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REVIEW ARTICLE

COVID-19: A Veterinary and One Health Perspective

Deepak Kumar[1], *Jagadeesh Bayry*[2] *and Nagendra R. Hegde*[3*]

Abstract | Interface with animals has been responsible for the occurrence of a major proportion of human diseases for the past several decades. Recent outbreaks of respiratory, haemorrhagic, encephalitic, arthropod-borne and other viral diseases have underlined the role of animals in the transmission of pathogens to humans. The on-going coronavirus disease-2019 (COVID-19) pandemic is one among them and is thought to have originated from bats and jumped to humans through an intermediate animal host. Indeed, the aetiology, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), can infect and cause disease in cats, ferrets and minks, as well as be transmitted from one animal to another. The seriousness of the pandemic along with the zoonotic origin of the virus has been a red alert on the critical need for collaboration and cooperation among human and animal health professionals, as well as stakeholders from various other disciplines that study planetary health parameters and the well-being of the biosphere. It is therefore imminent that One Health principles are applied across the board for human infectious diseases so that we can be better prepared for future zoonotic disease outbreaks and pandemics.

1 Introduction

The COVID-19 pandemic is a stark reminder that we live in a time where pathogens spread faster than we can track them. The incidence of other diseases in humans such as severe acute respiratory syndrome (SARS) and Middle East respiratory syndrome (MERS),[1] H1N1 pandemic influenza,[2] H5N1 avian influenza,[3] Ebola haemorrhagic fever,[4] etc. in just the last two to three decades has also highlighted that globalization and animal–human interface are major factors in the transmission of pathogens from wild and domestic animals to humans.

Recent advances, especially in genomics, have spurned the understanding of diseases in terms of their aetiology, origin, identification of index case, routes of spread and potential transmission, evolution of the pathogen, minutest details of host–pathogen interaction and pathogenesis, and vaccine and/or drug discovery, facilitating disease mitigation strategies. At least one new infectious disease is thought to emerge or re-emerge every year.[5,6] Between 1940 and 2004, there were 335 emerging infectious diseases, about 60% of them originating from animals, with not much change in decade-wise proportion of zoonotic diseases.[7] About three-fourths of all emerging and re-emerging human diseases can be traced back to animals, particularly wild animals,[7] and it has been propounded, probably rather radically, that every species of Kingdom *Animalia* may be a potential carrier of human pathogens.[8]

2 SARS-CoV-2 and Its Origin

The SARS-CoV-2 belongs to the family *Coronaviridae* and has one of the largest single-stranded RNA genomes (29.9 kilo bases) for a virus. The major structural proteins encoded by SARS-CoV-2 are spike (S), nucleoprotein, envelope and membrane proteins. Among these structural

[1] *Ella Foundation, Genome Valley, Turkapally, Hyderabad, Telangana 500078, India.*
[2] *Department of Biological Sciences and Engineering, Indian Institute of Technology Palakkad, Nila Campus, Pudussery, P.O. Kanjikode West, Palakkad, Kerala 678623, India.*
[3] *National Institute of Animal Biotechnology, Opposite Journalist Colony, Extended Q City Road, Near Gowlidoddi, Gachibowli, Hyderabad, Telangana 500032, India.*
**hegde@niab.org.in*

proteins, the S protein is critical for the receptor-mediated entry of the virus into susceptible cells. The receptor binding domain (RBD) of the S protein binds the cellular receptor, the angiotensin converting enzyme-2 (ACE2),[9] facilitating entry of the virion particle. Further, transmembrane protease serine 2 (TMPRSS2) helps in the priming of the S protein, where the S protein is cleaved so as to allow the fusion of viral envelope with cellular membrane.[9] In vitro, ACE2 from as many as 44 mammals has been shown to bind to the RBD.[10,11] On the other hand, modelling studies have returned supporting as well as conflicting results on the interaction between S and ACE2.[12–15] Together, these studies only suggest interactions while receptor expression and other host factors may dictate infection, replication and pathogenesis as well as transmission to other hosts.

The first cases of COVID-19 are thought to have originated from live animal markets in Wuhan, China. Analysis of the genomes of SARS-CoV-2 has suggested that the virus may have originated from the Asian bats belonging to the *Rhinolopus* species[16–19] and that the transmission to humans may have involved an intermediate host, possibly the pangolin.[16,17,20–23] However, both the precise origin and the exact intermediate host are conjectures at best. On the other hand, higher sequence similarities of SARS-CoV-2 with bat coronavirus-RaTG13 (96.2%) and Guangdong Pangolin-CoV (92.4%)[22,24] support the zoonotic origin of the virus. However, the SARS-CoV-2 has a unique "PRRA" motif at the junction of the S1 and S2 subunits of the S protein, which makes it distinct from RaTG13 or the Guangdong Pangolin-CoV. Further, the binding affinity of pangolin ACE2 receptor with RBD has been shown to be low.[25] Recent genetic analysis has revealed that three viruses in bats from the limestone karstic terrain in North Laos, BANAL-52, BANAL-103 and BANAL-236 are very close to SARS-CoV-2 with only one or two mutations in the RBD and the absence of a cleavage site for the cellular enzyme furin. These viruses are therefore considered to be the closest match to SARS-CoV-2 in nature.[26]

3 Animal Models for SARS-CoV-2 Infection

Experimental reproduction of COVID-19 in mice requires adaptation of SARS-CoV-2 through serial passage[27] as wild-type mice are resistant to infection.[28] However, mouse adaptation also leads to changes in SARS-CoV-2, which is not ideal for challenge studies. When mutations relevant to mouse adaptation were introduced through reverse genetics, the resultant virus replicated in the upper and the lower respiratory tract of BALB/c mice when the virus was administered intranasally.[29] The main reason for the species restriction appears to be the receptor, since SARS-CoV-2 not adapted to mice or adapted to grow in cell culture can efficiently infect transgenic mice expressing human ACE2 (hACE2),[28–31] and such mice are considered suitable for challenge studies. Some transgenic mice such as *HFH4*-hACE2 mice express the receptor in the respiratory tract and the central nervous system, resulting in lethal encephalitis upon infection through the respiratory route.[29,30,32] A sole study has also reported that when administered intragastrically, the virus could potentially be transmitted by the faecal–oral route[33]; however, the implications of this to transmission in humans are not clear, although SARS-CoV-2 causes gastroenteritis and is excreted in the faeces in humans, but faecal–oral transmission needs further evidence.[34]

Transient expression of hACE2 has also been employed for mouse infection studies. This method has the advantage of utilizing mice from diverse genetic backgrounds. Adenovirus or adeno-associated virus-mediated transduction has been used to express hACE2 in the respiratory tract of mice.[35,36] When mice were transduced with human adenovirus 5 expressing hACE2 and subsequently infected with SARS-CoV-2 through intranasal or intranasal and intravenous route, only the peripheral and not the systemic route resulted in lung infection in mice.[35] In mice transduced with adeno-associated virus 9 expressing hACE2, the transcriptome profile mimicked those in COVID-19 patients, in that interferon (IFN)-stimulated genes and inflammatory cytokines were up-regulated during SARS-CoV-2 infection. It was also observed that type I IFNs were responsible for pathological changes rather than controlling SARS-CoV-2 replication.[36]

Unlike mice, hamsters are susceptible to SARS-CoV-2 infection without the need for adaptation of the virus.[30,37,38] Upon infection, hamsters lose weight initially but regain it by 14 days post-infection. Highest viral loads are detected in the nasal turbinates, lungs and trachea, facilitating the transmission of the virus to in-contact hamsters.[37] Similar to humans, aerosol and droplet transmission between hamsters was higher with the D614G mutant of the virus.[30]

Two mustelids, which are used for commercial (minks) or experimental (ferrets) purposes, are highly susceptible to SARS-CoV-2. Minks undergo efficient upper and lower respiratory

tract infection, with viral RNA being detected in the nasal turbinates, soft palates, tonsils, all lung lobes and submaxillary lymph nodes and infectious virus being detected in most of these samples. Severe pathological conditions are observed in infected minks with extensive and diffuse consolidation of the lungs. Nasal mucosa and submucosa of the vestibular, respiratory and olfactory regions show inflammatory infiltrates, epithelial degeneration and necrosis. Notably, the SARS-CoV-2-mediated respiratory system damage is similar to what is observed in severe human COVID-19 cases. Transmission of SARS-CoV-2 between minks through droplets has also been demonstrated.[39]

Ferrets are also suitable animal models. SARS-CoV-2-infected ferrets show infectious virus in the upper respiratory tract[40] and virus is shed in saliva, urine and faeces.[41] Infected ferrets transmit the virus through respiratory droplets to direct and indirect contact ferrets.[42] Similar to ferrets, racoon dogs infected with SARS-CoV-2 shed the virus through nasal route, leading to infection of in-contact animals. However, the racoon dogs do not show any clinical signs.[43]

Experimentally, SARS-CoV-2 has also been shown to replicate in cats and be excreted in respiratory secretions, and infected cats can transmit the virus to co-housed cats.[44] On the other hand, virus replication is poor in bank voles, cattle, dogs, pigs, chicken, ducks and tree shrews.[40,45–48].

Experimental studies have also been carried out to study the SARS-CoV-2 infection in non-human primates (NHP). Infection produces acute respiratory distress and interstitial pneumonia in rhesus macaques, and severe pneumonia in baboons,[49] but no clinical signs in cynomolgus monkeys.[50] Irrespective of the clinical signs, SARS-CoV-2-infected NHPs show highest viral load in the upper and lower respiratory tract, indicating that NHP's are a good model to study COVID-19 pathogenesis and protective efficacy of vaccines.

