



Sex and sex steroids impact influenza pathogenesis across the life course

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Abstract

Males and females differ in the outcome of influenza A virus (IAV) infections, which depends significantly on age. During a typical seasonal influenza epidemic, young children (< 10 years of age) and aged adults (65+ years of age) are at greatest risk for severe disease, and among these age groups, males tend to suffer a worse outcome from IAV infection than females. Following infection with either pandemic or outbreak strains of IAVs, females of reproductive ages (i.e., 15–49 years of age) experience a worse outcome than their male counterparts. Among females of reproductive ages, pregnancy is one factor linked to an increased risk of severe outcome of influenza, although it is not the sole factor explaining the female-preponderance of severe disease. Small animal models of influenza virus infection illustrate that inflammatory immune responses and repair of damaged tissue following IAV infection also differ between the sexes and impact the outcome of infection. There also is growing evidence that sex steroid hormones, including estrogens, progesterone, and testosterone, directly impact immune responses during IAV infection to alter outcomes. Greater consideration of the combined effects of sex and age as biological variables in epidemiological, clinical, and animal studies of influenza pathogenesis is needed.

Keywords Estrogen · Gender · Immunopathology · Pandemic · Progesterone · Testosterone

Among humans, the prevalence (i.e., number of infected individuals within a population) and intensity (i.e., viral load within an individual) of viral infections, including influenza, differs between males and females [1]. Behavioral gender-associated factors, including occupation, personal hygiene (e.g., hand washing), and familial responsibilities (e.g., caring for children or the elderly), can influence exposure to viruses, including influenza A viruses (IAVs) [2]. Several studies further illustrate that biological sex differences can lead to differential immune responses and outcomes following infection. Females often are less susceptible to viral infections because they mount stronger immune responses than males. The innate recognition and response to viruses as well as downstream adaptive immune responses differ between males and females during viral infections [3]. Sex differences in immune responses to viral infections may further depend on age-related

factors and differ prior to puberty, after puberty, or after reproductive senescence [4].

Influenza is a significant public health threat, with influenza A viruses (IAVs) causing seasonal epidemics, occasional outbreaks, and sporadic pandemics. Pulmonary disease following infection with IAV is caused by excessive and aberrant inflammatory responses to the virus, which leads to immunopathology and tissue damage [5]. Effective therapies for limiting severe pulmonary disease following IAV infection often limit the “cytokine storm” and pulmonary inflammation [6, 7], in addition to controlling viral replication. The severity of influenza disease is typically worse for young children, aged adults, individuals with compromised immune function, and pregnant women. Rarely are biological sex or gender-related factors considered when assessing the pathogenesis of influenza. In this review, we aim to illustrate that in humans, the age, sex, and reproductive status (i.e., sex steroid hormonal milieu) of an individual can predict the outcome of IAV infection, but rarely are these biological factors considered together in either epidemiological or clinical studies. Furthermore, age, biological sex, and reproductive status are rarely reported or systematically evaluated in studies utilizing animal models. The primary goal of this

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review is to summarize available data on the effects of biological sex and sex steroid hormones on influenza pathogenesis, with consideration of how these factors change over the life course.

Age-associated sex differences in influenza pathogenesis (Figure 1)

Birth to puberty

The severity of influenza is generally greater prior to the onset of puberty than during adulthood. For example, hospitalization rates were higher in children under the age of 10 than those in older age groups during the 2009 H1N1 pandemic [8]. Studies utilizing mice further illustrate that pre-pubertal animals typically suffer greater disease than adult animals following IAV infections [9, 10]. In contrast, pre-pubertal male ferrets have milder disease than adult males following IAV infection [11]. In ferrets, influenza virus infection is primarily an upper respiratory tract infection, whereas in mice, the lower airways are involved [12].

