Mammalian adaptation of influenza A(H7N9) virus is limited by a narrow genetic bottleneck

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Human infection with avian influenza A(H7N9) virus is associated mainly with the exposure to infected poultry. The factors that allow interspecies transmission but limit human-to-human transmission are unknown. Here we show that A/Anhui/1/2013(H7N9) influenza virus infection of chickens (natural hosts) is asymptomatic and that it generates a high genetic diversity. In contrast, diversity is tightly restricted in infected ferrets, limiting further adaptation to a fully transmissible form. Airborne transmission in ferrets is accompanied by the mutations in PB1, NP and NA genes that reduce viral polymerase and neuraminidase activity. Therefore, while A(H7N9) virus can infect mammals, further adaptation appears to incur a fitness cost. Our results reveal that a tight genetic bottleneck during avian-to-mammalian transmission is a limiting factor in A(H7N9) influenza virus adaptation to mammals. This previously unrecognized biological mechanism limiting species jumps provides a measure of adaptive potential and may serve as a risk assessment tool for pandemic preparedness.
In February 2013, avian influenza A(H7N9) virus crossed the species barrier in China and for the first time caused human infections. As of November 2014, 457 human infections had been reported, with a 30% case fatality rate. Epidemiological evidence has linked human cases with exposure to live-bird markets. Several sporadic clusters of H7N9 virus transmission among family members have been reported, however, as yet there is no evidence of sustained human-to-human transmission. Previous studies have shown that airborne H7N9 virus transmission can occur, albeit with low efficiency in ferrets, the standard model used to simulate transmissibility among humans. Several viral factors can contribute to the adaptability of avian-like viruses to mammals: virus morphology, receptor-binding specificity, changes in glycosylation patterns of the hemagglutinin (HA), polymerase activity, the acid stability of the HA, and the HA-neuraminidase (NA) balance. Variation in these traits may be controlled by only a few amino-acid substitutions in a virus genome. Only a few amino-acid changes are required to allow an avian-adapted virus to become airborne-transmissible between mammals, as was demonstrated in the influenza A(H5N1) viruses.

To elucidate the transmission dynamics and transmission barriers of the emerging H7N9 influenza viruses, we evaluated the replication efficiency, genomic diversification and host adaptation of A/Anhui/1/2013 (H7N9) influenza virus after the inoculation of chickens and ferrets and during ferret-to-ferret transmission. We provide evidence that H7N9 virus infection of chickens, while asymptomatic, promotes genetic diversity in the virus population, increasing the likelihood of substitutions that favour mammalian infection and transmission. Conversely, the virus shows poor airborne transmissibility and no evidence of further adaptation upon replication in ferrets, likely due to a narrow bottleneck constraining genetic diversification.

Results

Replication and genetic diversity in chickens. The H7N9 virus was isolated mainly from chickens in live-bird markets suspected to be the source of human infections. Thus, we investigated the virulence and replication of A/Anhui/1/2013 (H7N9), one of the first human H7N9 viruses isolated, in chickens. A/Anhui/1/2013 shares at least 99% identity at the nucleotide and protein levels with H7N9 influenza viruses isolated from birds and live-bird markets.

Table 1 | Titres of A/Anhui/1/2013 (H7N9) influenza virus in chicken oropharyngeal swabs.

| Dpi | No. shedding/total | Mean virus titre (log_{10}EID_{50} per ml ± s.d.) |
|-----|-------------------|---------------------------------------------|
| 3   | 4/4               | 3.75 ± 1.33                                 |
| 5   | 4/4               | 3.94 ± 1.54                                 |
| 7   | 2/4               | 1.50 ± 0.00                                 |
| 10  | 0/4               | <0.75                                       |

Dpi, days post inoculation; No., number.

Virus replication and transmission studies showed signs of illness or succumbed to infection, indicating an intravenous pathogenicity index of 0. We then determined the extent and duration of virus shedding in groups of four chickens inoculated with the A/Anhui/1/2013 virus via the natural routes (nares, trachea and eyes). Inoculated chickens showed no signs of illness but shed on average 3.75 log_{10}EID_{50} (50% egg infectious doses) per ml of virus from the upper respiratory tract at 3 days post inoculation (dpi), and shedding lasted for as long as 7 dpi (Table 1), suggesting that they can sustain H7N9 virus in the environment with little burden to their health. We then investigated the extent of genetic diversity of H7N9 viruses after replication in chickens. Deep sequencing of viral RNA from oropharyngeal swabs of inoculated birds revealed many synonymous and non-synonymous mutations (see ‘chickens’, Fig. 1a; Supplementary Data 1). All the gene segments except NS accumulated multiple amino-acid substitutions (Supplementary Table 2), although the HA genetic pool observed in the egg-grown parental stock was more or less maintained. The substantial genetic diversity, together with protracted asymptomatic virus shedding and close human-poultry contact in live-poultry markets, provide an optimal environment for the generation of viruses with the ability to infect humans.

