

Review

Within-Host Evolution of Human Influenza Virus

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The rapid global evolution of influenza virus begins with mutations that arise *de novo* in individual infections, but little is known about how evolution occurs within hosts. We review recent progress in understanding how and why influenza viruses evolve within human hosts. Advances in deep sequencing make it possible to measure within-host genetic diversity in both acute and chronic influenza infections. Factors like antigenic selection, antiviral treatment, tissue specificity, spatial structure, and multiplicity of infection may affect how influenza viruses evolve within human hosts. Studies of within-host evolution can contribute to our understanding of the evolutionary and epidemiological factors that shape influenza virus's global evolution.

Why Study How Influenza Viruses Evolve within Human Hosts?

Influenza viruses evolve rapidly on a global scale [1–4], and this evolution begins with mutations that arise *de novo* within infected hosts (Figure 1). As influenza viruses replicate during an infection, they quickly mutate [5–9] to form genetically diverse populations [10–13]. A small proportion of within-host variants transmit and found a new infection [14–16], and of those, a small number of variants may eventually fix in the global population of influenza viruses. Influenza virus's evolution at the within-host scale is important because it provides the substrate for global evolution.

How do influenza viruses evolve within human hosts, and how does this within-host genetic variation give rise to influenza virus's rapid global evolution? Within hosts, influenza viruses infect heterogeneous cell populations that are arranged in complex spatial structures [17,18]. Viruses encounter innate immune defenses, such as mucus barriers and interferon responses [19], as well as adaptive immune responses, such as antibodies that accumulate over the lifetime of the host [20,21]. In some cases, influenza viruses also encounter antiviral drugs such as adamantanes and oseltamivir [22–24]. These factors can shape how influenza viruses evolve within humans as well as what viral variants arise and eventually transmit from one individual to another [25].

In this review, we summarize recent progress in understanding how and why influenza viruses evolve during the course of an infection, and how evolution within human hosts relates to the virus's global evolution. High-throughput sequencing now makes it possible to “deep sequence” the viral population within a host to measure genetic diversity, so we begin by surveying current deep-sequencing methods and their limitations. We then present studies that use deep sequencing to assess viral genetic variation during acute human influenza A infections as well as during chronic influenza infections in immunocompromised human hosts. We consider how factors such as antigenic selection, antiviral treatment, tissue specificity, spatial structure, and multiplicity of infection may shape how influenza viruses evolve within hosts. Finally, we discuss how this within-host diversity might relate to global evolution.

Highlights

Influenza viruses experience selection at the within- and between-host evolutionary scales.

Deep sequencing measures the genetic diversity of influenza viruses within human hosts.

Influenza virus accumulates relatively little diversity within typically short, acute human infections, although it can undergo substantial evolution during long-term human infections.

Influenza viruses replicate in a heterogeneous, spatially structured environment within hosts.

Transmission bottlenecks limit the genetic diversity that is passed from human to human.

Evolutionary and epidemiological factors shape how the within-host diversity of influenza virus relates to its global genetic change.

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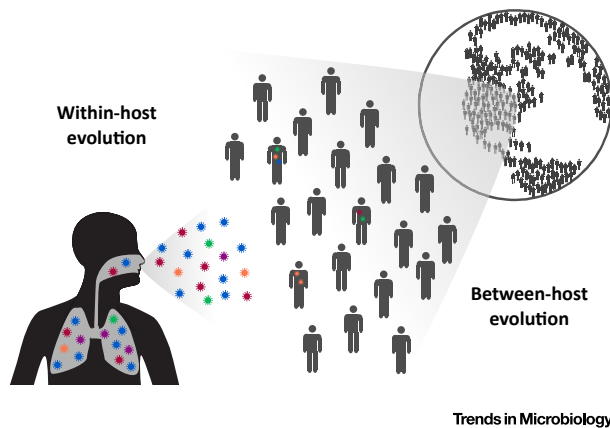


Figure 1. Within- and Between-Host Evolutionary Scales. The rapid global evolution of influenza virus begins with *de novo* mutations that arise within individual infected hosts.

How Is Deep Sequencing Used to Measure Within-Host Viral Diversity?

Traditionally, the viral population within an influenza infection is summarized as a single consensus sequence, representing the most frequent nucleotide at each genome position. For instance, public databases contain tens of thousands of influenza virus sequences, nearly all of which are consensus sequences [26–28]. But in reality, each influenza infection generates a genetically diverse cloud of viral variants that are formed through *de novo* mutation, and variants can also be transmitted from host to host [10–13,29]. Most mutations in a viral population are expected to reach very low frequencies (Box 1), and very few of these viral variants ever reach majority status in an infection. But the genetic *diversity* within an infection can reveal important evolutionary dynamics — and provides the material on which Darwinian selection can act.