White-tailed deer produced subclinical infection upon intranasal administration of a SARS-CoV-2 isolate from a tiger, with the virus excreted in nasal secretions.[51] Pregnant deer could transmit the virus through direct contact and vertically from doe to the foetus, with similar genome proportions in the tissues of the primary and in-contact animals and foetuses.[52] Experimental infection of sheep with SARS-CoV-2 resulted in a mild infection and the viral RNA could be detected in nasal and oral swabs one day post-infection. However, the transmission of the virus from the infected sheep to naïve sheep was limited. Similar to white-tailed deer,[52] when sheep were co-infected with two lineages of SARS-CoV-2, the ancestral lineage A appears to have less advantage over the α variant. However, these experiments have used 1:10 ratio of lineage A and α variant virus for the infection, making appropriate interpretation difficult.[53]

Details of the experimental infection of SARS-CoV-2 in animals are compiled in Table 1.

4 Natural Infection of Animals with SARS-CoV-2

Till date, 31 countries have reported SARS-CoV-2 infection in more than ten animal species (Table 2). While most of the infections are reported from pet animals, outbreaks have also been reported from organized mink farms, and zoo and wild animals.

Several observations have established that pet animals can be infected by SARS-CoV-2 (Table 2). Tests on 17 dogs and 8 cats from COVID-19 households in Hong Kong confirmed positivity in two dogs by molecular and serological assays, with virus being isolated in one case[54,55]; there has also been a press report of a dog showing mild respiratory symptoms and testing positive for SARS-CoV-2 in North Carolina, USA, but a cat and another dog from the same COVID-19 household tested negative.[56]

From a Belgian COVID-19 household, a cat showed respiratory and gastrointestinal symptoms and shed the virus in faeces and gastric fluid, but recovered.[57] Two cats from two independent households in New York state also tested positive by reverse transcription—polymerase chain reaction (RT-PCR), one from a COVID-19 household and the other within an affected neighbourhood and allowed to go outdoors, with the latter reportedly showing respiratory symptoms.[58,59] A cat from Hong Kong also showed positivity without symptoms.[60] Further, 15 (14.7%) of 102 cats tested after the outbreak started in Wuhan were found to carry antibodies to SARS-CoV-2 by enzyme-linked immunosorbent assay (ELISA), and 11 samples showed neutralization of SARS-CoV-2 and no cross-reactivity with feline coronavirus; these samples had been obtained from stray cats, at a veterinary hospital and from animals owned by patients.[61] Thus, it appears that while cats and other felids can be infected, the infection rate may be low, and a symptomatic outcome is rare. In support of this, a study has reported no infection of 9 cats and 12 dogs which were in close contact with COVID-19 patients in a veterinary campus in France,[62]

Table 1: Experimental infection of SARS-CoV-2 in animals.

Animals	SARS-CoV-2 strain	Dose	Inoculation route	Symptoms	Findings	References
HFH4-hACE2 C3B6 mice	SARS-CoV-2 (IVCAS 6.7512)	Primary infection: 3×10^4 $TCID_{50}$ Challenge: 7×10^5 $TCID_{50}$	Intranasal	No visible clinical signs up to 3 DPI; respiratory distress and recovery; some show rapid weight loss	Interstitial pneumonia; virus replication in lungs, brain. Some animals showed death with neurological symptoms. Pre-exposure to virus protects mice from high-dose virus challenge	32
Mice expressing *hACE2* by CRISPR/Cas9 knock-in	SARS-CoV-2 strain (BetaCoV/Wuhan/AMMS01/2020)	4×10^5 PFU	Intranasal	Interstitial pneumonia	Virus replication in lungs trachea and brain. Intragastric route led to respiratory tract infection	33
		4×10^6 PFU	Intragastric	–		
Transgenic mice expressing *hACE2*	SARS-CoV-2 strain HB-01	10^5 $TCID_{50}$	Intranasal	Weight loss	Virus replication in lungs. interstitial pneumonia and infiltration of macrophages and lymphocytes	28
Mice (BALB/c)	SARS-CoV-2 MA10 (SARS-CoV-2 MA passaged ten times in mice to obtain)	10^2,10^3,10^4 and 10^5 PFU	Intranasal	Dose-dependent increase in morbidity and mortality	Mortality rates of 20% for 10^4 PFU dose and 60% for 10^5 PFU dose	27
Mice (BALB/c)	SARS-CoV-2 MA (Recombinant SARS-CoV-2 with designed spike for mouse adaptation)	10^5 PFU	Intranasal	Mild to moderate disease	Virus replication high in lung tissue on 2 DPI but was cleared by 4 DPI	29
Mice transduced with adeno-associated virus 9 encoding hACE2 (5×10^9 genomic copies/ animal, intratracheal)	SARS-CoV-2 isolate USA-WA1/2020	10^6 PFU	Intranasal	–	No significant difference between viral RNA or viral titre between IFN-α receptor–deficient B6/J mice, IFN regulatory factor 3/7 double knockout B6/J, and wild type B6/J AAV-hACE2–infected mice. Antibody response observed between 4 and 7 DPI which increased till 14 DPI	36
BALB/c Mice transduced with adenovirus 5 expressing hACE2 (2.5×10^8 PFU/animal, intranasally)	SARS-CoV-2 strain 2019 n-CoV/USA_WA1/2020	10^5 Focus Forming Unit	Intranasal or Intranasal and intravenous	Weight loss	High level of viral RNA detected in lung. Viral RNA not detected in kidney, gastrointestinal tract tissues, or in serum	35

Table 1: (continued)

Animals	SARS-CoV-2 strain	Dose	Inoculation route	Symptoms	Findings	References
Mice (*HFH4*-hACE2)	SARS-CoV-2	10^5 PFU	Intranasal	–	40% of infected mice died. Virus detected in lungs on 2 and 5 DPI. It was also detected in brain on 5 DPI	[29]
Mice (K18-hACE2 mice)	SARS-CoV-2 (strain 2019n-CoV/USA_WA1/2020)	2.5×10^4 PFU	Intranasal	Weight loss	Highly susceptible, succumb to disease by 7 DPI. High levels of virus and viral RNA detected in the lungs	[31]
Mice (*HFH4*-hACE2)	Recombinant SARS-CoV-2 virus with D614G mutation in spike derived from WA1 strain	10^3 PFU	Intranasal	Minimum body weight loss	High viral titres in lungs and brain tissue. Similar susceptibility to wild-type and D614G variant	[30]
Syrian Hamster	SARS-CoV-2 isolated from Honk Kong patient	10^5 PFU	Intranasal	Weight loss, rapid breathing	Animal-to-animal transmission demonstrated through direct contact. On 14 DPI, all infected hamsters had neutralizing antibody titres $\geq$ 1:427	[37]
Syrian Hamster	SARS-CoV-2/UT-NCGM02/Human/2020/Tokyo and SARS-CoV-2/UW-001/Human/2020/Wisconsin	$10^{5.6}$ or 10^3 PFU	Intranasal and intraocular	Weight loss	High susceptibility	[38]
Syrian Hamster	Recombinant SARS-CoV-2 virus with D614G mutation in spike derived from WA1 strain	10^3 PFU	Intranasal	Weight loss	High susceptibility for D614G variant with significantly faster spread between hamsters through aerosol and droplets	[30]
Mink	SARS-CoV-2/HRB25/human/2020/CHN (HRB25, GISAID access no. EPI_ISL_467430)	5×10^6 PFU	Intranasal	Weight loss between 10 and 20% at around 8 DPI; 5% in in-contact animals	Highly susceptible. Upper and lower respiratory tract infection. Viral RNA and infectious virus detected in most of the respiratory tract samples, with severe lung pathology. Virus transmission through droplet observed	[39]

Table 1: (continued)

Animals	SARS-CoV-2 strain	Dose	Inoculation route	Symptoms	Findings	References
Ferrets	SARS-CoV-2/F13/environment/2020/Wuhan or SARS-CoV-2/CTan/human/2020/Wuhan	10^5 PFU	Intranasal	Fever and loss of appetite	Viral RNA and infectious virus detected in the nasal turbinate, soft palate, and tonsils of infected ferrets. Virus replication in upper respiratory tract up to 8 days without causing severe disease or death	[40]
Ferrets	SARS-CoV-2 isolate from South Korea (NMC-nCoV02)	$10^{5.5}$ $TCID_{50}$	Intranasal	Fever, acute bronchiolitis	Highest infectious virus and viral RNA detected in nasal washes of infected ferrets on 4 DPI. Virus also shed in saliva, urine and faeces. Viral RNA detected in nasal washes and faeces of contact animals. Ferret-to-ferret transmission detected	[41]
Ferrets	SARS-CoV-2 (isolate BetaCoV/Munich/BavPat1/2020)	6×10^5 $TCID_{50}$	Intranasal	Not defined	Ferret-to-ferret transmission demonstrated through direct contact and indirect contact through respiratory droplets. Infectious titre ranged between 0.75 and 2.75 $\log_{10}$ $TCID_{50}$/ml in the donor ferrets, from 0.75 to 3.5 $\log_{10}$ $TCID_{50}$/ml in the direct contact ferrets from 0.75 to 4.25 $\log_{10}$ $TCID_{50}$/ml in the indirect contact ferrets. Infected ferrets in all groups seroconverted by 21 DPI or exposure	[42]
Cats	SARS-CoV-2 isolate UT-NCGM02/Human/2020/Tokyo	5.2×10^5 PFU	Combination of intranasal, intratracheal, oral and ocular	–	Virus detected in all inoculated cats by 3 DPI. Virus detected in co-housed animals by 5 DPI	[44]

Table 1: (continued)