Viral transmission and adaptation in ferrets. We next investigated the virus’s virulence and its transmissibility among ferrets via contact and airborne routes. Inoculated ferrets displayed only transient weight loss and fever (Supplementary Fig. 1) despite substantial (average 6.95 log_{10} TCID_{50} (50% tissue culture infectious doses) per ml of virus on 2 dpi) and protracted (maximum, 6 days) virus shedding from the upper respiratory tract, as determined in nasal washes (Fig. 2a). Lung virus titres peaked 5 dpi at an average of 10^{5} TCID_{50} per gram, indicative of substantial lower respiratory tract infection (Fig. 2d). Histological analysis revealed mild tracheitis, bronchitis with submucosal gland involvement and bronchoalveolar pneumonia (Fig. 3). Minor virus replication was detected in the brain and large intestine in one of the three inoculated ferrets (Fig. 2d). Virus was transmitted from inoculated (donor) ferrets to the cage-mates by direct contact (DC) within 1–2 days and to one of the four ferrets by airborne contact (AC) within 7 days (Fig. 2b,c). Virus titres and duration of shedding were comparable in ferrets infected by DC and AC. All the four DC ferrets and two of the four AC ferrets became seropositive (Supplementary Table 3). This limited mammalian transmission by respiratory droplets is consistent with epidemiologic reports of limited human-to-human transmission of H7N9 virus in only a few familial clusters and with data from other ferret studies.
Genetic diversity of H7N9 viruses in ferrets. To compare the genetic diversity generated during replication of H7N9 virus in a mammalian versus an avian host and to screen for selection of amino-acid substitutions after airborne transmission in mammals, we performed deep sequence analysis of viral RNA isolated from ferret nasal washes during both rounds of replication. Round 1 included ferrets and donor ferrets inoculated with parental A/Anhui/1/2013 (H7N9) influenza virus, while round 2 included other ferrets with airborne contact. Variation frequency was calculated using positions that are variable in at least one of the examined samples. Variation frequency was expressed as the negative log. *P<0.05, two-tailed Mann–Whitney U-test. P, parental virus; D, donor; DC, direct contact; AC, airborne contact.
of the experiments. Overall, viral RNAs from ferrets were significantly less diverse ($P<0.05$, two-tailed Mann–Whitney $U$-test) than those isolated from chickens (Fig. 1b, Supplementary Table 4, Supplementary Data 2) suggesting the existence of a constraint, or narrow bottleneck, in genetic diversification during replication in mammals. On comparing the genetic diversity of the surface glycoproteins, we found significantly less genetic diversity in the HA gene in ferrets than in chickens, but no significant difference between the diversity of the NA genes (Supplementary Fig 2). These results suggest that a strong purifying selection pressure was imposed on the HA gene during replication in ferrets. At the amino-acid level, four variant residues (PB1-D76N, NP-I365V, NA-E73K and NA-I300V; N9 numbering) occurred at a high frequency ($\geq 40\%$) in the AC isolate and were maintained in ferrets inoculated with AC virus (Supplementary Fig 3b,c and f), (Supplementary Table 5).

**Effect of selected substitutions on protein function.** We next examined the effect of substitutions present at high frequency after airborne transmission on virus polymerase and NA activity in vitro. In minigenome replication assays, the dual PB1-D76N and NP-I365V substitutions reduced the polymerase activity by 23%, but single substitutions had no effect (Fig. 4a). Overall, the polymerase activity of both the parental and mutant polymerase complexes was significantly lower at 33°C (human upper respiratory tract temperature) than at 37°C (avian upper respiratory tract temperature) despite the presence of the mammalian-adaptive PB2-E627K substitution\textsuperscript{27}. Reversing the substitution to the avian-like PB2-627E reduced polymerase activity markedly (to 6–8% of wild-type (WT) activity). The NA-I300V substitution reduced NA activity by 23% (by 33% when combined with NA-E73K) without altering its cell surface expression (Fig. 4b,c). The negative effects of these mutations on virus protein functions suggest that these residue changes...
either were present in the viral inoculum at low levels and their fixation during the transmission study was somewhat stochastic or that they had ‘hitchhiked’ along with adaptive mutations.

