reduce the rate of contact among individuals and so reduce the transmission rate of all genotypes. As a result, social distancing will decrease the $\Delta\beta$ s (for example, by 60% in Figure 3E) and so will weaken selection for increased transmission rates. That said, because social distancing will maintain a large population of susceptibles, S , for longer, this epidemiological feedback will increase the average strength of selection over the outbreak. In addition, social distancing spreads infections out over a longer period of time (that is, it flattens the curve). This, in turn, allows selection to act over a longer time period, resulting in a larger cumulative amount of evolution (Box 2). Overall, adaptive mutations therefore typically reach a higher final frequency with social distancing than without (compare black curves in Figure 3A,E), although the net effect depends on the details.

Evolution, in turn, can affect the epidemiology of the disease, both in terms of infection prevalence (compare cumulative effects on the remaining number of susceptibles in Figure 3E with and without evolution, solid and dashed blue lines, respectively) and

the cumulative number of deaths (inset bars in Figure 3E with and without evolution, red and pink, respectively). The public health importance of any evolutionary change depends also on the mutation's effect size; illustrated is a mutation that increases transmission by 20%.

Finally, some mutations may become more strongly selected in the presence of social distancing if they allow for viral transmission despite the intervention (for example, mutations affecting aerosolization or persistence in the environment). Other interventions, like rapid contact tracing and testing, essentially eliminate some transmission chains, but we would not expect this to affect the strength of selection among untraced cases, as long as genotypes are equally likely to be traced.

Asymptomatic infections

How selection acts on the proportion of asymptomatic cases, f , depends on the source of most new infections. Based on current estimates [24], <10% of new infections originate from asymptomatic individuals. As long as asymptomatic individuals play a smaller role in transmission than individuals who will develop symptoms, selection will favor a reduction in number of asymptomatic cases (lower f ; Figure 3B,F). In technical terms, as long as the 'reproductive value' of infections proceeding through the asymptomatic route in Figure 2 is lower than that for individuals who will eventually develop symptoms (see Supplemental Information), selection acts to lower f , because doing so increases the overall transmission of the virus. This result can be seen most clearly in equation (1) but holds in the full model as well (equation (S6)).

Equation (1) also reveals that the strength of selection on the fraction of asymptomatic cases is proportional to the density of susceptible hosts, just as with selection on transmission. As a result, selection for genotypes that produce a lower fraction of asymptomatic infections will also be strongest in dense populations with a large number of immunologically naive individuals.

Public health measures aimed at isolating people once they develop symptoms will weaken this selection,

Box 2. Evolution and flattening the curve.

The key public health interventions used against COVID-19 focus on reducing contact rates, isolating travelers and sick individuals, and contact tracing. These interventions aim to reduce transmission (the β s) and ‘flatten’ the trajectory describing the time-course of infections or, even better, squash it to zero. These interventions are essential for health care systems to manage the influx of cases and to save lives.

Flattening the epidemic curve has a secondary effect though: by prolonging the duration of the epidemic, it increases the time period over which evolutionary change accumulates. As seen in Figures 3 and 4 (compare top and bottom panels), these interventions often result in a greater total change in gene frequency. This finding is perhaps not as obvious as it first seems. Evolutionary adaptation requires that new infections be generated and old ones lost at rates that differ among genotypes. Thus, it seems reasonable to expect that the cumulative amount of evolutionary change in gene frequency that occurs over an epidemic is positively related to the total number of new infections that occur (that is, the outbreak size). And since public health interventions typically reduce outbreak size, we might expect them to also reduce the total amount of evolution. However, this is not true. The rate of evolution is determined by the difference in growth rate of infections carrying the two different alleles (this is the selection coefficient in equation (1)), whereas the total outbreak size is determined by the values of these growth rates themselves. This is what evolutionary biologists refer to as the distinction between relative *versus* absolute fitness. So interventions like social distancing that flatten the curve can slow the rate at which an epidemic grows without slowing the rate at which evolution occurs. Because such interventions typically extend the duration of the epidemic, all else equal, they will thereby result in a greater total amount of evolutionary change. Of course, all else need not be equal, because social distancing can also affect the strength of selection (see main text). The net outcome will therefore depend on the balance of these effects.