Animals	SARS-CoV-2 strain	Dose	Inoculation route	Symptoms	Findings	References
Cats	SARS-CoV-2/CTan/human/2020/Wuhan	10^5 PFU	Intranasal	–	Viral RNA detected in nasal turbinates, soft palates, tonsils, trachea, or small intestine. Viral RNA not detected in lungs. Virus detected in the upper respiratory tract, tonsils, tracheas, and lungs but not in the small intestines. Younger cats more susceptible than older cats. Cat-to-cat transmission detected	40
Cats	SARS-CoV-2 virus strain WA1/2020WY96	3 X 10^5 PFU	Intranasal	No clinical signs	Virus shed up to 5 DPI. Contact cat shed virus up to 7 DPI. Seroconversion by 7 DPI. Neutralizing antibody titres $\geq$ 1:2560 by 14 DPI. Virus shedding not detected in challenged cats	45
Rhesus macaques	SARS-CoV-2 isolate nCoV-WA1–2020	2×10^5 $TCID_{50}$	Intranasal	Initial weight loss, irregular respiratory pattern and piloerection, reduced appetite, hunched posture, pale appearance, dehydration	High susceptibility. Virus shedding highest in nose, throat and bronchioalveolar lavage (BAL). Virus isolated from nose and BAL on 1 and 3 DPI. Pulmonary infiltrates visible in lung radiographs	106
		4×10^5 $TCID_{50}$	Oral			
		16×10^5 $TCID_{50}$	Intratracheal			
		2×10^5 $TCID_{50}$	Ocular			
Rhesus macaques	SARS-CoV-2/WH-09/human/2020/CHN	Primary infection on day 0: 10^6 $TCID_{50}$/mL Reinfection on day 28: 10^6 $TCID_{50}$/mL	Intratracheal	Interstitial pneumonia and systemic viral dissemination mainly in the respiratory and gastrointestinal tracts	Initial infection with SARS-CoV-2 protects against reinfection during early recovery phase. Reinfection increased neutralizing antibodies	107
Rhesus macaques	SARS-CoV-2 USA-WA1/2020	Primary infection: 1.1×10^4 or 1.1×10^5 or 1.1×10^6 PFU Reinfection on 35 days: doses same as primary infection	Intranasal and Intratracheal	Interstitial pneumonia	High viral loads in the upper and lower respiratory tract. Primary infection with SARS-CoV-2 protects against rechallenge on 35 DPI. Up on reinfection, median viral load reduced by 5 log_{10} in BAL and nasal mucosa	108

Table 1: (continued)

Animals	SARS-CoV-2 strain	Dose	Inoculation route	Symptoms	Findings	References
Rhesus macaques	SARS-CoV-2 USA-WA1/2020	1.05×10^6 PFU	Ocular, intratracheal and intranasal	Acute respiratory distress. Mild-to-moderate pneumonia	Old and young age groups recover in two weeks. T cell memory and bystander cytokine production. Lower titres of specific IgG antibodies in old animals	49
Cynomolgus macaques	SARS-CoV-2 (isolate BetaCoV/Munich/BavPat1/2020)	10^6 $TCID_{50}$	Intranasal and Intratracheal	No clinical sign	Virus shedding from nose and throat. SARS-CoV-2 antigen detected in type I and II pneumocytes in affected lung and in ciliated epithelial cells of nasal, bronchial, and bronchiolar mucosae	50
Baboons	SARS-CoV-2 USA-WA1/2020	1.05×10^6 PFU	Ocular, intratracheal and intranasal	Acute respiratory distress, severe pneumonia	Infectious virus detected on 3 DPI. Highest viral load in rectal swab	49
Marmosets	SARS-CoV-2 USA-WA1/2020	1.05×10^6 PFU	Ocular, intratracheal and intranasal	Mild infection	Viral RNA peaked at 3 DPI	49
White-tailed deer	SARS-CoV-2 TGR/NY/20 (isolated from infected tiger)	$5 \times 10^{6.3}$ $TCID_{50}$	Intranasal	Subclinical infection	Virus shedding detected in nasal secretions from all inoculated and contact animals	51
White-tailed deer	SARS-CoV-2/human/USA/WA1/2020 lineage A SARS-CoV-2/human/USA/CA_CDC_5574/2020 lineage B.1.1.7 VOC	2 ml dose of 1×10^6 $TCID_{50}$ per animal (1:1 titre ratio of both viruses)	Intranasal and oral	Subclinical infection	Virus shedding through nasal and oral secretions of infected animals and contact animals. B.1.1.7 isolate sequence more than the lineage A WA1 isolate sequence. Virus transmission through direct contact and vertically from doe to foetus	52
Sheep	SARS-CoV-2/human/USA/WA1/2020 lineage A SARS-CoV-2/human/USA/CA_CDC_5574/2020 lineage B.1.1.7	2 ml dose of 1×10^6 $TCID_{50}$ per animal (1:10 titre ratio of lineage A: lineage B)	Intranasal and oral	Mild infection	Oral and nasal swab positive on 1 DPI. Viral RNA detected in respiratory tract and lymphoid tissues at 4 and 8 DPI. Virus transmission to naïve animals were limited	53

Table 1: (continued)

Animals	SARS-CoV-2 strain	Dose	Inoculation route	Symptoms	Findings	References
Dogs	SARS-CoV-2 virus strain WA1/2020WY96	1.4×10^5 PFU	Intranasal	No clinical signs	Virus shedding not detected. Neutralizing antibody titres between 1:40 and 1:80 at 14 to 21 DPI	45
Dogs	SARS-CoV-2/CTan/human/2020/Wuhan	10^5 PFU	Intranasal	No clinical signs	Low susceptibility. 2 out of 4 dogs seroconverted. Dog-to-dog transmission not detected	40
Racoon dogs	SARS-CoV-2 2019_nCoV Muc-IMB-1	10^5 $TCID_{50}$	Intranasal	No clinical signs	Virus detected in nasal and oropharyngeal swab samples on days 2–4. 66.6% of the contact animals infected	43
Cattle	SARS-CoV-2 strain Muc-IMB-1	10^5 $TCID_{50}$	Intranasal	No clinical signs	Virus replication and seroconversion in 2 or 6 animals. Cattle-to-cattle transmission not detected	47
Tree shrews	SARS-CoV-2 (strain not defined)	10^6 PFU	Intranasal	Fever in young and old than adult animals	Low susceptibility. Highest viral load in pancreas in one animal	48
Bank voles	SARS-CoV-2 strain Muc-IMB-1	10^5 $TCID_{50}$	Intranasal	No clinical signs	Seroconversion within 8 days and viral RNA detected in nasal tissue for up to 21 days. Transmission to contact animals not detected	46
Pigs, chickens and ducks	SARS-CoV-2/CTan/human/2020/Wuhan	10^5 PFU	Intranasal	No clinical signs	Not susceptible	40

DPI days post-infection, ***PFU*** plaque-forming units, ***TCID50*** 50% tissue culture infective dose

Table 2: Natural infection of SARS-CoV-2 in animals.

Species	Number	Country	Month and year	References
Pet animals				
Dog	2	Hong Kong	February to March 2020	[55]
	1	Netherlands	April 2020	https://www.rijksoverheid.nl/documenten/kamerstukken/2020/05/15/kamerbrief-over-corona-bij-dieren
	18	USA	June to July 2020	https://www.aphis.usda.gov/animal_health/one_health/downloads/sars-cov2-in-animals.pdf
	1	Denmark	June 2020	https://www.oie.int/fileadmin/Home/MM/Update_1_Letter_to_OIE_about_the_COVID-19_situation_in_Denmark.pdf
	2	Hong Kong	July to Sept 2020	https://wahis.oie.int/#/report-info?reportId=15464 https://wahis.oie.int/#/report-info?reportId=15471 https://wahis.oie.int/#/report-info?reportId=15620 https://wahis.oie.int/#/report-info?reportId=15702
	4	Japan	July 2020 to November 2020	https://wahis.oie.int/#/report-info?reportId=16168
	12	USA	August to September 2020	https://www.aphis.usda.gov/animal_health/one_health/downloads/sars-cov2-in-animals.pdf
	10	Mexico	August 2020 to March 2021	https://wahis.oie.int/#/report-info?reportId=16869
	1	Canada	October 2021	https://www.oie.int/fileadmin/Home/MM/CFIA_ACIA-_14346824-v3-OIE_SARS-CoV-2_in_dog_letter__002_.pdf
	4	Argentina	October 2021	https://wahis.oie.int/#/report-info?reportId=25035
	18	Brazil	October 2020 to March 2021	https://wahis.oie.int/#/report-info?reportId=16113 https://wahis.oie.int/#/report-info?reportId=16847 https://wahis.oie.int/#/report-info?reportId=31367
	6	Hong Kong	November 2020 to January 2021	https://wahis.oie.int/#/report-info?reportId=16336 https://wahis.oie.int/#/report-info?reportId=16423 https://wahis.oie.int/#/report-info?reportId=16464 https://wahis.oie.int/#/report-info?reportId=16524 https://wahis.oie.int/#/report-info?reportId=16700 https://wahis.oie.int/#/report-info?reportId=16939
	2	Germany	November 2020	https://www.oie.int/fileadmin/Home/MM/Germany_1_December.pdf
	1	Hong Kong	January to February 2021	https://wahis.oie.int/#/report-info?reportId=17017
	1	Bosnia and Herzegovina	February 2021	https://wahis.oie.int/#/report-info?reportId=28184
	17	USA	October 2020 to November 2021	https://wahis.oie.int/#/report-info?reportId=42300
	4	Argentina	March 2021	https://wahis.oie.int/#/report-info?reportId=30744
	2	Croatia	April 2021	https://wahis.oie.int/#/report-info?reportId=32538
	1	Switzerland	April 2021	https://wahis.oie.int/#/report-info?reportId=35662
	1	Thailand	May 2021	https://wahis.oie.int/#/report-info?reportId=33320
	1	Uruguay	May 2021	https://wahis.oie.int/#/report-info?reportId=33930
	2	Brazil	May 2021	https://wahis.oie.int/#/report-info?reportId=34358
	1	Japan	May 2021	https://wahis.oie.int/#/report-info?reportId=34040
	4	Croatia	June to November 2021	https://wahis.oie.int/#/report-info?reportId=34882
	1	Switzerland	July 2021	https://wahis.oie.int/#/report-info?reportId=38903

Table 2: (continued)

