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Review article

The conneXion between sex and immune responses

In the format provided by the authors and unedited

	Pathogen	Pathogen prevalence and incidence	Pathogen load and disease severity	Mouse models & mechanisms/pathways of sex bias
VIRUS	SARS-CoV-1, SARS-CoV-2	Higher incidence of infection in males[1-10]	Adult males (45-79yrs) have higher mortality for SARS-CoV1 and 2[5,6 9] Females infected with SARS-CoV2are more likely to be diagnosed with Long Covid[11,12]	Male mice are more susceptible to SARS-CoV infection[13-15] Male mice infected with SARS-CoV have increased accumulation of inflammatory macrophages and neutrophils in the lung[3,13] Estrogen receptor signaling is protective after SARS-CoV-infection[13,16] The SARS-CoV-2 entry receptor ACE2 is biallelically expressed in females, and may contribute to sex bias through regulation of viral entry and its function in the renin-angiotensin-aldosterone pathways [4,17]
	Influenza Virus	Infant males and older adult males have increased incidence of infection[18-23]	Males (pre-pubescent or elderly) have higher mortality than females [19,23] Females are more likely to be symptomatic after infection and have a wider range of symptoms compared to males[24] Females (ages 15-49yrs) had higher mortality during the 1957-1958 H2N2 pandemic as well as after H5N1 infection[25] Females (ages 20-49yrs) had higher morbidity rates compared to their male counterparts during the 2009 H1N1 pandemic, whereas younger (<20yrs) and older (>80yrs) males had higher morbidity	Male mice are more resistant to influenza viruses than female mice, with female mice exhibiting lower LD50 values for mouse adapted H1N1 and H3N2 viral strains[25] Sex differences in morbidity after infection with mouse-adapted influenza (H1N1, H3N2) are dose-dependent, where female mice have greater body mass loss, more hypothermia, and lower rates of survival than male mice at median doses[29] Female mice have a greater level of protective immunity following influenza vaccination[30,31] Lower levels of testosterone in male mice correlate with poorer protection from influenza A virus[32-35] Estriol was shown to protect female mice from severe disease after infection of influenza A virus and decreases influenza viral replication[36]

			rates than similarly aged females[25] Pregnancy is associated with worse outcomes from seasonal, outbreak, and pandemic influenza viral infections, and contributes to higher overall morbidity and mortality in females[18,26-28]	
	Hepatitis A Virus	Males are more likely to be hospitalized[37]	Males have higher mortality[37]	n/a
	Hepatitis C Virus	Similar incidence rates between males and females[38]	Males have greater disease severity (HCV-associated cirrhosis) [38] Females are more likely to clear virus[38]	n/a
	West Nile Virus	One case study shows a higher percentage of affected males[39]	Similar initial viremia in males and females[39] A meta-analyses revealed that females report a higher diversity of symptoms[39] Males have an altered cytokine response compared to females in the post-IgM phase, with elevated levels of CCL2, CCL11, IL-15, and CXCL10[40] Infected males have higher hospitalization rates and higher incidence of neuroinvasive disease and increased mortality[39,40]	n/a
	Human Immunodeficiency Virus (HIV)	Females have higher incidence[41] Females have higher levels of immune activation and interferon	Females have lower viral loads in the early stages of infection, but comparable viral loads at the advanced stage [42,43]	Male-to-female transmission appears more efficient than female-to-male transmission[44]

		signature gene expression[42]	No sex difference with regards to disease progression or clinical outcomes[42,43]	
	Human cytomegalovirus (HCMV)	Females (post-puberty and pre-menopausal) have higher incidence of HCMV seroprevalence[45]	One study reported that HCMV infection suppressed reactivity to TLR2 and TLR7/8 stimulation in females but not males[46]	n/a
	Herpes Simplex Virus (HSV)	Females have higher prevalence of HSV-2 (15.9% females) than males (8.2%)[47,48]	No sex differences with symptoms[47,48]	Female mice are more susceptible to infection[49] Female mice have higher HSV titers in brain tissue[49] Higher mortality in male mice[50] Ovariectomy of female mice or estrogen treatment of male mice eliminated sex differences after infection[49] Sex-biased survival differences depend on type I IFN signaling and DAP12 signaling[49]
	Coxsackievirus	n/a	n/a	Male mice have increased mortality[49,51] Males develop more severe cardiac inflammation due to T_H1 – skewed responses[51] Females are more resistant to infection and exhibit predominantly T_H2-type responses[51]
	Ebola Virus		Males have higher mortality[52]	n/a
	Measles Virus	At ages 45-64, females have a higher incidence[53], whereas at ages age 0-45, males have a higher incidence of infection[54]	Females (ages 0-49) have higher mortality, particularly post-puberty and pre-menopause[53].	n/a
	Respiratory Syncytial Virus (RSV)	Males have higher incidence[55,56], but a metanalysis of acute respiratory infections in Africa did not identify sex as a factor in RSV prevalence[57]	Males have higher rates of hospitalizations[55]	Male neonatal mice have higher viral gene expression after RSV infection, and delayed viral resolution[58] After early-life RSV infection, male mice exposed to allergens have severe allergic exacerbation (female mice are protected). The TSLP pathway