In addition, reducing the total number of infections will reduce the input of SARS-CoV-2 mutations, and thus slow adaptation, especially if complex mutations underlie fitness gains. Furthermore, even if rapid epidemics end the potential for evolution locally (see ‘X’s in Figures 3 and 4), evolution will continue globally as long as SARS-CoV-2 is still circulating in the human population. To determine the net impact of public health measures on evolutionary change in this context requires models that consider the appearance of mutations and their geographic spread.

by reducing the reproductive value of infections leading to symptoms. The direction of selection will remain the same, however, as long as more infections arise from pre-symptomatic individuals than asymptomatic individuals.

That said, the conclusions of this subsection are those that are most subject to change in light of new data, because the reproductive values of the different infection routes strongly depend on how much time each class is infectious and on the relative transmission rates from asymptomatic, pre-symptomatic, and symptomatic cases, for which we lack direct estimates (see Supplemental Information). Also uncertain is whether genetic mutations are available to the virus

that could alter the fraction of asymptomatic cases, which may depend more on characteristics of the host at the time of infection (age, health status, etc.).

Disease progression

Natural selection generally favours a lengthening of the pre-symptomatic phase (that is, smaller values of κ_p), including mutations that reduce the morbidity of the disease so that people remain less aware of their symptoms. Simply put, the longer the pre-symptomatic period, the longer the duration over which the virus can transmit (Figure 3C,G).

Whereas the special-case model without any disease class structure (equation (1)) suggests that selection on the length of the pre-symptomatic

class should be insensitive to the number of susceptible individuals and the extent of social distancing (which do not affect the length of the pre-symptomatic phase, $\Delta\kappa_p$), the full model is sensitive to both (for example, see social distancing effect in grey regions, Figure 3G) because of changes to the reproductive value of the pre-symptomatic class relative to the other types of infected individuals. In addition, by flattening the curve, public health measures allow selection to act over a longer period of time (Box 2). Thus, mutations that increase the length of the pre-symptomatic phase reach a higher frequency under social distancing (compare black curves in Figures 3C,G).

Disease virulence

In general, disease-induced mortality, α , is selected to decrease (Figure 3D,H; Supplemental Information), when considered as a trait on its own (no pleiotropy). However, this selection tends to be weak because most individuals with COVID-19 recover and the costs of mortality are paid only late in the course of the disease, after substantial transmission has already occurred (in the pre-symptomatic and early symptomatic phases). This can be seen most clearly in equation (1) where we have assumed that only pre-symptomatic individuals transmit. In that case, selection on virulence is entirely absent.

Again, public health measures change how natural selection acts upon SARS-CoV-2. In particular, the widespread recommendation to self-isolate once symptoms appear has likely weakened direct selection against virulence, although this effect must be small given that direct selection against virulence was already weak (as seen in Figure 3D,H). Moreover, the benefits of self-isolation in terms of disease containment massively outweigh the small potential costs of reduced selection against virulence (compare inset bar charts in Figure 3D,H).

Pleiotropic mutations

Viral mutations that affect the course of the disease will often impact more than one life-history trait. The fate

of such pleiotropic mutations will depend on the sum of the selective effects on each trait (equation (S6)). Furthermore, accurate predictions about the evolutionary future of SARS-CoV-2 require data about the impact of mutations on viral dynamics, viral load, and disease progression within an individual and how these relate to the life history traits governing the spread of the pathogen. In the absence of such data, modeling can help guide our understanding about the range of possibilities.

A crucial question is how virulence will evolve [28]. As discussed above, direct selection on virulence is weak (Figure 3D,H). Thus, virulence evolution will be driven largely by the indirect effects of pleiotropy. In Figure 4, we consider two potential examples. First, consider mutations that couple a higher transmission rate, the β s, with higher mortality, α (positive pleiotropy, Figure 4A,C), as might occur if mutations increase viral replication rates. In this case, evolution will lead to higher mortality (see inset bars), as an indirect consequence of selection for increased transmission (see Supplemental Information and also [12,29]). Alternatively, consider a mutation that alters tissue tropism such that the disease tends to preferentially infect cells of the upper respiratory tract, rather than the lower respiratory tract. Such infections could lead to a higher transmission rate but be less virulent (negative pleiotropy) [30]. This would generate indirect selection for lower mortality rates (Figure 4B,D).

Of course, pleiotropy may link virulence evolution with any of the life history traits of SARS-CoV-2. For example, selection to prolong the infectious stage, the κ s, might reduce virulence as a side consequence (for example, if a weaker immune reaction is elicited). Or selection for more symptomatic cases (lower f) may lead to a pleiotropic increase in virulence. Pleiotropy is hard to predict, which is why it is not possible to say with any confidence whether evolution of SARS-CoV-2 will translate into meaningful effects for patients (positive or negative) or for the spread of the disease.