Species	Number	Country	Month and year	References
	2	UK	August to November 2021	https://wahis.oie.int/#/report-info?reportId=38348 https://wahis.oie.int/#/report-info?reportId=42489
	3	Japan	August to October 2021	https://wahis.oie.int/#/report-info?reportId=38745 https://wahis.oie.int/#/report-info?reportId=40553 https://wahis.oie.int/#/report-info?reportId=40968
	1	Myanmar	October 2021	https://wahis.oie.int/#/report-info?reportId=40712
Cat	1	Belgium	March 2020	https://www.oie.int/fileadmin/Home/eng/Our_scientific_expertise/docs/pdf/COV-19/Belgium_28.03.20.pdf
	1	Hong Kong	March 2020	https://wahis.oie.int/#/report-info?reportId=14765 https://wahis.oie.int/#/report-info?reportId=14982
	11	China	April 2020	[109]
	1	Spain	April 2020	https://www.oie.int/fileadmin/Home/eng/Our_scientific_expertise/docs/pdf/COV-19/E_Nota_Informe_gato_OIE_ESP.pdf
	2	USA	April 2020	https://www.aphis.usda.gov/animal_health/one_health/downloads/sars-cov2-in-animals.pdf
	2	France	May 2020	[72] https://www.oie.int/fileadmin/Home/eng/Our_scientific_expertise/docs/pdf/COV-19/covid_chat_ENVT-1_France.pdf
	1	Germany	May 2020	https://www.oie.int/fileadmin/Home/MM/Germany_on_13_May_2020.pdf
	1	Spain	May 2020	https://www.oie.int/fileadmin/Home/eng/Our_scientific_expertise/docs/pdf/COV-19/Nota_Gato_SARS-CoV-2_spain.pdf
	3	Netherlands	May 2020	https://www.oie.int/fileadmin/Home/eng/Our_scientific_expertise/docs/pdf/COV-19/Bruschke_CVOs_Mink_SARS_CoV2_15May2020.pdf
	1	Russia	May 2020	https://wahis.oie.int/#/report-info?reportId=15107 https://wahis.oie.int/#/report-info?reportId=15280
	3	Chile	June 2020	https://wahis.oie.int/#/report-info?reportId=25032
	40	USA	June to September 2020	https://www.aphis.usda.gov/animal_health/one_health/downloads/sars-cov2-in-animals.pdf
	1	UK	July 2020	https://wahis.oie.int/#/report-info?reportId=15477
	5	Hong Kong	July–September 2020	https://wahis.oie.int/#/report-info?reportId=15464 https://wahis.oie.int/#/report-info?reportId=15471 https://wahis.oie.int/#/report-info?reportId=15620 https://wahis.oie.int/#/report-info?reportId=15702
	2	Japan	July 2020 to November 2021	https://wahis.oie.int/#/report-info?reportId=16168
	2	Argentina	October 2020	https://wahis.oie.int/#/report-info?reportId=25035
	12	Brazil	October 2020 to March 2021	https://wahis.oie.int/#/report-info?reportId=16113 https://wahis.oie.int/#/report-info?reportId=16847 https://wahis.oie.int/#/report-info?reportId=31367
	2	Hong Kong	November 2020 to January 2021	https://wahis.oie.int/#/report-info?reportId=16423 https://wahis.oie.int/#/report-info?reportId=16464 https://wahis.oie.int/#/report-info?reportId=16524 https://wahis.oie.int/#/report-info?reportId=16700 https://wahis.oie.int/#/report-info?reportId=16939
	1	Canada	November 2020	https://www.oie.int/fileadmin/Home/MM/Canada_cat_21.12.2020.pdf
	2	Germany	November 2020	https://www.oie.int/fileadmin/Home/MM/Germany_1_December.pdf

Table 2: (continued)

Species	Number	Country	Month and year	References
	1	Switzerland	December 2020	https://www.oie.int/fileadmin/Home/MM/Switzerland_03.12.2020_Research_on_SARS-CoV-2_-_confirmation_in_a_cat_in_the_Canton_of_Zurich.pdf
	1	Italy	December 2020	https://www.oie.int/fileadmin/Home/MM/Italy_01.12.pdf
	2	Greece	December 2020	https://www.oie.int/fileadmin/Home/MM/Greece_cat_23.12.2020.pdf
	2	Canada	January 2021	https://www.oie.int/fileadmin/Home/MM/Canada_cat_10.02.2021.pdf
	3	Switzerland	January to April 2021	https://wahis.oie.int/#/report-info?reportId=16941 https://wahis.oie.int/#/report-info?reportId=35662
	1	Latvia	February 2021	https://wahis.oie.int/#/report-info?reportId=17105
	1	Italy	March 2021	https://wahis.oie.int/#/report-info?reportId=30889
	1	Estonia	March 2021	https://wahis.oie.int/#/report-info?reportId=30463
	2	Argentina	March 2021	https://wahis.oie.int/#/report-info?reportId=30744
	3	Japan	March 2021	https://wahis.oie.int/#/report-info?reportId=31685
	2	Latvia	March 2021	https://wahis.oie.int/#/report-info?reportId=31360
	1	Croatia	April 2021	https://wahis.oie.int/#/report-info?reportId=32666
	1	Uruguay	May 2021	https://wahis.oie.int/#/report-info?reportId=33930
	3	Brazil	May 2021	https://wahis.oie.int/#/report-info?reportId=34358
	1	Thailand	June 2021	https://wahis.oie.int/#/report-info?reportId=34106
	27	USA	October 2020 to November 2021	https://wahis.oie.int/#/report-info?reportId=42300
Ferret	1	Slovenia	December 2020	https://wahis.oie.int/#/report-info?reportId=28156
Captive zoo animals				
Lions	3	USA	March–April 2020	[110] https://www.aphis.usda.gov/animal_health/one_health/downloads/sars-cov2-in-animals.pdf
	4	Spain	November 2020	https://www.oie.int/fileadmin/Home/MM/Spain_lions_21.12.2020.pdf
	5	Sweden	January 2021	https://www.oie.int/fileadmin/Home/MM/Sweden_25.01.2021_lion_tiger.pdf
	1	Estonia	January 2021	https://www.oie.int/fileadmin/Home/MM/Estonia_22.01.2021_Lion.pdf
	17	India	June 2021	https://www.dailymail.co.uk/news/article-9540377/Eight-LIONS-test-positive-Covid-19-Indian-zoo.html https://www.dailymail.co.uk/news/article-9659687/Lioness-dies-COVID-19-Indian-zoo-eight-tested-positive.html
	19	USA	October 2020 to November 2021	https://wahis.oie.int/#/report-info?reportId=42300
	3	South Africa	July 2021	https://wahis.oie.int/#/report-info?reportId=36771
	5	Singapore	November 2021	https://wahis.oie.int/#/report-info?reportId=42534
Tiger	4	USA	March–April 2020	[110] https://www.aphis.usda.gov/animal_health/one_health/downloads/sars-cov2-in-animals.pdf
	1	Sweden	January 2021	https://www.oie.int/fileadmin/Home/MM/Sweden_15.01.2021_tiger_zoo.pdf
	19	USA	October 2020 to November 2021	https://wahis.oie.int/#/report-info?reportId=42300
	2	Indonesia	September 2021	https://wahis.oie.int/#/report-info?reportId=39313

Table 2: (continued)

Species	Number	Country	Month and year	References
Puma/ Cougar	1	South Africa	July 2020	https://wahis.oie.int/#/report-info?reportId=15584
	1	USA	October 2020 to November 2021	https://wahis.oie.int/#/report-info?reportId=42300
	1	Argentina	February 2021	https://wahis.oie.int/#/report-info?reportId=25065
Snow Leopard	3	USA	December 2020	https://www.aphis.usda.gov/aphis/newsroom/stakeholder-info/sa_by_date/sa-2020/sa-12/ky-snow-leopard-covid https://www.aphis.usda.gov/animal_health/one_health/downloads/sars-cov2-in-animals.pdf
	10	USA	October 2020 to November 2021	https://wahis.oie.int/#/report-info?reportId=42300
Gorillas	13	USA	October 2020 to November 2021	https://wahis.oie.int/#/report-info?reportId=42300
Coatimundi	1	USA	October 2021	https://wahis.oie.int/#/report-info?reportId=41500
Fishing cat	1	USA	October 2021	https://wahis.oie.int/#/report-info?reportId=41500
Binturong	1	USA	October 2021	https://wahis.oie.int/#/report-info?reportId=41500
Asian small-clawed otter	7	USA	October 2020 to November 2021	https://wahis.oie.int/#/report-info?reportId=42300
Spotted Hyena	2	USA	November 2021	https://wahis.oie.int/#/report-info?reportId=42300
Captive farm animals				
Mink	69 farms	Netherlands	April 2020 to January 2021	https://www.oie.int/fileadmin/Home/eng/Our_scientific_expertise/docs/pdf/COV-19/OIE_SARS_CoV%202_infection_of_mink_in_the_Netherlands_26April2020.pdf https://www.oie.int/fileadmin/Home/MM/Netherlands_6_January_2021_to_OIE_update_situation_SARS-CoV-2_in_mink.pdf [85]
	290 farms	Denmark	June 2020 to December 2020	https://old.oie.int/fileadmin/Home/eng/Our_scientific_expertise/docs/pdf/COV-19/Denmark_Sars-CoV-2_17-06-2020.pdf https://old.oie.int/fileadmin/Home/MM/Update_1_Letter_to_OIE_about_the_COVID-19_situation_in_Denmark.pdf https://old.oie.int/fileadmin/Home/MM/Update_3_Letter_to_OIE_about_the_COVID-19_situation_in_Denmark.pdf https://old.oie.int/fileadmin/Home/MM/Update_4_Letter_to_OIE_on_Sars-CoV-2_in_mink_farms_in_Denmark.pdf https://old.oie.int/fileadmin/Home/MM/Update_5_Letter_to_OIE_on_Sars-CoV-2_in_Denmark.pdf https://old.oie.int/fileadmin/Home/MM/Update_6_Letter_to_the_OIE_on_Sars-CoV-2_in_Denmark_5_november2020.pdf [111]
	2 farm	Spain	December 2020 to January 2021	https://www.oie.int/fileadmin/Home/MM/Informe_visones_OIE_16.07.20_.pdf https://wahis.oie.int/#/report-info?reportId=16924 https://wahis.oie.int/#/report-info?reportId=16851
	16 farms	USA	August to November 2020	https://www.aphis.usda.gov/animal_health/one_health/downloads/sars-cov2-in-animals.pdf
	13 farms	Sweden	October to December 2020	https://www.oie.int/fileadmin/Home/MM/Sweden_Update_1_29.10.2020.pdf https://www.oie.int/fileadmin/Home/MM/Sweden_mink_6Nov2020.pdf https://www.oie.int/fileadmin/Home/MM/Sweden_1.12.2020.pdf