				(which impacts IFNβ production) alters male immune environment after neonatal infection[58]
BACTERIA	*Heliobactor pylori*	Males have greater *H. Pylori* sero-prevalence[59,60] After adjusting for age, males have 33% greater odds of infection. The prevalence of infection is 5% higher for males[59]	Males have more severe inflammation, atrophy, and intestinal metaplasia[61]	Male mice are more susceptible to *H.pylori* infection Males have higher colonization levels for *babA* virulence factor of H. pylori[62] Male mice treated with estradiol produce less IFNγ and IL-1-β, and increased IL-10 and T_H2 associated IgG1 levels[62] Estrogen is protective against gastric lesions; ovarectomy increases severity of gastritis and gastric cancer[62]
	Pseudomonas aeruginosa	Young females are more likely to be infected than young males[63]	Female patients with cystic fibrosis have worse disease prognosis upon infection compared to male patients with cystic fibrosis[64]	Female mice are more susceptible to infection[65] Female mice mount strong inflammatory response in lungs[65] Estradiol upregulates expression of secretory leucoprotease which inhibits TLR-dependent IL-8 release in bronchial epithelial cells during *P.aeruginosa* infection[65]
	Salmonella	Higher incidence rates of salmonellosis in males up to age 15 [66] Females have higher incidence rates (ages 15–64) [66]		n/a
	Chlamydia trachomatis; Chlamydia pneumoniae	Males have greater prevalence (*C. pneumoniae*)[67] Females have higher prevalence (*C. trachomatis*)[68]	Males have higher levels of *C. pneumoniae*[69] Females have higher infection rates because they are more likely to be screened (*C.trachomatis*)[70] Estrogen levels correlate with chlamydial load[69]	n/a

			Chlamydia-induced arthritis more common in men[71]	
	Brucella spp.	Males have higher incidence[72] No sex bias with regards to prevalence[72]	Males more likely to develop Brucellosis[73]	n/a
	Borrelia burgdorferi (Lyme disease)	Males have higher incidence (USA 1992-1998)[74] Females >45 have greater incidence (Sweden 1992-1993)[75,76] Females are more likely to be re-infected after 5 years. [75,76]	Males have more hospitalizations and likelihood for disseminated disease[77] Lyme neuroborreliosis is more common in female patients[78] Females have increased production of IFNγ, IL-4, IL6, IL-10, TNF[75]	Male mice exhibit more evidence of infection across tissues and higher spirochete loads compared to female mice[79]
	Mycobacterium tuberculosis	Males have higher incidence (male/female ratio is 1.7)[80]	Males exhibit higher mortality rates (global)[81] Pregnancy increases risk of disease complications[82] Females usually have less symptoms[69]	Male mice have accelerated disease progression, increased morbidity and mortality[83] Males have higher *M. tuberculosis* loads[83] Testosterone treatment increases susceptibility to infection[83]
	Mycoplasma pulmonis			Male mice are more susceptible than female mice, and they develop more severe disease in lung parenchyma. Removal of reproductive organs in males reduced disease severity[84]
	Coxiella burnettii	Males have higher incidence[85]	Males are more likely to become sympotomatic with Q fever (symptoms include fever, granulomatous hepatitis, myocarditis, pericarditis, pneumonia)[69,85] Pregnancy increases risk for persistent infections, and impaired immunity negatively impacts pregnancy[69]	Male mice have higher bacterial loads[69] Estrogen treatment of ovariectomized mice reduces bacterial loads and granulomas[86] C. burnetti infection results in sex-specific gene expression profiles: males upregulate IL-10 and IFNγ production; females exhibit altered expression of circadian rhythm genes.[87]