**Replication kinetics of recombinant viruses in vitro.** The observed reduction in polymerase activity in the minireplicon assay and the decreased NA activity in vitro suggests that an influenza virus carrying the identified amino-acid substitutions would be attenuated in cell culture. To assess this possibility we generated recombinant (rg) A/Anhui/1/2013 influenza viruses with single or multiple amino-acid substitutions in the gene/s of interest and compared their replication kinetics with the WT rg-virus in Madin Darby canine kidney (MDCK) cells. In line with expectations, the combination of these substitutions attenuates virus replication in vitro.

**Receptor-binding specificity.** We detected six variant HA residues (Supplementary Table 5) in the stock parental A/Anhui/1/2013 (H7N9) virus, including the L235Q mutation (L217Q in H3 numbering), which confers a human-to-avian shift in receptor-binding preference \(^{25}\). The frequency of the L235Q variant increased to \(~90\%\) in one chicken isolate but was undetectable in four of the six chicken specimens analysed. Conversely, and against expectations, the L235Q mutation increased (albeit slightly) in frequency in ferrets inoculated with the parental virus but decreased in frequency among the DC ferrets. This mutation became undetectable in the AC ferret and in ferrets inoculated with the parental virus but decreased in frequency among the DC ferrets. This mutation became undetectable in the AC ferret and in ferrets inoculated with the parental virus but decreased in frequency among the DC ferrets. This mutation became undetectable in the AC ferret and in ferrets inoculated with the parental virus but decreased in frequency among the DC ferrets. This mutation became undetectable in the AC ferret and in ferrets inoculated with the parental virus but decreased in frequency among the DC ferrets. This mutation became undetectable in the AC ferret and in ferrets inoculated with the parental virus but decreased in frequency among the DC ferrets. This mutation became undetectable in the AC ferret and in ferrets inoculated with the parental virus but decreased in frequency among the DC ferrets. This mutation became undetectable in the AC ferret and in ferrets inoculated with the parental virus but decreased in frequency among the DC ferrets. This mutation became undetectable in the AC ferret and in ferrets inoculated with the parental virus but decreased in frequency among the DC ferrets.

We then compared the binding preference of the parental and airborne-transmitted (AC) viruses to a wide array of glycans (Fig. 5). Both the viruses bound both avian (\(\alpha-2,3\)) and human
Avian-origin influenza viruses have the potential to cross the species barrier and cause influenza pandemics in humans, depending on their adaptive capacity. Our results are consistent with the hypothesis that the adaptive potential of the A(H7N9) virus population is limited by the loss in genetic variation from the tight genetic bottleneck imposed by selection in the mammalian host environment. For any given avian influenza virus, a combination of genetic traits must be selected to enable the adaptation to mammalian hosts. While a subpopulation of virions in a host may possess some of these factors,23,24, the genetic bottleneck imposed on the virus population remains a barrier to the selection and survival of those variants.

Several pieces of evidence, including the isolation of the H7N9 virus from chickens at live-bird markets and the exposure history of infected patients, suggest that live-poultry markets are a source of human infection4,5,36,37. Specifically, chicken layers and quail have been shown to be susceptible to H7N9 influenza virus infection and to shed virus at much higher titres than other avian species, including pigeons and Pekin ducks38. Closure of live-bird markets in China temporarily halted the H7N9 outbreak39. After the markets reopened and the winter season began, a new wave of infection emerged. Nearly 460 human cases had been reported as of November 2014 (ref. 2), raising new concern about the pandemic threat posed by this virus.

Our data show that the H7N9 virus replicates in chicken with moderate efficiency and that the infected chickens shed virus for a protracted period. This shedding appears to be sufficient to allow contact transmission of H7N9 virus among chickens, although with poor efficiency38. The ability of the H7N9 virus to replicate in chickens is likely aided by its internal gene cassette, derived from the H9N2 viruses of chicken origin40. The silent (asymptomatic) replication of the virus in chickens results in undetected spread of the H7N9 virus in the poultry markets and increases the risk of human infection through exposure to infected, asymptomatic chickens. Other bird species may play a role in spread of the H7N9 virus between bird markets and across provinces. One study showed that wild birds, including finches, sparrows and parakeets, support replication of H7N9 viruses41. The diversity generated through replication in these hosts and the potential role they play in H7N9 outbreaks remains to be investigated.