Table 2: (continued)

Species	Number	Country	Month and year	References
	1 farm	Italy	October 2020	https://www.oie.int/fileadmin/Home/MM/Italy_COVID_30.10.2020.pdf https://www.oie.int/fileadmin/Home/MM/Italy_mink_11_11_2020-DGSAF-MDS-P.pdf https://www.oie.int/fileadmin/Home/MM/Ordinanza_21_novembre_2020.pdf
	11 farms	Greece	December 2020 to February 2021	https://wahis.oie.int/#/report-info?reportId=17059 https://wahis.oie.int/#/report-info?reportId=17127
	4 farms	France	November 2020	https://wahis.oie.int/#/report-info?reportId=16335 https://wahis.oie.int/#/report-info?reportId=16701
	4 farm	Lithuania	November 2020 to March 2021	https://wahis.oie.int/#/report-info?reportId=16373 https://wahis.oie.int/#/report-info?reportId=16666 https://wahis.oie.int/#/report-info?reportId=31409
	2 farm	Canada	November to December 2020	https://wahis.oie.int/#/report-info?reportId=25040 https://wahis.oie.int/#/report-info?reportId=25045
	1 farm	Poland	February 2021	https://wahis.oie.int/#/report-info?reportId=17018
	1 farm	Spain	March 2021	https://wahis.oie.int/#/report-info?reportId=31188
	1 farm	Italy	April 2021	https://wahis.oie.int/#/report-info?reportId=32262
	1 farm	Latvia	April 2021	https://wahis.oie.int/#/report-info?reportId=32647
	1 farm	Canada	May 2021	https://wahis.oie.int/#/report-info?reportId=33510 https://wahis.oie.int/#/report-info?reportId=34464 https://wahis.oie.int/#/report-info?reportId=36972 https://wahis.oie.int/#/report-info?reportId=40991
	10 farm	Spain	June to October 2021	https://wahis.oie.int/#/report-info?reportId=31188 https://wahis.oie.int/#/report-info?reportId=34510 https://wahis.oie.int/#/report-info?reportId=35308 https://wahis.oie.int/#/report-info?reportId=35310 https://wahis.oie.int/#/report-info?reportId=35311 https://wahis.oie.int/#/report-info?reportId=35314 https://wahis.oie.int/#/report-info?reportId=35655 https://wahis.oie.int/#/report-info?reportId=36329 https://wahis.oie.int/#/report-info?reportId=36331 https://wahis.oie.int/#/report-info?reportId=37890 https://wahis.oie.int/#/report-info?reportId=39636 https://wahis.oie.int/#/report-info?reportId=40677 https://wahis.oie.int/#/report-info?reportId=41492 https://wahis.oie.int/#/report-info?reportId=41617
	1 farm	Poland	June 2021	https://wahis.oie.int/#/report-info?reportId=35103
	2 farm	Greece	August to September 2021	https://wahis.oie.int/#/report-info?reportId=38527 https://wahis.oie.int/#/report-info?reportId=39170
	1 farm	Sweden	August 2021	https://wahis.oie.int/#/report-info?reportId=38730 https://wahis.oie.int/#/report-info?reportId=41009
Beavers	1 farm	Mongolia	September 2021	https://promedmail.org/promed-post/?id=8664608
Wild animals				
White-tailed deer	8	USA	August 2021	https://wahis.oie.int/#/report-info?reportId=38714
Mink (free-ranging)	1	USA	August to October 2020	https://www.reuters.com/article/us-health-coronavirus-usa-mink-idUSKBN28O2UR

Adapted from https://www.avma.org/resources-tools/animal-health-and-welfare/covid-19/depth-summary-reports-naturally-acquired-sars-cov-2 and updated with the latest information available from various sources

and only one asymptomatic (but positive by RT-PCR) cat among 12 dogs, 8 cats, 2 rabbits and one guinea pig from 17 confirmed COVID-19 households in Spain.[63] In addition, a serological survey of preserved sera from 487 dogs and 87 cats from among 1914 samples from 35 species of animals from China showed no positivity, although the samples probably predated COVID-19.[64] Studies on pets which belong to COVID-19 patients in Brazil also indicated that the pet animals were susceptible to SARS-CoV-2 infection. Nine out of 29 dogs and four out of 10 cats were seropositive for SARS-CoV-2. Partial genome sequence of SARS-CoV-2 was obtained from the samples, but no virus isolation was attempted.[65] In most of the documented cases of SARS-CoV-2 infection in dogs and cats, the symptoms were variable; while most of the animals were asymptomatic, some of the animals had mild respiratory distress. Recent studies have also linked myocarditis as one possible outcome with SAR-CoV-2 B.1.1.7 variant infection of dogs and cats.[66]

Direct or indirect evidence of SARS-CoV-2 infection in pet animals during the COVID-19 pandemic exists from Germany, Italy, Peru, the USA, France and several other countries.[65,67–71] In multiple cases, genome sequences of SARS-CoV-2 obtained from pet animals were similar to that of the circulating human strains. For example, the SARS-CoV-2 genome sequence from a cat had D614G mutation specific to the phylogenetic clade A2 observed in the French SARS-CoV-2 genome sequences.[72] Studies in France also showed that the SARS-CoV-2 genome sequences from a pet dog and its COVID-19 affected owners were of B.1.160 lineage with 99–100% identity.[73] The SARS-CoV-2 genome from a domestic cat was close to the human B.1.1.39 lineage in Switzerland.[74] Similar observations have been made in Argentina, where the SARS-CoV-2 genome sequence from domestic cats belonged to the B.1.499 lineage, which circulated in humans in that region.[75] In one instance, the SARS-CoV-2 genome sequence of the owner and the pet animals (dog and cat) from the same household were found to be identical and belonged to the B.1.575 lineage.[76]

In a seroprevalence study on samples collected from cats (2160 samples) from Germany, the UK, Italy and Spain, 96 samples (4.4%) were positive by virus neutralization test and 92 samples (4.3%) were positive by an ELISA for the RBD. Since the samples were collected for some other ailments and not for SARS-CoV-2 infection, the presence of antibodies against SARS-CoV-2 during the COVID-19 pandemic in the samples from cats indicates possible human-to-cat transmission.[77] In Slovenia, a pet ferret of a COVID-19-affected owner was positive for SARS-CoV-2 by RT-PCR,[78] and this supports the findings of the experimental studies where ferrets were documented to be highly susceptible for SARS-CoV-2 infection.[40–42]

5 SARS-CoV-2 Infection in Captive Animals

Apart from pet animals, SARS-CoV-2 can also infect captive and farm animals. Mild respiratory symptoms were reported in five tigers and three lions in the Bronx zoo, New York, supposedly from being in contact with a COVID-19 asymptomatic zookeeper; SARS-CoV-2 was confirmed by RT-PCR,[79] the virus was isolated, and complete viral genome sequence was elucidated in the case of a Malayan tiger.[80] Virus isolation was not attempted from other zoo animals. Interestingly, SARS-CoV-2 genome sequence from tigers and lions was of different genotypes, which indicates two independent sources of infection.

Other zoo and captive animals that can be affected include puma, mink (farmed and wild), lion, tiger, ferret, snow leopard, gorilla, otter, cougar, coatimundi, binturong, Canada lynx and hyena.[78,81] While most of the animals showed mild symptoms of cough and respiratory distress with or without nasal discharge and recovered later, four snow leopards succumbed to SARS-CoV-2 infection at the Great Plains Zoo, South Dakota, USA.[82,83]

Fur industry across various countries has been affected severely due to the high susceptibility of minks to SARS-CoV-2. Netherlands reported the first outbreak of SARS-CoV-2 in a mink farm in April 2020. Since then, the disease has been reported from Denmark, the USA, France, Greece, Italy, Poland, Lithuania, Canada, Spain and Sweden. Minks are housed in confined spaces, and the infection could spread rapidly among them through droplets. Severity of respiratory sickness is pronounced in minks with high mortality and post-mortem findings of acute interstitial pneumonia.[84] Considering the severity of the disease, Denmark, Spain, the Netherlands and France culled entire affected mink colonies and the Netherlands has banned mink farming permanently.

In the Netherlands, one mink farm worker was found positive for the virus and clear evidence of mink-to-mink transmission was established.[85] Three out of 11 tested cats in one of the farms were also positive for anti-SARS-CoV-2

antibodies, but no viable virus could be detected,[86] although the direction of transmission is not clear in this case. In one of the outbreaks, a probable mink-to-feral cat transmission was recorded.[87] Mink-to-human transmission was also established based on the sequence data from the Netherlands,[111] Denmark[88] and the USA.[89] SARS-CoV-2 virus isolates obtained from minks with Spike Y453F/D614G mutation have higher affinity to hACE2.[90] Whole-genome sequencing of the SARS-CoV-2 from minks revealed 170 mutations, and the mink-specific mutations of SARS-CoV-2 were also found in 300 samples collected from humans indicating mink-to-human transmission.[91] By contrast, the mink SARS-CoV-2 genome from Greece lacked the Y453F mutation in the S protein,[92] suggesting differential adaptability or simply randomness in the emergence of the variants.