Recent advances in high-throughput sequencing have made it possible to assess mutation frequencies and measure within-host genetic diversity (Figure 2A) [30,31]. Common deep-sequencing approaches can detect viral mutations above frequencies of approximately 1% in the total within-host viral population [32,33], though it remains difficult to determine linkage among these mutations [30,31]. But, despite its power, deep sequencing is subject to important technical limitations that are essential to consider when designing experiments and analyzing data [31–33].

Experimental Design

A fundamental challenge of viral deep sequencing is the fact that, in clinical samples, viral genetic material is often dwarfed by that of the host and co-occurring microbes. To compensate, most studies rely on PCR amplification to enrich for viral genetic material [32,34–36]. This amplification is relatively straightforward for the influenza-virus genome, which contains conserved regions at the ends of each gene segment [37]. Following reverse transcription, the entire genome can be amplified using a single set of PCR primers complementary to these conserved regions [38–40] or a primer cocktail that is complementary to the conserved regions along with noncoding sequence specific to each gene [35,37].

Various aspects of the sample and its preparation affect how accurately deepsequencing measures the actual viral variant frequencies within an infected individual [31–33,41,42]. Of these factors, the most important by far is viral load (Figure 2B) [32,43]. During whole-genome

Box 1. Within-Host Diversity of Influenza Viruses under Neutral Evolution

How much genetic diversity is expected to arise as influenza viruses replicate within human hosts? In evolutionary biology, it can be useful to estimate what variation would be observed if all mutations were purely neutral. Simple frameworks that model neutral evolution can establish basic expectations, even though purifying and positive selection clearly affect the mutation frequencies observed in real infections.

In human hosts, influenza virus populations expand exponentially at the beginning of an acute infection. Viral titers peak 2–4 days after the infection's start, and afterwards, titers decline for 3 or 4 days until the virus reaches undetectable levels [57,108]. Mutations that arise early in the exponential expansion can reach high frequencies through Luria-Delbruck dynamics [109].

To estimate how many mutations are expected to reach detectable frequencies under neutral evolution, we use the stochastic birth-death model proposed by Bozic *et al.* to describe how neutral mutations accumulate as cells expand clonally during cancer evolution [110]. In this model, a viral population begins with a single starting genotype, although natural human infections begin with anywhere from one to several hundred initial genotypes [62,61]. Viruses reproduce at rate b and leave the population at rate d . Neutral mutations occur at a rate of u mutations per genome per replication cycle, and all sites are completely linked. Bozic *et al.* demonstrate that the expected number of mutations m above frequency α is:

$$m = \frac{u(1-\alpha)}{(1-\frac{d}{b})\alpha} \quad [1]$$

We estimate b and d using Beauchemin's and Handel's models of influenza-virus kinetics within human hosts [108]. If influenza viruses expand exponentially with rate $b-d$ for the first phase of the infection and then decline exponentially with rate d after viral titers peak, then we estimate $b \approx 5.7/\text{day}$ and $d \approx 3.2/\text{day}$. Most studies in cell culture estimate mutation rates ranging from 10^{-6} to $10^{-5}/\text{site/generation}$ depending on the type of mutation and exact method of estimation [5–8], although one recent study estimates a higher rate of $10^{-4}/\text{site/generation}$ [9]. These per-site mutation rates correspond to $u \approx 0.013$ to $u \approx 1.3$ across the 13 kb viral genome. Since the number of expected mutations is directly proportional to the viral mutation rate, this variation has a large effect on estimates of genetic diversity (Figure 1).

Future work that refines estimates of mutation rate would help to establish more confident expectations about within-host viral diversity. It will also be important to develop models with more realistic assumptions about initial within-host genetic diversity, as well as how purifying and positive selection would affect this variation. By comparing these models with empirical observations, we can improve our understanding of how influenza viruses evolve within human hosts.

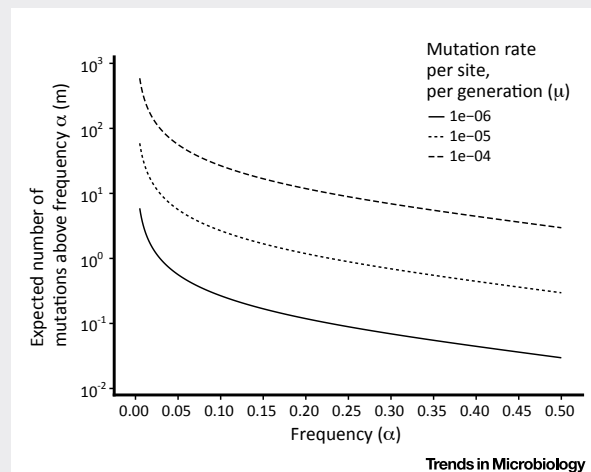


Figure 1. Expected Number of Within-Host Variants m above a Given Variant Frequency α under Neutral Evolution. Expectations are displayed for different values of the per-site, per-generation mutation rate μ , which is multiplied by the number of base pairs in the genome of influenza virus to obtain the per-genome mutation rate u .