Most case reports of seasonal influenza do not analyze data for differences between males and females or if they do, then they often do not consider the interaction between sex and age. Examination of the limited available reported seasonal influenza cases that required hospitalization reveals that the severity of infection is typically greater in pre-pubertal males compared with age-matched females [13–15] (Fig. 1). Data

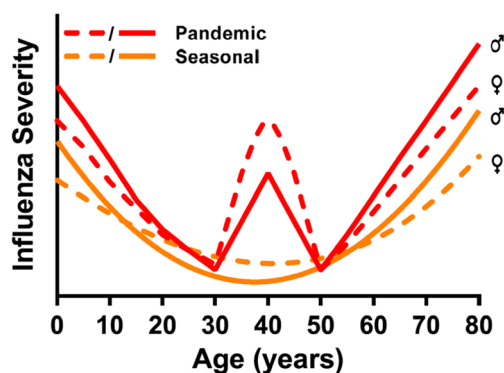


Fig. 1 Differential severity of seasonal and pandemic influenza A viruses (IAVs) based on age and sex. During typical seasonal IAV epidemics, young children (<10 years of age) and aged adults (>65 years of age) are at greatest risk of severe disease. In contrast, during pandemics of IAVs (e.g., the 2009 H1N1 pandemic), in addition to children and aged adults, young adults of reproductive ages often experience disproportionately more severe outcomes. Layered on top of the age distribution is the observation that among children and aged adults, males tend to suffer more severe outcomes than females, whereas females experience more severe outcomes of both seasonal and pandemic IAVs during the reproductive years. Although pregnancy is one factor that impacts female-biased susceptibility to IAVs during the reproductive years, other factors, including greater risk of inflammation and tissue damage, may also contribute [2]

from Denmark suggest that differences between males and females in the risk of hospitalization from seasonal influenza virus shift at puberty. Thus, males are more likely to have severe seasonal influenza illness before puberty, whereas females are more likely to have severe seasonal influenza illness after puberty and before menopause [16]. To date, no animal studies have evaluated whether the pathogenesis of influenza differ between the sexes prior to puberty.

Reproductive ages

The 1918 H1N1 influenza pandemic was the most deadly influenza pandemic to date [17]. This influenza pandemic was disproportionately fatal in young adult males (i.e., 20–40 years of age) and was exacerbated by co-infection with tuberculosis, which is also considered to be a male-dominant disease [18, 19]. Unlike the 1918 H1N1 pandemic, the 1957 H2N2 pandemic was the first pandemic that was lethal without a secondary bacterial infection. The 1957 H2N2 pandemic resulted in higher fatality rates among adult females than males (i.e., <50 years of age), despite the widespread use of vaccine therapy [20, 21]. Many of the fatal cases during the H2N2 pandemic had underlying cardiac or pulmonary conditions; thus, sex-biased comorbid conditions may have contributed to the increased rates of severe disease and mortality among young adult females during the 1957 H2N2 pandemic [21].

During the 2009 H1N1 pandemic in the USA, females were more likely to develop severe disease than males (53.2% female vs. 46.8% male hospitalizations) [2] (Fig. 1). Age at the time of infection, however, was strong predictor of the male-female differences in the incidence, severity of 2009 H1N1 pandemic infection, and mortality rates. Among adults, females were at a higher risk of hospitalization and death from 2009 H1N1 infection than males [22]. In Japan, a similar female bias was observed in clinical disease following infection with 2009 H1N1 influenza among adults of reproductive ages, which contrasted with the male bias observed prior to puberty [23]. In Canada, during the first wave of the pandemic, a majority of critically ill patients with confirmed or probable 2009 H1N1 influenza were young adult females [24] (Fig. 1). The reason for the greater proportion of hospitalized adult females than males in Canada is not known, but many cases involved comorbid conditions, including chronic lung disease (e.g., asthma), which is typically more severe in young adult females than males [25]. The Canadian government has led the way by requiring disaggregation and analysis of data by sex and gender, which is the most parsimonious explanation for why male-female differences were so widely reported in Canada, and not in other countries, including the USA, during the 2009 H1N1 pandemic.

Avian H5N1 is a highly pathogenic influenza virus that affects the lower respiratory tract in humans and is primarily

transmitted from diseased poultry to humans, with rare person-to-person transmission. Worldwide, the incidence and severity of H5N1 infection and mortality caused by H5N1 infection have been greater among young adult females (10–39 years of age) than those among males [26]. There is annual, as well as country, variation in the male-female differences suggesting that gender-related factors, including occupational exposure, play a significant role. Furthermore, during the 2013–14 H7N9 avian influenza outbreak, while aged males were more likely than any other sex and age-matched cohort to be hospitalized with severe disease, it was females of reproductive ages (i.e., 18–50 years of age) who were most likely to die from H7N9 infection [27].