Recently, transmission of SARS-CoV-2 was recorded from Syrian hamsters to humans in a pet shop at Hong Kong. Further investigation revealed that Syrian hamsters from both pet shop (50%) and warehouse (58%) were positive for SARS-CoV-2 with RT-qPCR which resulted in the culling of about 2000 hamsters across Hong Kong. The SARS-CoV-2 genome sequence from affected humans and Syrian hamsters belonged to the delta variant (AY.127), and analyses pointed to multiple hamster-to-human transmission events. Interestingly, other animals from the pet shop such as dwarf hamsters, rabbits, guinea pigs, chinchillas and mice tested negative for SARS-CoV-2. This incident is the only documented evidence of Syrian hamsters acquiring SARS-CoV-2 infection in natural settings.[93]

About 40% of the serum samples from white-tailed deer collected by the United States Department of Agriculture between January 2020 and March 2021 were positive for SARS-CoV-2 antibodies.[94] Based on the initial finding, further study was initiated to understand the SARS-CoV-2 strains circulating in deer. Retropharyngeal lymph nodes were collected from white-tailed deer from Iowa between April 2020 and January 2021. Whole-genome sequence of SARS-CoV-2 from white-tailed deer indicated the presence of 12 lineages of SARS-CoV-2, with the predominance of B.1.2 (54.5%), B.1.311 (20%), B.1 (7%) and B.1.234 (6%) lineages. Surprisingly, the B.1.2 lineage was also the most abundant lineage circulating in humans in Iowa during that period, suggesting multiple human-to-deer and deer-to deer transmissions; however, deer-to-human transmission could not be interpreted from this study.[95]

Brazil has reported the presence of SARS-CoV-2 nucleic acid in wild animals such as Giant anteaters, black-tailed marmoset and West Indian manatee.[96] Since these reports were based on random surveillance, the source of infection could not be determined. However, these findings have further widened the list of animals susceptible to SARS-CoV-2 infection.

6 The Veterinary and One Health Perspective

SARS-CoV-2 infection has been confirmed so far in canids (dogs and raccoon dogs), felids (cats, tigers, lions, puma/cougar, lynx and snow leopard), mustelids (ferrets and minks), viverrids (binturongs), procyonids (coatimundis), hyaenids (hyenas), cervids (white-tailed deer, mule deer), cricetids (Syrian hamster), callitrichids (black-tailed marmoset), myrmecophagids (giant anteater), trichechids (West India manatee), castorids (beaver) and primates (gorilla). With such a wide range of hosts available for the virus, it is possible that the virus can mutate, adapt and be transmitted widely.[97] The close similarity of the SARS-CoV-2 genome sequence between humans and pet animals and the higher incidence of SARS-CoV-2 infection in pet animals during the human pandemic strongly suggest that humans can transmit SARS-CoV-2 to closely in-contact pets such as cats and dogs. On the other hand, transmission of SARS-CoV-2 from cats or dogs to humans is yet to be established and needs further investigation. Though there is no documented evidence of transmission of SARS-CoV-2 from animals to humans, except from minks and Syrian hamsters, animal owners and veterinarians must be vigilant while handling animals with respiratory illness to minimize the potential risk of transmission from pets.

One way to mitigate transmission from animals is to vaccinate the animals. In addition, this could also save endangered animals. Since SARS-CoV-2 has broad host range, it may be practically impossible to vaccinate all the animals. However, susceptible pet animals and captive animals that are in close proximity with humans should be vaccinated in order to avoid any animal-to-human transmission of SARS-CoV-2. However, very few vaccines have been tested or are available for use in animals. An aluminium-adjuvanted subunit vaccine based on modified S protein was demonstrated to protect minks from SARS-CoV-2 challenge. Upon challenge, the virus was not detected in any of the organs that were tested in the vaccinated group while high titre of

the virus was detected in all the organs of control animals.[39] Similarly, black-footed ferrets, which are endangered in North America, could produce neutralizing antibodies when immunized with commercially available purified SARS-CoV-2 Spike protein adsorbed to aluminium oxyhydroxide (alhydrogel® 2%). More than 100 captive animals were then vaccinated in a similar way, and the detailed scientific data are awaited.[98]

Early this year, Russia announced the development and testing of an inactivated SARS-CoV-2-based vaccine named *Carnivac-Cov* for animals. As per the available information, it has been tested in dogs, cats, minks and foxes and found to be safe and immunogenic.[99] In September 2021, the Finnish Breeders' Association (FIFUR) announced in collaboration with the University of Helsinki the development of *Furcovac*, a vaccine for minks. However, scientific details of the vaccine are not in the public domain.[100] Currently, zoo animals and minks in the USA are vaccinated with an adjuvanted SARS-CoV-2 trimeric spike protein-based subunit vaccine.[101] Further scientific data are awaited.

Veterinary professionals can not only contribute to control of animal infectious diseases and play a critical role in contributing to the gross domestic product (GDP) of any nation through improving animal health and farmer's welfare (to quote Mohandas Gandhi, "the greatness of a nation can be judged by the way its animals are treated"), but also are an important cog in the public health system. Along with other disciplines, the veterinary profession has an equal part in approaching zoonotic diseases holistically, and this includes COVID-19.

Indeed, One Health has its beginnings in veterinary medicine. When the cattle plague rinderpest was decimating bovine populations and disrupting the human food supply, Pope Clement XI is reported to have instructed the papal physician Giovanni Lancisi to provide a solution. This led to Lancisi in 1914, followed by Thomas Bates in England, to recommend culling of affected animals and burying their carcasses and implement restrictions in animal movement.[102] The contributions of Rudolf Virchow also cannot be ignored. Son of a butcher by profession, he experimented on the lifecycle of the parasite *Trichinella* in the pig muscle as well as cysticercosis and tuberculosis in cattle. He stated that "between animal and human medicine, there are no dividing lines, nor should there be," and coined the word 'zoonosis'.[103] In recent times, veterinary public health specialists James Steele and Calvin Schwabe pioneered the holistic approach to infectious disease medicine. The word One Medicine was coined by Calvin Schwabe in the 1970s. As per this concept, both human and veterinary medicine are considered indifferent and contribute to the development of each other. Later, the concept of "One Medicine" was extended to "One Health" through practical application.[104]

International organizations such as the World Organization for Animal Health (WOAH), the Food and Agriculture Organization (FAO), the World Health Organization (WHO) and the One Health Commission have come together to promote "One Health" and its implementation at various levels.[105] In March 2022, the United Nations Environment Programme (UNEP) joined this One Health alliance. As human, animal, plant and environmental health are intricately intertwined, there is need for concerted efforts for cross-sectoral dialogue and cooperation at all levels in order to promote the well-being of humans and animals. Ultimately, we should move towards Planetary Health. However, the risk of zoonosis or their reporting is not uniform worldwide. Tropical, mostly low-to-middle income countries tend to be at greatest risk of zoonoses, and they need to evolve locally feasible solutions, including developing infrastructure, indigenous low cost diagnostics such as lateral flow assays, strengthening of reporting systems and flow of information, improving care systems in the case of disease outbreaks and implementation of preventive measures, including development of locally deployable vaccines and immunization programs.

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Declarations

Conflict of interest

We declare that we have no financial or other conflicts of interest.

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References

1. Al-Tawfiq JA, Memish ZA (2020) Middle east respiratory syndrome coronavirus and severe acute respiratory syndrome coronavirus. Semin Respir Crit Care Med 41:568–578