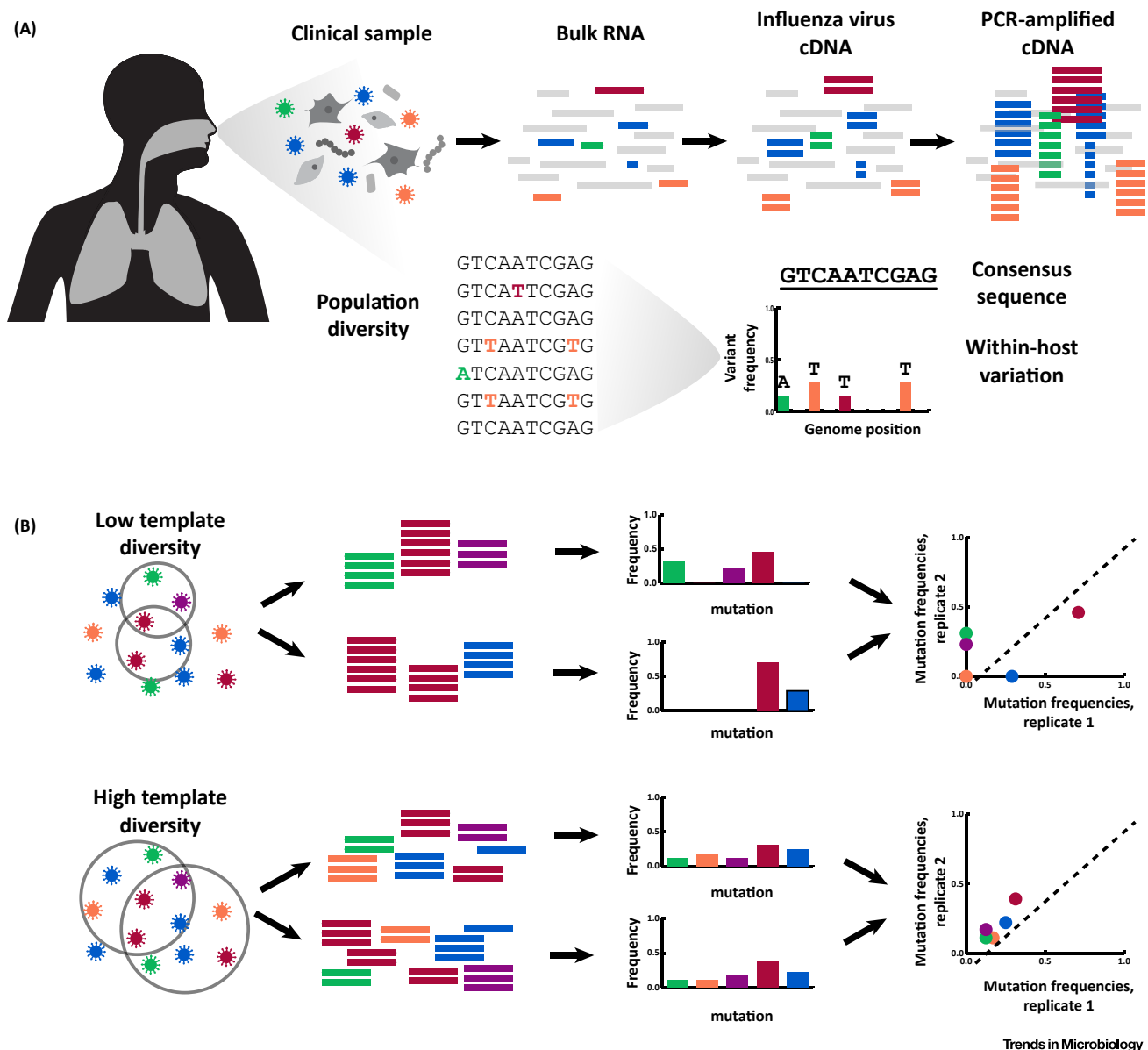


Figure 2. Deep-Sequencing Approaches to Measuring Within-Host Genetic Diversity. (A) Common deep-sequencing workflows can identify variants that make up approximately 1% of the within-host population. (B) Most studies amplify viral genetic material prior to deep sequencing. Low template diversity, typically due to low viral load, can distort the variant frequencies measured by deep sequencing. Replicate libraries are important for identifying and excluding samples with low viral load that should be excluded from downstream analyses.

amplification, anywhere from 20 to 35 cycles of PCR may be required to produce sufficient material for sequencing. When the number of starting viral template molecules is low, below about 1000 copies per μl total RNA [32], this amplification can significantly distort variant frequencies [32,43,44]. By comparison, errors that accumulate during reverse transcription, PCR, and Illumina sequencing have smaller effects for samples with typical low viral loads [32,43].