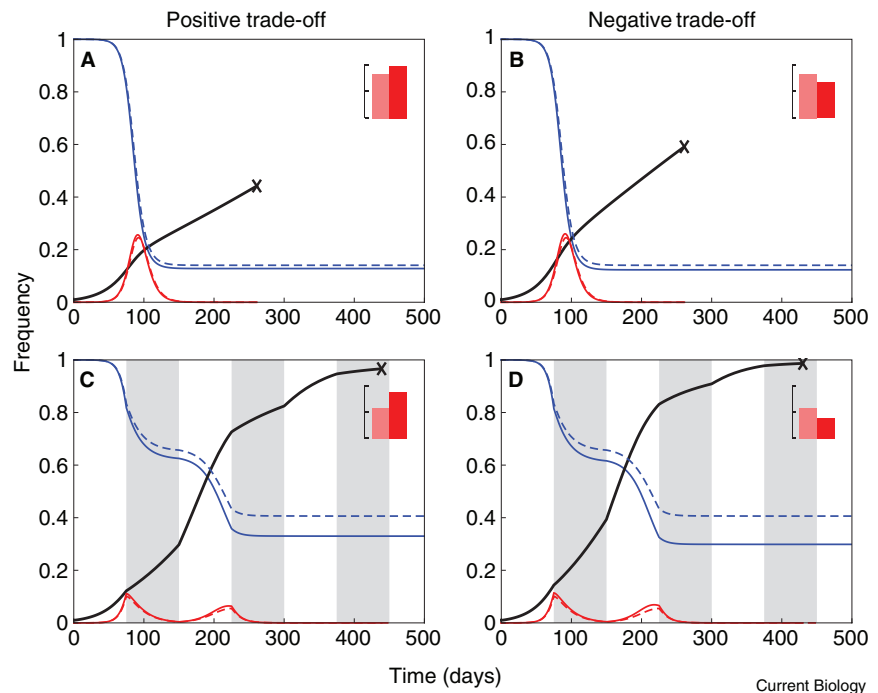


Figure 4. Simulations of SARS-CoV-2 evolution with pleiotropy.

Evolutionary and epidemiological dynamics of a mutation with pleiotropic effects on both transmission (all transmission rates multiplied by 1.2) and virulence, either doubling virulence ($\alpha^m = 0.01$, panels (A) and (C)) or eliminating it ($\alpha^m = 0$, panels (B) and (D)). See Figure 3 for additional details.

Conclusion

In the midst of the COVID-19 pandemic, there is great uncertainty about the course of the disease, and this uncertainty is heightened by concerns about how the virus might evolve (Box 3). It would be surprising if no mutations were available that could increase fitness of SARS-CoV-2 in its novel human host. But considering the array of life history traits under selection and the myriad ways that mutations can link these traits (Figure 2), it is difficult to make clear predictions for the impact on disease. Before we incorporate evolutionary considerations into mitigation efforts — given the costs of mistakes both in human lives and in public health dollars — we must hold claims that a variant increases viral fitness to a high evidentiary standard. This requires both that neutral explanations be rejected and that a clear link be documented between the mutation and characteristics of the disease. To date, none of the SARS-CoV-2 variants reported have met this standard (Box 1).

Of course, the absence of evidence is not the same as evidence of absence. At present, we know very little about the scope for adaptation or the functional significance of existing genetic variants. This knowledge gap is exacerbated by the lack of accessible data linking disease outcomes with genetic variants. The fact that the virus already displays effective human-to-human transmission might mean that there is little opportunity for further adaptation. Likewise, the low mutation rate of SARS-CoV-2 compared to influenza suggests that it may evolve more slowly in response to selection, although the relative rates of evolution depend too on how many sites are targeted by selection (SARS-CoV-2's genome is double the size of influenza A's). On the other hand, we also know that the virus often fails to infect close contacts [31], suggesting that there is ample scope to increase transmission further. Moreover, the large number of viruses circulating within a patient implies that every possible genomic mutation is likely to

Box 3. Take home messages.