2. Tyrrell CS, Allen JLY, Gkrania-Klotsas E (2021) Influenza: epidemiology and hospital management. Medicine (Abingdon) 49:797–804
3. Philippon DAM, Wu P, Cowling BJ, Lau EHY (2020) Avian influenza human infections at the human-animal interface. J Infect Dis 222:528–537
4. Ohimain EI, Silas-Olu D (2021) The 2013–2016 Ebola virus disease outbreak in West Africa. Curr Opin Pharmacol 60:360–365
5. Anonymous (1996) The status of world health. The world health report 1996—fighting disease, fostering development. The World Health Organization, Geneva
6. Paules CI, Eisinger RW, Marston HD, Fauci AS (2017) What recent history has taught us about responding to emerging infectious disease threats. Ann Intern Med 167:805–811
7. Jones KE et al (2008) Global trends in emerging infectious diseases. Nature 451:990–993
8. Patel S (2017) Every member of the kingdom Animalia is a potential vector of human pathogens. Microb Pathog 109:1–3
9. Hoffmann M et al (2020) SARS-CoV-2 cell entry depends on ACE2 and TMPRSS2 and is blocked by a clinically proven protease inhibitor. Cell 181:271-280e278
10. Li Y, Wang H, Tang X, Ma D, Du C, Wang Y, Pan H, Zou Q, Zeng J, Xu L, Farzan M, Zhong G (2020) Potential host range of multiple SARS-like coronaviruses and an improved ACE2-Fc variant that is potent against both SARS-CoV-2 and SARS-CoV-1. bioRxiv
11. Liu Y, Hu G, Wang Y, Zhao X, Ji F, Ren W, Gong M, Ju X, Li C, Hong J, Zhu Y, Cai X, Wu J, Lan X, Xie Y, Wang X, Yuan Z, Zhang R, Ding Q (2020) Functional and genetic analysis of viral receptor ACE2 orthologs reveals a broad potential host range of SARS-CoV-2. bioRxiv
12. Damas J et al (2020) Broad host range of SARS-CoV-2 predicted by comparative and structural analysis of ACE2 in vertebrates. bioRxiv
13. Lam SD, Bordin N, Waman VP, Scholes HM, Ashford P, Sen N, van Dorp L, Rauer C, Dawson NL, Pang CSM, Abbasian M, Sillitoe I, Edwards SJL, Fratenali F, Lees JG, Santini JM, Orengo CA (2020) SARS-CoV-2 spike protein predicted to form stable complexes with host receptor protein orthologues from mammals, but not fish, birds or reptiles. bioRxiv
14. Praharaj MR, Garg P, Khan RIN, Sharma S, Panigrahi M, Mishra BP, Mishra B, Kumar GS, Gandham RK, Singh RK, Majundar S, Mohapatra T (2020) Prediction analysis of SARS-CoV-2 entry in livestock and wild animals. bioRxiv
15. Zhai X et al (2020) Comparison of SARS-CoV-2 spike protein binding to ACE2 receptors from human, pets, farm animals, and putative intermediate hosts. J Virol. https://doi.org/10.1128/JVI.00831-20
16. Boni MF, Lemey P, Jiang X, Lam TT-K, Perry B, Castoe TM, Rambaut A, Robertson D (2020) Evolutionary origins of the SARS-CoV-2 sarbecovirus lineage responsible for the COVID-19 pandemic. bioRxiv
17. Lau SKP et al (2020) Possible bat origin of severe acute respiratory syndrome coronavirus 2. Emerg Infect Dis. https://doi.org/10.3201/eid2606.200239
18. Lu R et al (2020) Genomic characterisation and epidemiology of 2019 novel coronavirus: implications for virus origins and receptor binding. Lancet 395:565–574
19. Zhou P et al (2020) A pneumonia outbreak associated with a new coronavirus of probable bat origin. Nature 579:270–273
20. Liu P et al (2020) Are pangolins the intermediate host of the 2019 novel coronavirus (SARS-CoV-2)? PLoS Pathog 16:e1008421
21. Wahba L et al (2020) An extensive meta-metagenomic search identifies SARS-CoV-2-homologous sequences in pangolin lung viromes. mSphere. https://doi.org/10.1128/mSphere.00160-20
22. K. Xiao *et al.*, Isolation of SARS-CoV-2-related coronavirus from Malayan pangolins. *Nature*, (2020).
23. Zhang T, Wu Q, Zhang Z (2020) Probable pangolin origin of SARS-CoV-2 associated with the COVID-19 outbreak. Curr Biol 30:1578
24. Lam TT et al (2020) Identifying SARS-CoV-2-related coronaviruses in Malayan pangolins. Nature 583:282–285
25. Andersen KG, Rambaut A, Lipkin WI, Holmes EC, Garry RF (2020) The proximal origin of SARS-CoV-2. Nat Med 26:450–452
26. Temmam SKV, Salazar EB, Munier S, Bonomi M, Régnault B, Douangboubpha B, Karami Y, Chretien D, Sanamxay D, Xayaphet V, Paphaphanh P, Lacoste V, Somlor S, Lakeomany K, Phommavanh N, Pérot P, Donati F, Bigot T, Nilges M, Rey F, van der Werf S, Brey P, Eloit M (2021) Coronaviruses with a SARS-CoV-2-like receptor-binding domain allowing ACE2-mediated entry into human cells isolated from bats of Indochinese peninsula. Preprint Server: Research Square (2021)
27. Leist SR et al (2020) A mouse-adapted SARS-CoV-2 induces acute lung injury and mortality in standard laboratory mice. Cell 183:1070-1085e1012
28. Bao L et al (2020) The pathogenicity of SARS-CoV-2 in hACE2 transgenic mice. Nature 583:830–833
29. Dinnon KH 3rd et al (2020) A mouse-adapted model of SARS-CoV-2 to test COVID-19 countermeasures. Nature 586:560–566
30. Hou YJ et al (2020) SARS-CoV-2 D614G variant exhibits efficient replication ex vivo and transmission in vivo. Science 370:1464–1468
31. Winkler ES et al (2020) SARS-CoV-2 infection of human ACE2-transgenic mice causes severe lung inflammation and impaired function. Nat Immunol 21:1327–1335

32. Jiang RD et al (2020) Pathogenesis of SARS-CoV-2 in transgenic mice expressing human angiotensin-converting enzyme 2. Cell 182:50-58e58
33. Sun SH et al (2020) A mouse model of SARS-CoV-2 infection and pathogenesis. Cell Host Microbe 28:124-133e124
34. Guo M, Tao W, Flavell RA, Zhu S (2021) Potential intestinal infection and faecal-oral transmission of SARS-CoV-2. Nat Rev Gastroenterol Hepatol 18:269–283
35. Hassan AO et al (2020) A SARS-CoV-2 infection model in mice demonstrates protection by neutralizing antibodies. Cell 182:744-753e744
36. Israelow B et al (2020) Mouse model of SARS-CoV-2 reveals inflammatory role of type I interferon signaling. J Exp Med 217:e20201241
37. Chan JF et al (2020) Simulation of the clinical and pathological manifestations of coronavirus disease 2019 (COVID-19) in a golden syrian hamster model: implications for disease pathogenesis and transmissibility. Clin Infect Dis 71:2428–2446
38. Imai M et al (2020) Syrian hamsters as a small animal model for SARS-CoV-2 infection and countermeasure development. Proc Natl Acad Sci USA 117:16587–16595
39. Shuai L et al (2021) Replication, pathogenicity, and transmission of SARS-CoV-2 in minks. Natl Sci Rev 8:nwaa291
40. Shi J et al (2020) Susceptibility of ferrets, cats, dogs, and other domesticated animals to SARS-coronavirus 2. Science 368:1016–1020
41. Y. I. Kim *et al.*, Infection and Rapid Transmission of SARS-CoV-2 in Ferrets. *Cell Host Microbe* **27**, 704–709 e702 (2020).
42. Richard M et al (2020) SARS-CoV-2 is transmitted via contact and via the air between ferrets. Nat Commun 11:3496
43. Freuling CM et al (2020) Susceptibility of raccoon dogs for experimental SARS-CoV-2 infection. Emerg Infect Dis 26:2982–2985
44. Halfmann PJ et al (2020) Transmission of SARS-CoV-2 in domestic cats. N Engl J Med 383:592–594
45. Bosco-Lauth AM et al (2020) Experimental infection of domestic dogs and cats with SARS-CoV-2: pathogenesis, transmission, and response to reexposure in cats. Proc Natl Acad Sci USA 117:26382–26388
46. Ulrich L et al (2021) Experimental SARS-CoV-2 infection of bank voles. Emerg Infect Dis 27:1193–1195
47. Ulrich L, Wernike K, Hoffmann D, Mettenleiter TC, Beer M (2020) Experimental infection of cattle with SARS-CoV-2. Emerg Infect Dis 26:2979–2981
48. Zhao Y, Wang J, Kuang D, Xu J, Yang M, Ma C, Zhao S, Li J, Long H, Ding K, Gao J, Liu J, Wang H, Li H, Yang Y, Yu W, Jing Y, Zheng Y, Wu D, Lu S, Liu H, Peng X (2020) Susceptibility of tree shrew to SARS-CoV-2 infection. bioRxiv 2020
49. Singh DK et al (2021) Responses to acute infection with SARS-CoV-2 in the lungs of rhesus macaques, baboons and marmosets. Nat Microbiol 6:73–86
50. Rockx B et al (2020) Comparative pathogenesis of COVID-19, MERS, and SARS in a nonhuman primate model. Science 368:1012–1015
51. Palmer MV et al (2021) Susceptibility of white-tailed deer (*Odocoileus virginianus*) to SARS-CoV-2. J Virol. https://doi.org/10.1128/JVI.00083-21
52. Cool K et al (2021) Infection and transmission of SARS-CoV-2 and its alpha variant in pregnant white-tailed deer. bioRxiv
53. Gaudreault NN et al (2021) Susceptibility of sheep to experimental co-infection with the ancestral lineage of SARS-CoV-2 and its alpha variant. bioRxiv 2021.2011.2015.468720
54. ProMed-mail (2020) COVID-19 update (56): China (Hong Kong) animal, dog, final serology positive. ProMed
55. Sit THC, Brackman CJ, Ip SM, Ta KWS, Law PYT, To EMW, Tu VYT, Sims LD, Tsang DNC, Chu DKW, Perera RAPM, Poon LLM, Peiris M (2020) Infection of dogs with SARS-CoV-2. Nature 586:776–778
56. Williams D (2020) A pug in North Carolina may be the first dot in US to test positive for coronavirus. CNN News (2020)
57. ProMed-mail (2020) COVID-19 update (58): Belgium, cat, clinical case, RFI. ProMed No. 7151215, International Society for Infectious Diseases
58. Anonymous (2020) Confirmation of COVID-19 in two pet cats in New York. Press release (United States of America Department of Agriculture
59. Anonymous (2020) SARS-CoV-2/COVID-19, United States of America. Information received on 22/04/2020 from Dr. Mark Davidson, Associate Administrator, USDA-APHIS, United States Department of Agriculture, Washington, United States of America. OIE report, The World Organisation for Animal Health (OIE).
60. ProMed-mail (2020) COVID-19 update (51): China (Hong Kong) pet cat. 2020. ProMed (2020)
61. Zhang Q, Zhang H, Huang K, Yang Y, Hiu X, Gao J, He X, Li C, Gong W, Zhang Y, Peng C, Gao X, Che H, Zhu Z, Shi Z, Jin M (2020) SARS-CoV-2 neutralizing serum antibodies in cats: a serological investigation. bioRxiv **2020**
62. Temman S, Barbarino A, Maso D, Behillil S, Enouf V, Huon C, Jaraud A, Chevallier L, Backovic M, Perot P, Verwaerde P, Tiret L, van der Werf S, Eliot M (2020) Absence of SARS-CoV-2 infection in cats and dogs in close contact with a cluster of COVID-19 patients in a veterinary campus. bioRxiv **2020**
63. Ruiz-Arrondo I et al (2021) Detection of SARS-CoV-2 in pets living with COVID-19 owners diagnosed during the COVID-19 lockdown in Spain: a case of an asymptomatic cat with SARS-CoV-2 in Europe. Transbound Emerg Dis 68:973–976