It is therefore essential to maximize the amount of viral genetic material used in each RNA extraction, reverse-transcription, and PCR reaction to ensure that deep sequencing accurately measures variant frequencies in the viral population. It is also important to prepare and sequence replicate libraries [41], preferably beginning from independent reverse-transcription reactions [32]. Replicate libraries make it possible to identify samples with low viral load [32,35] or effective sequencing depth [41] that should be excluded from downstream analyses (Figure 2B). They also make it possible to empirically set variant-calling thresholds and exclude specific low-confidence viral variants whose frequencies vary extensively between replicates in an otherwise high-quality sample [32].

Limitations

Deep sequencing can identify rare mutations in a viral population, but it has limited power to determine patterns of linkage between mutations, which can reveal patterns of epistasis [45] and clonal competition [35]. Short reads can sometimes reveal linkage between closely spaced mutations [35,46–48], but the reads produced by Illumina sequencing are unable to span even the smallest influenza-virus genes. Several groups have successfully assembled viral haplotypes and assessed their frequencies by combining low-coverage PacBio sequencing, which produces long reads, with high-coverage Illumina sequencing [36]. But even these methods cannot directly determine linkage between mutations on different gene segments, even though intergenic epistasis [49–52] and gene reassortment [53] both affect influenza-virus evolution. In the absence of sequencing data that directly observe patterns of linkage between mutations, computational methods can sometimes infer longer haplotypes by assembling multiple short-read haplotypes [30,31,45,48] and tracking concordant changes in allele frequencies between mutations located on different genes [45,48]. Even with current technical limitations, deep-sequencing approaches to measure viral variation can still shed light on important within-host evolutionary dynamics.

How Do Influenza Viruses Evolve within Human Hosts?

Several recent studies have used deep sequencing to characterize the spectrum of genetic diversity within natural human influenza A infections, and we summarize their findings here. Most studies focus on typical acute infections in immunocompetent hosts, but some studies also examine viral evolution during the lengthy infections experienced by immunocompromised patients.

Acute Infections

Viruses such as HIV and hepatitis C virus establish long-term infections and evolve over years or decades to avoid the immune system and develop antiviral resistance [54–56]. In contrast, influenza infections typically last 5–7 days, and viral shedding peaks 2–4 days after infections begin [57,58]. These short infections provide little time for *de novo* mutations to arise, for selection to act on these mutations, and for selected mutations to reach frequencies at which they are detectable by deep sequencing (Box 1).

Most studies of natural, acute influenza infections analyze one or two nasal swab or nasal wash samples from each patient by deep sequencing the hemagglutinin gene [59,60] or the entire viral genome [34,61,62]. The exact number of viral variants identified is highly dependent on sample quality and sequencing methodology. But several studies have observed relatively limited genetic diversity within acute human influenza infections [34,60,62], identifying fewer than ten variants per infection across the influenza-virus genome at a limit of detection of approximately 1–2% [34,62]. Most of these mutations are rare, present in less than 10% of the viruses within a host [34,60,62], and the number and frequency of within-host viral variants

does not seem to correlate with how many days postinfection the samples were collected [34]. However, some acute infections harbor high genetic diversity due to apparent coinfection by multiple, related viral strains [61,62]. One study has found evidence of mixed infections in approximately half of the patients sequenced [61], and the contribution of coinfection to within-host genetic diversity requires further careful study. Overall, the limited genetic diversity found in many acute human influenza infections agrees with prior studies, in dogs and horses, that sequenced viral clones to measure within-host viral variation [63–66].

It remains unclear what influences the patterns of observed variation, although we discuss potential biological factors below. Generally, within-host variants tend to be dispersed across the viral genome [34,62], though one study observed some low-frequency variation in putative antigenic sites [60]. Another study estimated that the ratio of nonsynonymous to synonymous within-host variants is about 0.64 and suggested that purifying selection removes some deleterious variants in human infections [62]. Even if most acute human infections do not contain high-frequency mutations, the sheer number of influenza infections every year may allow the rapid global evolution of influenza virus to arise from limited within-host genetic diversity.