The human H7N9 isolates possess, or can readily acquire, several traits that support mammalian adaptation, including the PB2-E627K mutation42, which enhances replication in the mammalian upper respiratory tract, promoting virulence and airborne transmissibility24,27,34,44, and the HA-Q235L substitution (226 in H3 numbering)45, which confers human-like receptor preference. Indeed, the H7N9 virus replicated to titres similar to those of human H1N1 virus (A/Brisbane/59/2007; ref. 46) in the upper respiratory tracts of ferrets and was

(α-2,6-)-sialic acid receptors, but the AC virus’ affinity to the both receptors was markedly reduced. This drop in binding affinity may be due to the loss of several HA variants originally present in the parental stock or due to the reduction in NA activity; the cause remains to be investigated.

**Acid stability of wild-type H7N9 influenza viruses.** Acid stability has been described as one of the markers for regulating host range and virulence of influenza viruses21,23,28. We analysed the optimal pH at which the HA protein induces syncytia formation in infected Vero cells. The pH of HA activation of the three H7N9 viruses tested ranged between 5.6 and 5.8 (Supplementary Fig. 5). Thus, the HA proteins from these viruses are relatively unstable compared with those from human influenza viruses that are typically activated at pH 5.0–5.2 (refs 29,30). The HA activation pH values for the H7N9 viruses are more similar to those reported for the highly pathogenic avian H5N1 influenza viruses31,32.

**Discussion**

Our study revealed a previously unknown population-level factor restricting the further adaptation of avian A(H7N9) influenza virus to mammals. Although the H7N9 virus replicates to high titres in infected ferrets, replication in this host did not select for viruses with enhanced growth, virulence or transmissibility. In contrast, our data suggest that replication in ferrets lead to an attenuated phenotype. Because adaptation depends on the extent of the influenza virus population’s diversity in the host, we propose the existence of a ‘genetic bottleneck’ that limits the ability of avian A(H7N9) influenza virus to adapt to a mammalian host by limiting its genetic diversity in that host. By using a population-level approach and comparing the genetic diversity of the influenza virus population in the natural avian host and in infected mammals, we found that the genetic diversity of A/Anhui/1/2013 (H7N9) influenza virus was limited after its transmission to mammals. The loss in genetic variation imposed by the narrow genetic bottleneck appears to restrict the capacity of A(H7N9) virus to fully adapt to mammals.

Genetic bottlenecks occur frequently during the natural life cycles of RNA viruses33. Every RNA virus, including influenza A virus, exists as a heterogeneous genetic pool. This genomic diversity is an important component of influenza virus adaptation34. The genomic diversity of the inoculum population, the diversity generated during infection and the diversity transferred during airborne transmission contribute to adaptation to a given host16,35. A fully mammalian-adapted influenza virus can cause upper respiratory infection in humans and can be transmitted via the airborne route; the H7N9 virus appears to have the capacity for the former but not the latter.

### Table 2 | The effect of the identified substitutions in the NA and polymerase genes on the total amount of influenza virus produced over the course of the experiment using replication kinetic assays in MDCK cells.

| rg-A/Anhui/1/2013 (H7N9) influenza virus | AUCD24 (mean $\log_{10}$TCID$_{50}$ per ml$^{-1}$ ± s.d.) | $P$ value* |
|---------------------------------------|-----------------------------------------------|------------|
| WT                                   | 80.38 ± 3.11                                  | NA         |
| NA$_{E73K}$                           | 63.88 ± 2.29                                  | <0.05      |
| NA$_{E300V}$                          | 76.20 ± 2.26                                  | 0.07       |
| PB1$_{D76N}$                          | 81.10 ± 3.79                                  | 0.78       |
| NP$_{I365V}$                          | 77.19 ± 2.20                                  | 0.15       |
| NA$_{E73K}$ + NA$_{E300V}$            | 71.13 ± 2.07                                  | <0.05      |
| PB1$_{D76N}$ + NP$_{I365V}$           | 72.25 ± 1.67                                  | <0.05      |
| NA$_{E73K}$ + NA$_{E300V}$ + PB1$_{D76N}$ + NP$_{I365V}$ | 69.19 ± 3.74 | <0.05 |

* $P$ values were compared with WT virus by two-way analysis of variance.