64. Deng J et al (2020) Serological survey of SARS-CoV-2 for experimental, domestic, companion and wild animals excludes intermediate hosts of 35 different species of animals. Transbound Emerg Dis 67:1745–1749
65. Calvet GA et al (2021) Investigation of SARS-CoV-2 infection in dogs and cats of humans diagnosed with COVID-19 in Rio de Janeiro, Brazil. PLoS One 16:e0250853
66. Ferasin L et al (2021) Infection with SARS-CoV-2 variant B.1.1.7 detected in a group of dogs and cats with suspected myocarditis. Vet Rec 189:e944
67. Dileepan M et al (2021) Seroprevalence of SARS-CoV-2 (COVID-19) exposure in pet cats and dogs in Minnesota, USA. Virulence 12:1597–1609
68. Fritz M et al (2021) High prevalence of SARS-CoV-2 antibodies in pets from COVID-19+ households. One Health 11:100192
69. Jara LM et al (2021) Evidence of neutralizing antibodies against SARS-CoV-2 in domestic cats living with owners with a history of COVID-19 in Lima—Peru. One Health 13:100318
70. Klaus J et al (2021) SARS-CoV-2 infection in dogs and cats from southern Germany and northern Italy during the first wave of the COVID-19 pandemic. Viruses 13:1453
71. Krafft E et al (2021) Report of one-year prospective surveillance of SARS-CoV-2 in dogs and cats in France with various exposure risks: confirmation of a low prevalence of shedding, detection and complete sequencing of an alpha variant in a cat. Viruses 13:1759
72. Sailleau C et al (2020) First detection and genome sequencing of SARS-CoV-2 in an infected cat in France. Transbound Emerg Dis 67:2324–2328
73. Medkour H et al (2021) First evidence of human-to-dog transmission of SARS-CoV-2 B1160 variant in France. Transbound Emerg Dis. https://doi.org/10.1111/tbed.14359
74. Klaus J et al (2021) Detection and genome sequencing of SARS-CoV-2 in a domestic cat with respiratory signs in Switzerland. Viruses 13:496
75. Fuentealba NA et al (2021) First detection and molecular analysis of SARS-CoV-2 from a naturally infected cat from Argentina. Vet Microbiol 260:109179
76. Yaglom HD et al (2021) Genomic investigation of a household SARS-CoV-2 disease cluster in Arizona involving a cat, dog, and pet owner. One Health 13:100333
77. Schulz C et al (2021) SARS-CoV-2-specific antibodies in domestic cats during first COVID-19 wave, Europe. Emerg Infect Dis 27:3115–3118
78. OIE (2021) COVID-19 events in animals. World Organization for Animal Health
79. Bartlett SL et al (2021) Sars-Cov-2 Infection and Longitudinal Fecal Screening in Malayan Tigers (Panthera Tigris Jacksoni), Amur Tigers (Panthera Tigris Altaica), and African Lions (Panthera Leo Krugeri) at the Bronx Zoo, New York, USA. J Zoo Wildl Med 51:733–744
80. Wang L et al (2020) Complete genome sequence of SARS-CoV-2 in a tiger from a U.S. zoological collection. Microbiol Resour Announc 9:e00468-20
81. USDA (2021) Confirmed cases of SARS-CoV-2 in animals in the United States
82. ProMed-mail (2021) Coronavirus disease 2019 update (348): animal, USA, zoo, snow leopard, fatal, suspected 13 October 2021. International Society for Infectious Diseases.
83. ProMed-mail (2021) Coronavirus disease 2019 update (392): animal, USA, zoo, snow leopard, fatal 15 November 2021. International Society for Infectious Diseases
84. Molenaar RJ et al (2020) Clinical and pathological findings in SARS-CoV-2 disease outbreaks in farmed mink (Neovison vison). Vet Pathol 57:653–657
85. Oreshkova N et al (2020) SARS-CoV-2 infection in farmed minks, the Netherlands, April and May 2020. Euro Surveill 25:2001005
86. ProMed-mail (2020) COVID-19 update (189): Netherlands (North Brabant) Animal, Farmed Mink, Research, Cat, Dog. 2020. ProMed
87. van Aart AE et al (2021) SARS-CoV-2 infection in cats and dogs in infected mink farms. Transbound Emerg Dis. https://doi.org/10.1111/tbed.14173. Online ahead of print. Jun 3
88. Hammer AS et al (2021) SARS-CoV-2 Transmission between Mink (Neovison vison) and Humans, Denmark. Emerg Infect Dis 27:547–551
89. CDC (2021) Animals and COVID-19
90. Devaux CA et al (2021) Spread of mink SARS-CoV-2 variants in humans: a model of sarbecovirus interspecies evolution. Front Microbiol 12:675528
91. Mallapaty S (2020) COVID mink analysis shows mutations are not dangerous—yet. Nature 587:340–341
92. OIE (2020) SARS-CoV-2 infection in mink in northern Greece. OIE—World Organisation for Animal Health
93. Yen HL et al (2022) Transmission of SARS-CoV-2 delta variant (A.Y127) from pet hamsters to humans, leading to onward human-to-human transmission: a case study. Lancet 399:1070–1078
94. Chandler JC et al (2021) SARS-CoV-2 exposure in wild white-tailed deer (*Odocoileus virginianus*). Proc Natl Acad Sci USA 118:e2114828118
95. Kuchipudi SV et al (2021) Multiple spillovers and onward transmission of SARS-Cov-2 in free-living and captive white-tailed deer (*Odocoileus virginianus*). bioRxiv, 2021.2010.2031.466677
96. WOAH/OIE (2022) SARS-CoV-2 in animals (Inf. with), Brazil. World Organisation for Animal Health
97. Banerjee A, Mossman K, Baker ML (2021) Zooanthroponotic potential of SARS-CoV-2 and implications of reintroduction into human populations. Cell Host Microbe 29:160–164

98. AAHA, "Endangered black-footed ferret gets experimental COVID-19 vaccine in Colorado," (American Animal Hospital Association, 2020).
99. WSAVA, "COVID-19 - An update for WSAVA Members April 29th, 2021," (World Small Animal Veterinary Association, Ontario, Canada, 2021).
100. FIFUR (2021) FIFUR has obtained a conditional usage permit for mink vaccine from the Finnish Food Authority. Finnish Fur Breeders' Association, Finland
101. Sharun K, Tiwari R, Saied ARA, Dhama K (2021) SARSCoV- 2 vaccine for domestic and captive animals: an effort to counter COVID-19 pandemic at the human-animal interface. Vaccine 39:7119–7122
102. Diallo A (1988) 'Rinderpest' and 'peste des petits ruminants': constant threats to animal farming in many developing countries. Impact of Science on Society, UNESCO
103. Schultz M (2008) Rudolf Virchow. Emerg Infect Dis 14:1480–1481
104. Zinsstag J, Schelling E, Waltner-Toews D, Tanner M (2011) From "one medicine" to "one health" and systemic approaches to health and well-being. Prev Vet Med 101:148–156
105. FAO (2019) Taking a multisectoral one health approach : a tripartite guide to addressing zoonotic diseases in countries. FAO/OIE/WHO
106. Munster VJ et al (2020) Respiratory disease in rhesus macaques inoculated with SARS-CoV-2. Nature 585:268–272
107. Deng W et al (2020) Primary exposure to SARS-CoV-2 protects against reinfection in rhesus macaques. Science 369:818–823
108. Chandrashekar A et al (2020) SARS-CoV-2 infection protects against rechallenge in rhesus macaques. Science 369:812–817
109. Zhang Q et al (2020) A serological survey of SARS-CoV-2 in cat in Wuhan. Emerg Microbes Infect 9:2013–2019
110. McAloose D et al (2020) From people to panthera: natural SARS-CoV-2 infection in tigers and lions at the bronx zoo. MBio. https://doi.org/10.1128/mBio.02220-20
111. Oude Munnink BB et al (2021) Transmission of SARS-CoV-2 on mink farms between humans and mink and back to humans. Science 371:172–177

Dr. Deepak Kumar completed his graduation in Veterinary Medicine and post-graduation in Veterinary Microbiology from MHOW, Madhya Pradesh. Initially, he worked as Veterinary Officer at Poultry Diagnostics and Research Center, Pune. Later, he worked in project positions at National Institute of Animal Nutrition and Physiology and Indian Institute of Science, Bengaluru. He then joined Ella Foundation, Hyderabad, in 2008 and worked at various capacities till March, 2022 and obtained PhD in Biotechnology from Jawaharlal Nehru Technological University, Hyderabad. Currently, he is working as Chief Manager, Research and Development at Indian Immunologicals Ltd., Hyderabad. His notable contributions are identification of a new species of anaerobic rumen fungus: Cyllamyces sp. and work towards development of pandemic vaccines. His research interests are viral-vectored vaccines and development of affordable and safe vaccines for animals and humans.

Prof. Jagadeesh Bayry is a graduate of Veterinary Medicine from Bengaluru with a specialization in Virology and Immunology from Indian Veterinary Research Institute. He received PhD from Sorbonne University, Paris, and following post-doctoral research at University of Oxford, he joined Institut National de la Santé et de la Recherche Médicale (INSERM), Paris, France, in 2006 as a faculty. In 2018, he became Director of Research at INSERM. In 2021, he joined IIT Palakkad as a Professor. Currently, he is Head, Department of Biological Sciences & Engineering, and also one of the Deans. His research is aimed at fundamental immunology, immunotherapy and infectious diseases. He has authored more than 290 articles with over 15,000 citations and h-index of 65. He serves as an Editor, Associate Editor or Editorial Board member of various journals and has edited four books. He is also a member of a commission at the European Research Council (ERC).

Dr. Nagendra Hegde has Bachelors in Veterinary Science, Masters in Veterinary Microbiology, PhD in Veterinary Immunology and postdoctoral training in virology and cell biology. He headed Ella Foundation, Hyderabad, for just over a decade before joining NIAB in April 2017. His research experience spans veterinary and human virology, immunology and microbiology. His interests are epidemiology, genomics and biology of viral and bacterial diseases, immune responses, vaccines and diagnostics. His key contributions include: (a) the first allele-specific peptide motif of any bovine MHC molecule, (b) the identification of first two viral inhibitors of the MHC class II pathway of antigen presentation, (c) vectored vaccine candidates for hantavirus pulmonary syndrome and Ebola haemorrhagic fever, (d) development of a cell culture-based H1N1 pandemic influenza vaccine and (e) epidemiology of bluetongue and bovine mastitis-associated staphylococci. He has published close to 100 research articles and serves as a reviewer or editor on several scientific journals. He has recently initiated work on One Health, particularly zoonoses and anti-microbial resistance.