Chronic Infections

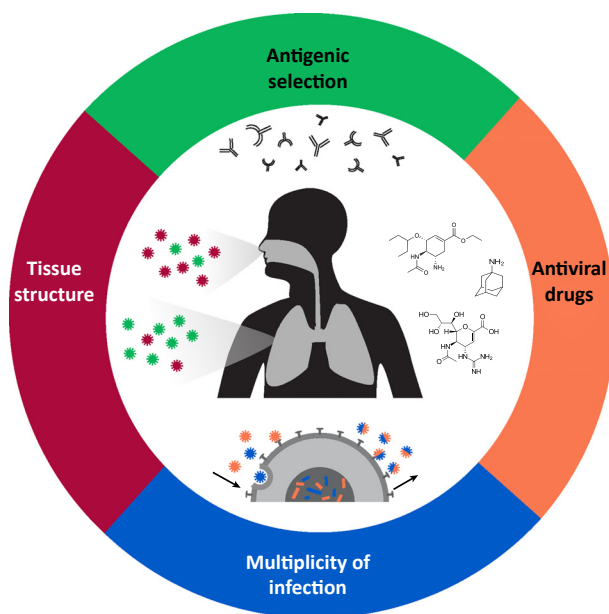
The vast majority of influenza infections are acute, but immunocompromised patients can experience severe infections lasting multiple weeks or months [67–69]. These chronic infections differ from acute infections in that host immune responses may be weakened or absent, infections are commonly treated with long courses of antiviral drugs, and influenza virus commonly co-occurs with other respiratory pathogens [67–69].

Nevertheless, chronic infections provide unusual opportunities to observe how influenza viruses evolve within humans over longer spans of time, when selection has more opportunities to shape viral variation. Immunocompromised patients often receive close clinical monitoring, and several studies have tracked within-host evolution longitudinally by deep sequencing clinical samples taken from different time points in an infection [35,36,70]. In these chronic infections, influenza viruses can display extensive evolution. Putative antigenic variants can arise and reach high within-host frequencies [35,71–73]. Multiple drug-resistant variants can also arise during these lengthy infections [35,36,70,73]. It is common for multiple beneficial mutations to compete with one another within a patient [35,36], displaying clonal interference dynamics commonly observed in experimental evolution [74–76].

The relatively weak immune responses mounted by immunocompromised hosts can have important evolutionary consequences, regardless of the exact underlying medical conditions. Small viral populations can survive and replicate in the presence of weak selection, making it easier for multiple adaptive mutations to emerge simultaneously [77]. In chronic influenza infections, relatively weaker immune responses can lead to much longer viral infections, enabling putative antigenic variants to arise in ways that sometimes parallel global evolutionary trends [35]. Overall, though, it remains unclear how much the evolutionary forces that act within chronic infections resemble selective pressures within more common, acute infections.

What Affects How Influenza Viruses Evolve within Humans?

Here, we consider evidence for how antigenic selection, antiviral treatment, tissue specificity, spatial structure, and multiplicity of infection may shape how influenza viruses evolve within humans (Figure 3).



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Figure 3. Factors Affecting the Evolution of Influenza Virus within Human Hosts. Antigenic selection, antiviral drugs, tissue structure, and multiplicity of infection can affect how influenza viruses evolve within hosts.

Antigenic Selection

Human influenza viruses undergo constant antigenic drift and occasional antigenic shift on a global evolutionary scale [20,78,79], but it is unclear how much immune selection takes place within a typical human infection. Recent deep-sequencing studies have identified few antigenic variants within acute infections [34,60,62], though it remains unclear whether antigenic variants are enriched or depleted relative to the frequency of within-host variants as a whole. In immunocompromised patients, putative antigenic variants can arise, display complex clonal dynamics, and even fix during an infection [35,71–73]. Some of the putative antigenic variants that arise in immunocompromised patients also reach a high frequency in the global population of influenza viruses [35].

Another source of antigenic selection might be vaccination, which boosts immune responses against influenza viruses. Two recent studies deep sequenced viral populations from vaccine recipients and control groups [34,60]. They found that vaccination status did not seem to affect consensus viral sequences, suggesting that infections in vaccinated individuals are not caused by specific resistant viral strains [34,60]. Moreover, they found that vaccination had no detectable effect on the number or population frequency of within-host variants [34,60]. One interpretation is that antigenic selection does not act detectably in most infections. An alternative explanation is that many unvaccinated individuals may already have strong immunity from natural infections, and vaccination may not alter immunity enough to exert additional antigenic selection.