- The RNA virus SARS-CoV-2 is genetically variable, but there is currently no conclusive evidence that existing variants affect viral fitness or disease progression.
- Claims of positive selection must be tested against null models that account for the stochasticity of disease spread and founder events, which can mimic the action of selection.
- Modeling reveals how selection would act on SARS-CoV-2 mutations that alter viral transmission, disease progression, disease severity, or combinations of these traits.
- Direct evidence linking mutations to disease characteristics is needed before evolutionary ideas can guide public health interventions.
- If functional differences are verified, rapid typing would allow limited resources for mitigation measures to be tailored and targeted most appropriately.

arise over the course of an infection (based on a median estimate of 100,000 viral copies per mL of saliva [32]). Thus, adaptation in response to strong selection for survival and transmission in human hosts could occur very rapidly and may have done so when it first switched into humans.

This paper is intended to provide a framework for thinking about the potential evolutionary routes that SARS-CoV-2 might take and to dispel some of the current misinformation that is circulating in the media. For example, in the absence of pleiotropy, the mortality rate due to COVID-19 is actually either selectively neutral or selected against. Furthermore, selection for increased transmission rate is at its strongest during the initial phase of an epidemic, when spread is exponential, even though one might initially think that selection would be stronger later, when host immunity is more widespread. Our analysis also shows that selection likely favors viruses that progress slowly towards disease and whose symptoms remain mild for longer, because such viruses will be transmitted more before people are aware that they are infected.

This contrasts with Ebola, where a major transmission route is contact with the dead, a situation that may strongly select for greater virulence [33,34]. On the other hand, if transmission is pleiotropically coupled with faster rates of viral replication, and the latter leads to greater virulence, then selection for more efficient transmission could result in

an evolutionary increase in virulence (as illustrated in Figures 4A,C).

As with any theoretical analysis, our predictions rely on some biologically informed simplifications. For example, we have neglected within-host evolution, the roles of age and spatial structure in the transmission process, and the potential importance of host genetics in disease susceptibility. Likewise, we have largely ignored the influence of stochasticity, despite the fact that chance events — like founder effects, genetic drift, and super-spreading — can be particularly important in emerging diseases. It is also important to emphasize that much remains unknown about SARS-CoV-2. As our understanding of the virus improves and new data emerge, it will be possible to refine predictions and explore other scenarios for the short- and long-term evolution of viral traits. Experimental data using cell lines and animal models will help reveal the pleiotropic effects of mutations in SARS-CoV-2. Phylogenetic methods will help reveal which, if any, genetic changes have been driven by positive selection. Such methods include classic approaches searching for sites that undergo amino acid changes more often than expected (for example, [35]), as well as newer methods that use the shape of the phylogeny to infer the effect of genetic variants on transmission rates and virulence [36]. A key challenge for future studies is to determine whether inferences are robust to the extreme stochasticity we are seeing with COVID-19, where

travelers seed infections on different dates from different sources, where a carrier can pass the virus on to dozens of individuals or to none, and where human behavioral responses vary widely in space and time.

A more powerful method to detect the functional importance of mutations would be to leverage the enormous world-wide effort to sequence SARS-CoV-2 genomes. We recommend that metadata be sought when viral samples are collected that provide information about disease outcomes (time since symptom onset, severity of symptoms at time of sampling) and, where available, with data on hospitalization rates, death rates, and transmission (if contact tracing is conducted). Relating genomic variants with patient health and epidemiological data is the most direct way to establish whether mutations are functionally important or not (as recently investigated by [37] using hospitalization data). These data are also needed to apply many of the new phylogenomic methods, as argued by [1].

Finally, if functionally important mutations are verified, how might this then inform intervention strategies? Although the answer to this question will depend on the details, it can be helpful to consider a few possibilities to reinforce the value of tracking evolution during a pandemic. If a variant is found to be more transmissible, then its spread could be mitigated by directing limited public health resources to populations in which this variant is most strongly selected (that is, dense, immunologically naive populations). Likewise, by using PCR tests to distinguish functionally important variants, public health officials could know which variants are circulating in their communities, which would allow them to loosen or tighten social interventions where milder or more severe forms arise. By knowing which variant a patient carries, doctors could also then adjust drug regimens, applying them earlier and/or more aggressively in higher risk situations (personalized medicine). Even intentional inoculations are possible if a particularly mild variant is discovered. But first we need to know

which, if any, variants are functionally important to COVID-19, with direct evidence linked to health outcomes.

SUPPLEMENTAL INFORMATION

Supplemental Information includes methods, discussion and references and can be found with this article online at <https://doi.org/10.1016/j.cub.2020.06.031>.

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AUTHOR CONTRIBUTIONS

All authors contributed equally. Authorship is alphabetical.

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