	Campylobacter spp.	Males have higher incidence[69]		Male mice are more susceptible to infection and colonization[88] Males have higher shedding rates [88]
	Clostridiodes difficile	Females have higher incidence[89] Females have increased risk of recurrent infection[61]	Increased disease severity in pregnant and peripartum females[89]	Progesterone and estrogen intermediates can inhibit spore germination in mice[61]
	Listeria monocytogenes	Females have higher incidence rates of invasive listeriosis[90] Pregnant females have higher incidence[69] Among older individuals, males have 2-4 higher incidence rates[90]	Pregnant females and older males have greater incidences of invasive disease[90] Older males have increased fatality rates[90]	Female mice are more susceptible to infection and exhibit greater lethality[91] Female mice have higher bacterial load; Infected females have increased IL-10, which inhibits Th1 differentiation and Th1-derived cytokines[91] Estrogen treatment reduced IL-12, IFNγ and TNF, increased IL-4 and IL-10, and reduced monocytes and lymphocyte accumulation at infection[92]
	Legionella pneumophila	Males have higher incidence, with male:female ratios of 1.7 to 5 in U.S, Europe, Australia, Japan[69]	Males are more likely to develop legionellosis and to have a poor prognosis[69]	n/a
	Leptospira spp.	Males have higher incidence[69]		n/a
	Francisella tularensis	Males have higher incidence[65]		No sex difference with regards to susceptibility. However, vaccinated female mice are more resistant to infection, with lower bacterial burdens, less tissue inflammation, and less proinflammatory cytokine production, and have more *F. tularensis*-specific antibodies in serum and lung[85]
	Escherichia coli	Females have higher incidence[69]		No sex difference with enterohemorrhagic *E.coli* disease in mice[69]
	Treponema pallidum (syphilis)	Males have higher incidence[93,94]		n/a
	Neisseria gonorrhea	Males have higher incidence[69] Infected males may also have increased expression of gonococcal	Most females lack symptoms[69] Complications in males include epididymitis, infertility,	Estrogen treated mice have increased susceptibility to gonococcal infection[98]

		antimicrobial resistance genes[95]	prostatitis, seminal vesiculitis[96] Elevated progesterone promotes gonococcal infection (human cervical epithelial cells)[97]	
	Streptococcus pneumoniae	Males have higher incidence for all types of pneumonia[69] Males (pre-puberty) have higher incidence	Males have greater hospitalization rates and increased mortality[69] Males are more frequently diagnosed with Legionellosis (1.7:5 male to female ratio)[99]	Male mice are more susceptible & have more severe disease[100] Males exhibit increased levels of pro-inflammatory cytokines (IL-6, IL-17A, IFNγ)[100] Estrogen is protective and regulates macrophage activity (for pneumococcal pneumonia)[101]
	Yersinia enterocolitica	Males have higher incidence for Yersiniosis[102]	Males have higher levels of IgG4 antibodies for Yersinia outer membrane proteins, which is associated with an anti-inflammatory response that is resistant to treatment[61]	n/a
	Sepsis: *Staphylococcus, Escherichia coli, Pseduomonas, etc*	Males have higher rates of sepsis and septic shock[65] Males are more likely to develop sepsis after trauma or surgery[65]	Conflicting results regarding a sex bias for mortality[103]	Male mice develop greater inflammatory responses, producing more pro-inflammatory cytokines[69] Males have more severe sepsis-induced cardiac dysfunction[85] Estrogen is protective, and female mice produced protective antibodies in response to estrogen; estrogen-driven antibodies were maternally transferrable to offspring[104]
WORMS	Pork tapeworm (Taenia solium) Neurocysticercosis	Females have higher incidence in some countries (Nigeria, Tanzania, Guatemala)[105] Females have more transitional cysts in brain (Ecuador)[106] No sex difference with regards to incidence in Vietnam[105]	Female patients have greater number of transitional cysts[106]	Estrogen increases and androgens decreases parasite loads in mice, either acting directly on the worm's reproduction or by altering host's immune response to favor T_H2 or T_H1 pathways, respectively (*Taenia crassiceps*)[107]