NA, not applicable.

AUCD$_{24}$, the area under virus titre hour curve from 0 to 24 h post inoculation. Values are mean and s.d. from two independent experiments (n = 4).
transmitted to contact ferrets at a similar rate, albeit with lower efficiency. In contrast, other avian-origin influenza viruses, such as H5N1 virus, are not transmitted among ferrets even by DC21,47,48. However, our results show that the mammalian transmissibility of H7N9 virus may deteriorate rapidly and is not sustained. Overall, the poor efficiency of H7N9 airborne transmissibility is consistent with previous reports11,25,26. The low transmission efficiency can be attributed to several key properties of the H7N9 virus: (1) mixed preference for both avian and human receptors; (2) suboptimal acid stability, with a fusion pH optimum higher than that reported for human-transmissible viruses23,29,49; and (3) reduced polymerase activity at the human upper respiratory tract temperature (33 °C).

The presence of a significant subpopulation of variants with the HA mutation Q235L, which confers human receptor-binding preference25, among the human isolates did not appear to result in a switch to fully human receptor preference; the H7N9 virus maintained the binding affinity for both human and avian receptors. This result could be attributed to the presence of a subpopulation (23%) of viruses containing the avian Q235 variant or to the enhanced NA binding12. In the aerosol contact-transmitted (AC) virus population, the Q235 variant population fell to <10%; the virus maintained preference for both avian and human receptors, albeit with markedly reduced affinity, suggesting that other residues might be masking the effect of the Q235L mutation. Several variants (N141D, A143T and N167D; residues 132, 134 and 158, respectively, in H3 numbering) that were present in the parental virus fell to undetectable levels in the AC virus population and in ferrets inoculated with the AC virus. These residues are located in the 130- and 150-loops of the receptor-binding domain (ref. 45) and could potentially play a role in the receptor preference of H7N9 virus. Further studies are required to elucidate the effect of these residues on receptor-binding preference and avidity.

In this study, we found that H7N9 viruses that had been transmitted via the airborne route were not better adapted or more transmissible in mammals than the parental strain. Four residues in the three genes were uniquely enriched after airborne transmission, and in the ferrets inoculated with AC virus in round 2 experiments. Two of these substitutions (E73K and I300V) located in the NA gene resulted in a decrease in NA activity, and the PB1-D76N and NP-I365V mutations reduced polymerase activity. These mutations also attenuated virus replication in vitro. Importantly, although a human H7N9 virus was passaged in eggs to prepare a sufficient stock for experiments, the effect of egg-selected variants was controlled by using the same parental strain to inoculate chickens and ferrets. Richard et al.11 previously demonstrated the failure of H7N9 virus to adapt to ferrets due to the selection of variants with higher avian receptor-binding affinity, higher pH of activation and lower thermal stability after airborne transmission. None of the enriched variants in our study coincided with the ones described by Richard et al.11 or with sequence heterogeneity detected within specimens from human patients50. Thus, genetic selection of H7N9 virus after airborne transmission is a stochastic event and it does not favour mammalian adaptation or mammalian transmissibility.

In comparing the genetic diversity of the surface glycoproteins, we observed differences in genetic diversity among species in the HA gene but not in the NA gene. At the amino-acid level, none of the HA variants in the parental virus stock were detectable in the transmitted virus population. This result strongly suggests that a purifying pressure acting mainly on the HA gene (virus entry) shapes the diversity bottleneck observed in ferrets. This purifying pressure did not appear to select variants with novel traits such as enhanced transmissibility of the virus in ferrets. Similar purifying pressure on the HA gene has previously been described in association with the airborne transmission of H5N1 virus. However, in the case of H5N1 the purifying pressure appeared to favour the selection of viruses with enhanced fitness after aerosol transmission31, which was likely aided by the laboratory forced pre-selection of a receptor-matched virus mutant before the inoculation of ferrets24. In our study the diversity bottleneck acting on H7N9 virus appeared to persist even after a subsequent passage of the aerosol-transmitted virus in ferrets. Together, these findings suggest that the H7N9 influenza virus is not readily adaptable to transmit in mammals, which could partially explain the absence of sustained human-to-mammalian transmission to date.