Antiviral Resistance

Antiviral agents are used to treat only a minority of acute influenza infections, but they can still exert important influences on viral evolution [22–24]. For instance, many influenza A strains are resistant to adamantanes [24,80], and resistance to oseltamivir swept to fixation in seasonal

H1N1 influenza viruses before they were replaced by pandemic H1N1 [24,81,82]. For antivirals such as oseltamivir, where drug resistance is not yet widespread in current strains, influenza viruses can gain resistance within individual infections by acquiring one or more *de novo* mutations [24]. As with antigenic selection, it is unclear how frequently drug resistance arises within typical, acute infections. In one case report, resistance arose even when oseltamivir was used for prophylaxis [83], but deep sequencing of viral populations from 13 individuals in a human challenge study detected no drug-resistant variants following early or standard oseltamivir treatment [48]. There is ample evidence, however, that resistance can arise rapidly during longer infections [35,36,67–69,73,84,85]. In some cases, multiple drug-resistant variants may even compete within a single patient [35,36]. Since the mutations and molecular mechanisms underlying antiviral resistance are well established, antiviral resistance can serve as a useful comparison for studying how other selective pressures may act within hosts.

Tissue Specificity and Spatial Structure

Influenza viruses infect heterogeneous, spatially structured populations of cells in the human airways. Differences between tissues, along with neutral processes of migration and genetic drift, may have important effects on viral evolution. One major difference between the upper and lower human airways is their distribution of sialic acid receptors, which influenza viruses use to enter host cells. Most human influenza infections primarily take place in the upper human respiratory tract, which contains a higher proportion of α 2,6-linked sialic acids than the lower airways, which contain a higher proportion of α 2,3-linked sialic acids [17,18]. These histological differences may affect which viruses are transmitted. In ferrets, for example, viruses tend to transmit from the upper respiratory tract [15], and viral variants that preferentially bind to α 2,6-linked receptors transmit more frequently than variants that bind α 2,3-linked receptors [86]. This combination of spatial structure and tissue specificity provides one possible explanation for why avian-derived viruses, which tend to be adapted to the α 2,3-linked sialic acid receptors in avian airways, can cause severe, lower lung infections in humans but rarely transmit from one human host to another [17,18,87]. Within these two broad linkage categories, sialic acid chains also vary extensively in length and chemical linkages and are distributed differently in the airways of avian and mammalian host species, potentially affecting influenza virus binding [88–90].

Even in the absence of tissue-specific selection, spatial structure can also limit genetic exchange between different parts of the human airways. For instance, one case report of a human infection documented the presence of distinct viral populations in the right and left lungs [91]. More generally, though, no deep sequencing studies have systematically compared viral populations sampled from different parts of the human airways, and the extent of tissue-specific selection remains an important open question.

Multiplicity of Infection

Spatial structure affects how densely viruses populate different parts of the human airways, and in turn, this within-host multiplicity of infection (MOI) determines how often two or more viruses coinfect the same host cell. When multiple viruses coinfect the same cell, viral gene segments have an opportunity to reassort, and they do so readily in cell culture and animal models [53,92,93]. New combinations of gene segments are important for purging deleterious mutations in an otherwise clonal population and for forming new, potentially advantageous combinations between mutations [53]. It is usually difficult to estimate rates of within-host reassortment because current deep sequencing techniques are unable to establish linkage across multiple gene segments. But one group has developed a population-genetics framework to infer recombination from longitudinal, short-read sequencing data and estimated that

the rate of effective within-host reassortment is low in human infections [48]. Rates of effective reassortment may be low even when viral load is high because spatial structure limits viral exchange so that most coinfection and reassortment occurs between genetically similar viruses.

Viral coinfection also provides opportunities for genetic complementation, which can decrease the efficacy of selection. If a wild-type virus and a virus carrying a deleterious mutation coinfect the same cell, the progeny virions can package both viral genomes, allowing the deleterious mutation to persist. The effects of complementation are especially clear in cell culture, where most influenza viruses are grown to a high MOI: defective viruses that carry large gene deletions quickly arise and spread through the population [94,95]. Large internal deletions have been documented in human influenza infections [96,97], and studies of influenza outbreaks in pigs and horses have documented the transmission of nonsense variants as well [66,98]. However, the overall prevalence of defective viral particles and their association with infection length and severity remain poorly understood.

Altogether, studies in cell culture and animal models suggest various biochemical and morphological factors that may affect how influenza viruses evolve within human hosts, but few deep-sequencing studies so far have had the power to detect their effects. Additional sequencing of viral populations collected from different human hosts and tissues will improve our understanding of how influenza viruses evolve within a complex host environment.

How Does Influenza Virus's Diversity within Hosts Relate to Its Global Evolution?