Sex differences in influenza pathogenesis have been systematically evaluated using small animal models [28–32]. Using murine models, most, but not all [33], studies have shown that females develop higher pulmonary inflammatory responses and experience a more severe outcome from IAV infection (i.e., with infection with H1N1, H3N1, H3N2, or H7N9 IAVs) than males, despite the sexes having comparable virus titers [27–29, 34, 35]. For example, pulmonary concentrations of proinflammatory cytokines (e.g., TNF- α , IFN- γ , IL-6, and IL-12) and chemokines (e.g. CCL2, CCL5, and CCL12) are greater during IAV infection in females than those in males [27, 28]. Male mice also repair damaged pulmonary tissue faster than females [36]. Repair of the damaged lung tissue following IAV infection is generally orchestrated by both immune cells (e.g., regulatory T cells and macrophages) and epithelial cells and involves the production of cytokines and growth factors [37, 38]. In response to damage, epithelial cells release factors, including amphiregulin (AREG), that can promote repair and integrity of lung tissue damaged during IAV infection [39]. Expression of AREG is greater in lung tissue as well as in respiratory epithelial cells derived from males as compared with females during IAV [36]. Males also depend on AREG more than females for faster recovery from IAV, because when AREG is deleted from mice, the impact on pulmonary inflammation and function is significantly greater for male than that for female mice [36]. Importantly, infection of young adult female mice with IAVs reduces ovarian function and concentrations of sex hormones [28, 40] suggesting that inhibition of sex hormones, including estrogens and progesterone (P4), may contribute to severe outcomes from IAV in females (see below).

Reproductive senescence

During a typical seasonal influenza epidemic, among older individuals (i.e., 65 years of age and older), males are at a higher risk of hospitalization from severe IAV disease than their female counterparts [41] (Fig. 1). Of the cases of H7N9 which have been reported throughout China, aged males (> 50 years of age) were at the greatest risk for contracting H7N9

infection, comprising approximately two thirds of the cases of H7N9 infection [42, 43]. Surveillance studies indicated that approximately 70% of all H7N9 cases were male, with around 75% of confirmed H7N9 cases being males over 45 years of age [44–48]. Therefore, both male sex and older age are risk factors for infection with H7N9 influenza virus. Whether older males are more likely to come in contact with diseased poultry or migratory birds has not been shown.

In animal models of IAV pathogenesis, advanced age is generally associated with increased morbidity (i.e., hypothermia and clinical disease) and mortality, which appears to be caused by reduced control of IAV replication and delayed resolution of pulmonary inflammation [32, 49]. Consistent with this, both the innate and adaptive immune responses are slower to initiate, reach lower peak magnitude, and are slower to resolve in aged compared with adult mice (sex either not specified or only female mice used) [49–53]. Despite a plethora of studies evaluating the mechanisms mediating the effects of aging on IAV pathogenesis, to date, no studies have evaluated the influence of biological sex on age-related changes in IAV pathogenesis.

Hormonal mechanisms mediating sex differences in influenza pathogenesis

Estrogens

Estrogens, including 17 β -estradiol (E2), occur in high concentrations in non-pregnant as well as pregnant females. E2 is responsible for the majority of the “classic” estrogenic effects in reproductive and non-reproductive tissues. Murine models of IAV pathogenesis demonstrate that E2 treatment protects females against infection-induced morbidity and mortality [28, 54, 55]. Treatment of mice with E2 protects against IAV disease by dampening the inflammatory responses associated with tissue damage, including excessive production of IFN γ , TNF α , and CCL2, and by promoting higher antibody responses to influenza vaccination [28, 54, 55]. Some [55], but not all [28, 30], studies suggest that treatment of females with E2 affects type I IFN responses and virus replication in the lungs. Treatment with E2 also increases production of chemoattractants for neutrophils, including CCL3 and CXCL1, pulmonary infiltration of neutrophils, and cytokine production by virus-specific CD8 $^{+}$ T cells as compared with placebo-treated females [30]. Neutrophils are critical regulators of inflammation, virus clearance, and tissue repair during influenza infection [56, 57]. Depletion of neutrophils in E2-treated females reverses the protective effects of E2 on the outcome of IAV infection and increases inflammatory cytokine production [30].