Despite their ability to infect humans, the currently circulating strains of H7N9 viruses did not readily acquire additional adaptive mutations during their limited passage in humans or a mammalian host like ferrets. Our results suggest that viral replication in chickens may enhance the diversity of the H7N9 viruses and increase the potential of a subpopulation of variants to enter the mammalian cells and replicate. Even though these variants can replicate in mammals, the stringency of the genetic bottleneck limits their ability to acquire subsequent mutations that would allow mammal-to-mammal transmission. Whether
such fitness enhancing variants get selected in nature is entirely dependent on random events, frequency of infection in the new species and time. Given the continued infection of humans with avian H7N9 viruses, the risk of adaptation and pandemic emergence remains plausible. Therefore, surveillance and risk assessment of H7N9 viruses in poultry along with monitoring infections in humans should remain a focus of pandemic preparedness efforts.

Materials and methods

Cells. MDCK epithelial cells, African green monkey kidney epithelial (Vero) cells and human embryonic kidney (HEK 293T) epithelial cells were obtained from the American Type Culture Collection. MDCK cells were maintained in MEM containing 5% heat-inactivated fetal bovine serum (FBS) and 0.5% penicillin–streptomycin. Vero cells were maintained in DMEM (Gibco) containing 10% heat-inactivated FBS and 2 mM L-glutamine. HEK 293T cells were maintained in Opti-MEM (Gibco) supplemented with 10% heat-inactivated FBS. All the cells were maintained at 37 °C in 5% CO₂.

Biosafety, biosecurity and animal care. All the experiments were performed in a biosafety level 3 enhanced (ABSL3 + ) containment laboratory in accordance with USDA 9 CFR 121; 7 CFR 331. All the experiments were approved by the Institutional Biosafety Committee and the Dual Use Research of Concern Sub-committee at St Jude Children’s Research Hospital. The work in this study was conducted prior to the current U.S. Government gain of function stop work order. The ABSL3 + facility has security and containment features that eliminate risks to humans and the environment. The experiments were carried out by a trained personnel approved for work in ABSL3 + facilities. Animal studies were approved by the Animal Care and Use Committee of St Jude Children’s Research Hospital. Food and water were provided ad libitum to all the animals.

Viruses. The human H7N9 viruses A/Anhui/1/2013, A/Shanghai/2/2013 and A/Shanghai/1/2013 were obtained through the World Health Organization network. The virus stock used in the chicken and ferret experiments was grown in 10-day-old embryonated chicken eggs at 35 °C for 48 h.

Virus infectivity. Virus stock was titrated by plaque assay in MDCK cells at 37 °C for 72 h with a 0.4% immunodiffusion grade agarose (MP Biomedical); and by trypsin treatment, titrated in 10-day-old embryonated chicken eggs incubated at 35 °C for 48 h. Virus from chicken cloacal and oropharyngeal swabs was collected in 1 ml sterile phosphate-buffered saline (PBS) with antibiotics, titrated in 10-day-old embryonated chicken eggs at 35 °C for 48 h and titrated as EID₅₀. Virus from ferret nasal washes and cell culture supernatants from replication kinetic experiments were titrated in MDCK cells at 37 °C for 72 h as TCID₅₀. Virus titres (log₃₀EID₅₀ per ml and log₁₀TCID₅₀ per ml) in nasal washes, swabs, and tissues were estimated by the Reed and Muench method³⁶ by using chicken red blood cells (0.5% in PBS). The lower limit of quantitation of the assay is 0.75 log₃₀ EID₅₀ per ml and 1.5 log₁₀ TCID₅₀ per ml.

Experimental infection of chickens. Three 6-week-old, specific-pathogen-free chickens (Mustela putorius furo; Triple F Farms) that were serologically negative by ELISA for H1, H3, H9, H10, H11, H12, H13, H15, H16, H17, H18, and H19 were inoculated intranasally with 10⁶ TCID₅₀ of virus in 0.5 ml PBS under isoflurane anaesthesia and placed in separate cages with directed air flow. At 1 dpi, four naive ferrets were placed in each of the inoculated ferrets’ cages (DC) and another four ferrets were placed in AC in an adjacent cage separated from the inoculated ferrets’ cage by a perforated divider with controlled air flow.