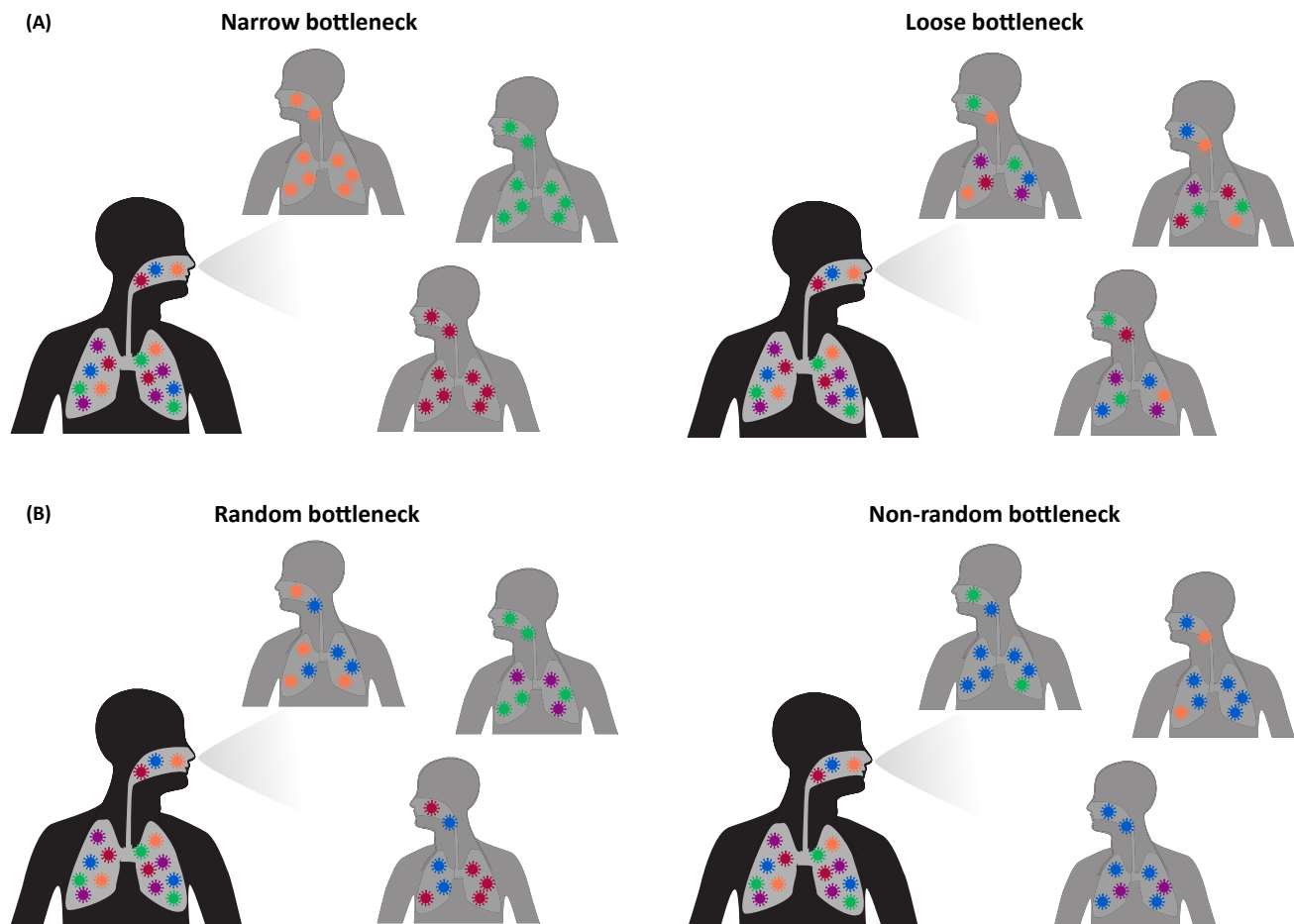
The within-host evolution of influenza virus ultimately provides the substrate for the virus's rapid global evolution, but the forces that transform within-host genetic diversity into global variation are largely unknown. Selection and drift can operate within hosts, but they also shape viral variation at transmission and at the host-population level.

Transmission

Only a small fraction of the influenza viruses within an infected individual go on to initiate subsequent infections (Figure 4). Transmission bottlenecks can limit the genetic diversity passed from one host to another and introduce stochasticity in variant frequencies along a transmission chain [29,62,61]. Transmission bottleneck sizes also affect how often genetically distinct strains of influenza virus infect the same individual [66,93], and looser bottlenecks increase the chance for beneficial reassortment [53,93].