	A. Lumbricoides	Females have higher incidence[108]		n/a
	Schistosoma masoni	Males have higher prevalence of infection[109]		Female and castrated male mice have greater morbidity after Schistosoma infection[110] Female mice have higher worm loads[110] Testosterone is protective for Schistosoma mansoni infections; female mice treated with testosterone had reduced worm burdens (if treated before infection)[110]
PARASITES	Plasmodium falciparum (malaria)		Male patients have greater disease severity[111]	n/a
	Cryptosporidium	Males have higher incidence[112]	Male patients have greater incidence of hospitalizations[113]	n/a
	Entamoeba histolytica (amoebiasis)	Asymtopmatic infection rates are the same across sexes[114]	Invasive amebiasis predominantly affects males; males have higher rates of invasive disease[114] Males have higher incidence of hepatic amebiasis[115]	Testosterone treatment induces proinflammatory responses in mouse (& human) classical monocytes, with increased production of CXCL1 and TNF[115]
	Leishmania	Males have higher incidence even when accounting for exposure[116] Adult males have higher incidence of cutaneous leishmaniasis[117] Childhood cutaneous leishmaniasis does not exhibit a sex bias[118] Males have higher incidence and greater risk ratio of visceral leishmaniasis[119] No sex bias for childhood cutaneous leishmaniasis[120]	Male patients exhibit higher rates of treatment failure and adverse effects[116]	Male mice have higher parasite burdens following infection (L.infantum)[121] Male mice express higher levels of IL-10 and TNF after infection and exhibit greater disease severity[121] Male mice (BALB/c congenic strains) are more susceptible to subcutanteous L.major, and exhibit more severe disease[116,122] Female mice heal small lesions following L. Mexicana infection, yet male mice exhibit persistent lesions, dependent on IL-4 levels[123]

				Male hamsters have increased disease severity and parasite burden with L. viannia infection. Testosterone-treated female animals had larger lesions than untreated females. Disease severity correlated with increased expression of IL-4, IL-10, and TGFβ[124] X-linked *Cxcr3* is biallelically expressed in T cells of female mice and contributes to increased cytokine production[125]
	Toxoplasma gondii		Sex differences with regards to infection-induced behavioral changes and personality shifts[126]	Female mice are more susceptible to infection and have higher cyst burdens[127] Female mice exhibit higher mortality after acute infection[127] Male mice produce higher levels of TNF after day 10 of infection; mortality of female mice did not correlate with lower TNF levels. Male mice produce higher levels of IFNγ and IL-10 early during infection[127]
FUNGI	*Aspergillus fumigatus*	Males have higher incidence (invasive pulmonary aspergillosis)[128] Male bias with regards to prevalence, incidence and severity[129] Males more susceptible to infection[129]		Female mice have higher antibody titers and levels of neutrophils, eosinophils and lymphocytes after infection[130]
	Cryptococcus neoformans	Males have higher incidence, with 3:1 male to female rations for HIV negative populations and 8:2 among HIV positive populations [131]	Males with cryptococcosis have more severe symptoms and worse outcomes[131]	Female mice express more cytokines in the plasma and have increased expression of TNF and IFNγ in spleen[132] Increased lethality for young male mice[132] Survival and fungal loads are similar between male and female mice[132]
	Paracoccidioides brasiliensis	Males have greater incidence (10:1 male to female ratio in Latin America)[133]	Male patients have faster disease progression[134]	Male mice are more susceptible[135]

				Macrophages from infected female mice exhibit greater fungicidal activity, with higher nitric oxide production[135] Estrogen is protective following P. brasiliensis infection, as castrated male treated with estradiol have higher levels of IFNγ and lower levels of IL-10 compared to normal males. Ovariectomized female mice treated with testosterone produce less IFNγ and more IL-10 compared to normal female mice after infection[135]
	Microsporum, Trichophyton, epigermophyton (Tinea or Dermatophytosi)	Males have higher incidence [136]		n/a
	Candida albicans	Females have higher incidence (oral candidiasis)[137] Females have higher incidence (candida onychomycosis), with 3/4 females (childbearing age) infected at least once in their life; and 1/10 females having a recurring event[137]	Male patients with seropositivity for *C.albicans* have increased odds for schizopherenia[138] Female patients with seropositivity for *C.albicans* have increased odds for lower cognitive scores[138]	n/a

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