Virus transmission in ferrets. Two rounds of transmission experiments were performed. During round 1, four ferrets were inoculated intranasally with 10⁶ TCID₅₀ of virus in 0.5 ml PBS under isoflurane anaesthesia and placed in separate cages with directed air flow. At 1 dpi, four naive ferrets were placed in each of the inoculated ferrets’ cages (DC) and another four ferrets were placed in AC in an adjacent cage separated from the inoculated ferrets’ cage by a perforated divider with controlled air flow.

For the second round of experiments (secondary respiratory droplet transmission), six naive ferrets were inoculated with a nasal wash sample containing 10⁶ AC virus obtained at 10 dpi (day 9 post contact) from the ferret infected via AC in the previous round of experiments. The nasal wash was diluted in saline at a dilution of 1:10³ TCID₅₀ per ml, transferred to AC in an adjacent cage as described above. Body weight and clinical signs were monitored for 21 dpi. Virus was titrated in nasal washes collected from inoculated and AC ferrets on 1 dpi and then every other day for 14 dpi or until no virus shedding could be detected for two consecutive sneezes as described above.

Serologic testing. Seroconversion was tested at 20 days post contact or at 21 dpi. Serum was treated with receptor–destroying enzyme (Seiken) overnight at 37 °C to destroy non-specific inhibitors, heat-inactivated at 56 °C for 30 min, and tested by hemagglutination inhibition assay with A/Anhui/1/2013 (H7N9) virus and 0.5% chicken red blood cells as described previously.³⁴

Deep amplicon sequencing and genetic analysis. Viral RNA was extracted by using an RNeasy kit (Qiagen); reverse-transcriptase PCR was then performed by using a SuperScript III first-strand synthesis kit (Invitrogen) with the Uni12 influenza primer. Multiplex PCR of all the eight gene segments was conducted by using PCR Sybr mix HiFi (Invitrogen) with the Uni12 primer and influenza A polymerase segment primers under previously described thermalycler conditions.³⁵ PCR products were purified on a spin column (Qiagen) and quantified by using the Quant-It Pico Green kit (Invitrogen). DNA libraries were prepared by using NEXtera XT DNA-Seq library prep kits (Iluminia) with 96 dual-index barcodes according to the manufacturer’s instructions. Pooled libraries were sequenced on an Illumina MiSeq Personal Genome Sequencer, using 150 base-pair paired-end reads.

Genomic sequences were analysed by using a custom work-flow protocol. In brief, sequence reads were filtered for quality scores by using the Nextera adapter trimming protocol, discarding low-quality terminal bases with PHRED scores > 20. A sample of 100,000 high-quality read pairs were aligned to the full set of complete NCBI influenza genomes in an exhaustive, competitive fashion to identify potential contaminating samples. Two rounds of alignment were performed: one pairwise alignment and one single-end alignment of unmapped reads from the first round. Genomes with at least one segment with a coverage > 0.7 were selected and used to generate a new reference genome. The final genome alignment was aligned to H7N9 and this reduced reference set, by using the same approach. Genomic log₁₀ H7N9 were detected by using an in-house single nucleotide variants (SNV) detection pipeline that considers base quality of a putative SNV, nucleotide quality base quality, strand bias of SNV and several other factors. Heat maps were generated by using the R programming software package (R Core Team, 2013). Mean variant frequency for each sample was calculated by using positions that are variable in at least one of the examined samples/reads. If a site had a minor variant frequency > 0 in any of the samples, it was included in the numerator; the denominator of the proportion was the total number of variable sites that was variable in all samples.

Polymerase activity assays. Viral ribonucleoprotein complex genes, including NP, PA, PB1 and PB2 of A/Anhui/1/2013 (H7N9) virus, were cloned into the pHW2000 plasmid to test the viral polymerase activity.³⁶ The PB1-D76N, PB2-K627E and NP-1365V mutations (primers listed in Supplementary Table 6) were generated in pHW2000 plasmids by using a site-directed mutagenesis system (Agilent Technologies). The polymerase activity of the mutant and wild-type polymerase complexes was measured as previously described.³⁷ In brief, HEK 293T cells were transfected with 0.1 μg each of pHW2000-PB2, pHW2000-PB1, pHW2000-PA, pHW2000-NP, pHW72-Luc and PMV-CMV-β-gal plasmids in 24-well-plates by using TransIT-LT1 transfection reagent (Mirus Bio). After 24 h, the cells were washed with PBS and lysed for 30 min with 100 μl of lysis buffer (Promega). The cells were then collected and the luciferase activity was assayed in triplicate by using the Promega luciferase assay system. Results were normalized to β-galactosidase activity.