Estrinol (E3) is an endogenous estrogen in females with broad biological activity. Exogenous E3 treatment of either

female or male mice improves the outcome of IAV infection [40]. Further, E3 significantly reduces the transcriptional activity of genes associated with proinflammatory cytokines and chemokines during early IAV infection, which was associated with reduced recruitment of immune cells into the lungs [40]. Reduced pulmonary inflammation in E3-treated mice correlates with improved pulmonary function and reduced morbidity and clinical disease. E3 treatment, however, does not alter the kinetics of virus replication and clearance, suggesting that E3-treated animals maintain sufficient antiviral immunity despite reduced overall inflammation [40]. Together, these data suggest that exogenous E2 or E3 treatment confers protection during IAV infection through immunomodulatory mechanisms and, thus, suggest that elevated concentrations in females do not cause severe IAV outcomes.

Progestins

Natural P4 is produced by the corpus luteum during the menstrual cycle in non-pregnant females, and its production is sustained at high levels by the placenta during pregnancy. Synthetic analogs of P4, termed progestins, are used as hormonal contraceptives. In C57BL/6 mice infected with IAV, treatment with either P4 or LNG prevents severe outcome by decreasing pulmonary inflammation and promoting faster recovery during a primary infection [31, 58]; in contrast, studies utilizing outbred CD-1 mice report minimal effects of P4 morbidity, mortality, and pulmonary inflammation following IAV infection [59]. P4-based treatments also promote pulmonary repair following clearance of IAVs by elevating levels of TGF- β , IL-6, IL-22, and increasing numbers of regulatory CD39+ Th17 cells in the lungs. Production of AREG is increased following P4 treatment, which promotes proliferation and repair of respiratory epithelial cells during IAV infection [31]. Treatment with either P4 or levonorgestrel also reduces IAV-specific antibody titers as well as IAV-specific memory CD8+ T cell numbers, which result in worse outcome following secondary IAV challenge in female mice [58]. While the anti-inflammatory effects of P4-based compounds protect against a primary virus infection, the reduction in memory T cell responses increase susceptibility to secondary influenza A virus challenge.

Androgens

Androgens, specifically testosterone and dihydrotestosterone (DHT), modulate immune responses and susceptibility to a variety of infectious and non-infectious diseases [60, 61]. For males, there is an initial surge of testosterone in early development, with concentrations increasing at puberty, reaching peak concentrations in early adulthood, and gradually declining with older age [62–64]. In male mice, lower concentrations of testosterone, either associated with aging (i.e.,

16–18 months of age) or caused by surgical castration of young males, are associated with increased IAV-associated pulmonary inflammation and morbidity, with no effect on the control of virus replication [32, 36]. Importantly, administration of exogenous testosterone to either aged male or castrated young male mice significantly improves the outcome of IAV, independent of changes in pulmonary viral load [32]. Although testosterone is protective in mouse models that are designed to allow for survival of infected mice, both testosterone and DHT minimally protect against lethal influenza virus infection [28]. Because disease following infection with sub-lethal doses of IAV is largely immune-mediated, while at higher doses of IAV, disease is driven by an inability to control viral replication, these data further illustrate that androgens affect IAV pathogenesis by modulating inflammation and not control of virus replication [65].

Conclusions

Sex is a biological variable that should be considered in studies of IAV pathogenesis. There are gaps in our understanding of the precise mechanisms mediating sex-biased immune responses and how this affects the outcome of IAV infection. Future research must continue to define the pathways mediating how hormones, as reviewed here, but also genes and even the microbiota, differently affect immunity to IAV in males compared with females. Future studies should continue to consider the age and reproductive status of individuals as well as whether females or even males are using exogenous hormones (either through contraceptives or replacement therapy) at the time of infection. We recommend that clinicians, epidemiologists, and basic biomedical scientists design experiments that include both males and females, develop a priori hypotheses that the sexes will differ in their responses to and the outcome of IAV infection across the life course, and statistically analyze outcome data by sex and age. The end goal should be that clinicians and researchers alike consider the sex of their patients or animals when interpreting data pertaining to IAV pathogenesis.

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