Deep sequencing of contact and recipient viral populations can help estimate transmission bottleneck sizes in natural infections. Narrower transmission bottlenecks increase the variance with which viral variants are transmitted [99]. Animal studies suggest that vaccination status [64] and route of transmission [15,16] can affect transmission bottleneck size, which appears to be looser for direct contact than for aerosol transmission [15,16]. Studies of influenza outbreaks in pigs and horses have suggested that transmission bottlenecks can be loose, with frequent mixed infections [65,66,98].

In human influenza infections, few studies have had the power to estimate transmission bottleneck sizes, and the two recent studies to do so have disagreed considerably in their results. Poon *et al.* estimate a relatively loose bottleneck size of approximately 200 distinct genomes for both H3N2 and pandemic H1N1 influenza virus based on a household cohort study performed during the first wave of the 2009 H1N1 pandemic [61], and a recent reanalysis



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Figure 4. Transmission Bottlenecks Shape Viral Evolution. The size (A) and randomness (B) of transmission bottlenecks affect how much of the viral genetic diversity generated within one host survives to initiate another infection.

of the same data supports these estimates [99]. More recently, McCrone *et al.* used similar analytical methods to infer a very narrow transmission bottleneck of one or two distinct genomes in a household cohort study that primarily sampled seasonal H3N2 influenza viruses from 2010 to 2015 [62].

It is unclear what accounts for the differences between these two estimates, although differences in study populations may contribute. For instance, influenza virus transmission depends on temperature and humidity [100]. The Poon *et al.* cohort was recruited in subtropical Hong Kong, while the McCrone *et al.* cohort was recruited in temperate Michigan, in the northern USA. Moreover, the Poon *et al.* study recruited index patients with acute respiratory illnesses and then prospectively followed their family members, whereas the McCrone *et al.* study prospectively enrolled households and queried participants weekly about symptoms of illness. Furthermore, estimates of transmission bottleneck size may also be highly sensitive to sample quality, library preparation and sequencing methods, and variant-calling thresholds.

Most studies assume that transmission bottlenecks act neutrally, but certain influenza-virus variants may be more likely than others to transmit and found new infections. For instance, one ferret study found that transmitted viruses tended to preferentially bind α 2,6-linked sialic acid receptors and most closely resembled viral populations in the soft palate [86]. Selection can also affect maladapted strains of human influenza virus. In one recent human challenge study, volunteers were inoculated with viral stocks that had acquired passage-adaptation mutations during growth in eggs and cell culture. Many of these passage-adaptation mutations in the viral inoculum were purged from the viral population during or shortly after inoculation [101]. Selection may also act at transmission to promote global antigenic evolution if novel antigenic variants transmit and found new infections more frequently when host populations are mostly resistant to circulating strains. The strength and evolutionary effects of transmission bottlenecks remain important areas of study for understanding how the genetic diversity of influenza virus within hosts relates to its global genetic variation.

Comparing Evolutionary Scales

New mutations must arise and fix in individual hosts before they can spread through a large host population, linking within-host evolutionary dynamics to global evolution [102]. How do drift, positive selection, and purifying selection act within and between hosts? Studies of Ebola virus [103], Lassa virus [104], and dengue virus [105] have compared the proportions of non-synonymous to synonymous within- and between-host variants to argue that purifying selection acts at within- and between-host scales to eliminate deleterious variants. However, the d_N/d_S ratio was originally developed to compare fixed variation between distantly diverged lineages, and within-host population dynamics can complicate its interpretation [106,107]. In cases where longitudinal deep-sequencing data are available, standard population-genetics models can be used to infer the influence of selection upon particular variants based on the changes in their allele frequencies over time [45,46,48]. But for most studies of within-host evolution, which lack longitudinal data, it remains a major challenge to develop appropriate methods that make use of deep-sequencing data to distinguish what evolutionary forces act on viral populations within hosts.

Concluding Remarks

By studying how influenza viruses evolve within humans, we can observe what biological factors affect the virus within its natural host environment (see Outstanding Questions). We can also determine what evolutionary and epidemiological forces transform within-host genetic diversity into global viral variation. As deep sequencing makes it easier to survey genetic diversity within hosts, it will be important to develop methodologies to systematically analyze within-host evolutionary dynamics and their relationship to global evolution.

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Outstanding Questions

What experimental designs and analytical approaches best identify rare viral variants in clinical samples?

How much does host immunity shape within-host viral genetic diversity?

How do viral populations evolve in different parts of the human airways?

What is the effective multiplicity of infection within human hosts?

How often do related viral strains co-infect the same host?

How do transmission bottlenecks shape the genetic diversity of founding viral populations?

How does host population immunity help transform within-host viral diversity into global genetic variation?

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