pH of HA activation. The pH of HA protein activation was measured by synthetic assay, as previously described.³⁸ In brief, Vero cells were inoculated with H7N9 influenza viruses (A/Anhui/1/2013, A/Shanghai/2/2013 and A/Shanghai/1/2013) and plated into six 96-well plates in 100 μl of 1:4 diluted IMDM containing 2% FBS, 1% non-essential amino acids, 1% sodium pyruvate, 100 μg/ml penicillin, 100 μg/ml streptomycin and 37 °C for 18 h to allow cell surface expression of the HA protein. Cells were then washed with PBS and treated with 5 mg/ml of TPCK (a-lysokidamo-2-phenylethyl)
chloromethyl ketone)-treated trypsin (Worthington) for 5 min, followed by neutralization with FBS. Cells were then washed twice with PBS and pulsed with PBS buffer with a pH increment of 0.1 M citric acid. The highest pH at which syncitia were observed was recorded as the pH of HA activation.

**NA activity.** The activity of cell surface viral NA proteins was assayed as previously described. In brief, the mutations E-to-K at residue 73 and I-to-V at residue 300 were introduced individually or in combination into the NA gene carried in a pHW2000 plasmid by using a site-directed mutagenesis kit (Agilent Technologies). The plasmid was transfected into 293T cells with the appropriate eight plasmids and the virus stocks were prepared as described above. The HA-tagged NA activities were then analysed by flow cytometry on a MACS Quant analyzer (Miltenyi Biotec). The mean fluorescence intensity above that of mock-transfected cells was quantified by FlowJo software.

**Viruses.** MDCK cells were infected with the HA-tagged NA plasmids carrying the mutations of interest (NAI300V and NAI73EK), WT plasmid and an empty pCAGGS expression plasmid (mock) by using TransIT-LTI (Mirus Bio) with the appropriate eight plasmids and the virus stocks were prepared as described above. To confirm the cell surface expression of NA protein, the Vero cells transfected with the HA-tagged NA plasmids were incubated at room temperature for 1 h, washed with PBS and overlaid with 2% heat-inactivated FBS. Fifty microlitres of the suspension was incubated with an equal volume of 2'-((4-methylumbelliferyl)-α-D-N-acetylneuraminic acid (MUNANA; Sigma-Aldrich) substrate (final concentration, 100 μM) for 30 min at 37 °C. The reaction was quenched with 100 μl 100 mM sodium hydroxide in 83% ethanol, and the fluorescence intensity of the released 4-methylumbelliferone product was measured on a Synergy 2 multi-mode microplate reader (BioTek Instruments) with excitation and emission wavelengths of 360 and 460 nm, respectively. NA activity was quantified as fluorescence above the background fluorescence of mock-transfected cells, expressed in picomoles of 4-methylumbelliferone product.

**Receptor-binding affinity.** Glycan array analysis was performed as described previously, using glass slides containing 6 replicates of each of the 58 forms (Supplementary Table 7) of sialic acid-containing glycans, including terminal sequences, N-linked and O-linked glycans found on mammalian and avian glycoproteins and glycolipids. Viruses were grown in MDCK cells, inactivated with 10% FBS, and an empty pCAGGS expression plasmid (mock) by using TransIT-LTI (Mirus Bio) with the appropriate eight plasmids and the virus stocks were prepared as described above. The HA-tagged NA was then analysed by flow cytometry on a MACS Quant analyzer (Miltenyi Biotec). The mean fluorescence intensity above that of mock-transfected cells was quantified by FlowJo software.

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Author contributions
H.Z. and T.B. designed and performed experiments, and drafted the manuscript; R.C., M.E., G.W. and I.Z. performed computational analysis; B.S.K., J.C.P., R.McB., M.-S.S., J.C.C., J.S., E.R., M.H. and T.F. performed the experiments. I.E.R. analysed the pathology data. J.R., H.Z., Y.G., S.S.-C., S.K., R.G.W., E.A.G. and C.J.R. designed the influenza virus infection experiments and contributed to writing the manuscript. R.J.W. designed and supervised the study, critically reviewed and revised the manuscript.

Additional information
Supplementary Information accompanies this paper at http://www.nature.com/naturecommunications

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