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Research
Coronavirus Disease 2019—Perspective

Natural Host–Environmental Media–Human: A New Potential Pathway of COVID-19 Outbreak

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ABSTRACT
Identifying the first infected case (patient zero) is key in tracing the origin of a virus; however, doing so is extremely challenging. Patient zero for coronavirus disease 2019 (COVID-19) is likely to be permanently unknown. Here, we propose a new viral transmission route by focusing on the environmental media containing viruses of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) or RaTG3-related bat-borne coronavirus (Bat-CoV), which we term the “environmental quasi-host.” We reason that the environmental quasi-host is likely to be a key node in helping recognize the origin of SARS-CoV-2; thus, SARS-CoV-2 might be transmitted along the route of natural host–environmental media–human. Reflecting upon viral outbreaks in the history of humanity, we realize that many epidemic events are caused by direct contact between humans and environmental media containing infectious viruses. Indeed, contacts between humans and environmental quasi-hosts are greatly increasing as the space of human activity incrementally overlaps with animals’ living spaces, due to the rapid development and population growth of human society. Moreover, viruses can survive for a long time in environmental media. Therefore, we propose a new potential mechanism to trace the origin of the COVID-19 outbreak.

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1. Introduction

In general, identifying the first infected case (patient zero) is key in tracing the origin of a virus; however, doing so is extremely challenging. Despite extensive efforts, scientists have not yet identified patient zero for the 1918 influenza pandemic, human immunodeficiency virus (HIV), or H1N1 influenza in 2009, and patient zero for severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is likely to remain unidentified as well. The challenge in identifying the origin of SARS-CoV-2 is that a great deal of interdisciplinary research is required; in particular, if patient zero was asymptomatic or had very mild symptoms, he or she may not have seen a doctor or generated a medical record. As a result, patient zero could forever remain unidentified. Therefore, what roadmap could be followed to skip over patient zero while still recognizing the origin of the virus?

Here, we propose a new virus transmission route (Fig. 1) by focusing on environmental media containing viruses such as SARS-CoV-2 or RaTG3-related bat-borne coronavirus (Bat-CoV), hereafter termed as the “environmental quasi-host.” We propose reasons why the environmental quasi-host is likely to be a key node in helping recognize the origin of SARS-CoV-2.

Viral transmission to humans occurs via natural host–human contact or environmental quasi-host–human contact, where the environmental quasi-host might be water, soil, or food contaminated by an animal host’s urine, saliva, feces, or secretions. Many researchers believe that SARS-CoV-2 may have come from the wild animal market. Nevertheless, they have focused on the natural host–human pathway [1–3], while ignoring the natural host–environmental quasi-host–human pathway.

Is it possible that SARS-CoV-2 infected patient zero through contact with an environmental quasi-host? With rapid industrialization and globalization, contacts between humans and environmental quasi-hosts are greatly increasing, as human activity spaces strongly overlap with animals’ living spaces. Moreover,
Viruses can survive for a long time in certain environmental media [4–6]. Many viral outbreaks in humans have been caused by direct human contact with environmental media containing a virus, such as virus-carrying water and soil, rather than by direct contact with a natural host [7–10].

Based on the following pieces of evidence from recent research and other viral transmission pathways, we consider that SARS-CoV-2 could have been transmitted from an environmental quasi-host.

2. SARS-CoV-2 detection in various environmental media

SARS-CoV-2 has been detected in various environmental media (Table 1 [11–22]), including wastewater, soil, floor surfaces, door handles, sinks, lockers, tables, windows, and packages, to name just a few. Between February and March of 2020, Liu and colleagues [11] at Wuhan University in China demonstrated the presence of SARS-CoV-2 RNA in the air by setting up aerosol capture devices in and around two hospitals. Ong’s group [12] detected SARS-CoV-2 on environmental surfaces in patients’ rooms and toilets. SARS-CoV-2 has also been detected in wastewater at Schiphol Airport in Tilburg, the Netherlands [13]. SARS-CoV-2 may exist in the habitats of species that are natural hosts for SARS-CoV-2. Therefore, further examination of environmental media in natural habitats for SARS-CoV-2 is needed.

3. Long-term virus survival in environmental media

Viruses can survive in environmental media for hundreds or even thousands of days and remain infectious under suitable conditions, which are often reported to be low temperatures, relatively closed conditions, less disturbed conditions, and highly heterogeneous environmental media. Mollivirus sibericum, which has been preserved in permafrost for 30,000 years, is still capable of infection after resuscitation [23]. Porcine parvovirus can survive in soil for more than 43 weeks [6], and poliovirus remains stable and active at 1 °C for 75 days [24]. In groundwater, human norovirus still has 10% activity after 1266 days [25]. In mineral water, hepatitis A virus and poliovirus only have a small reduction in infectivity for one year at 4 °C [4]. In contaminated water, norovirus can still be detected after 1343 days [5].

We have analyzed 482 scholarly papers published in the past 120 years (Table 2 [26–122]), which study the survival time of 116 different strains of viruses. From a statistical perspective, over 84% of the 116 different strains of viruses can survive for more than one week (Fig. 2 [26–122]). With the rapid development of global transportation, viruses in environmental media can be carried from one place in the world to another in days or weeks; thus, the origin of a virus could be far away from the location of its breakout. As the phylogenetic characteristics of a virus may greatly affect its survival time in environment media, the phylogenetic characteristics of viruses require further study.

### Table 1

| Environmental media                                      | Collection period          | Site or country                      | Reference |
|---------------------------------------------------------|----------------------------|------------------------------------|-----------|
| Aerosol                                                 | 2020-02–2020-03            | Wuhan, China                       | [11]      |
| Wastewater                                              | 2019-11-27                 | Florianopolis, capital of Santa Catarina in southern Brazil | [14] |
| Wastewater                                              | 2019-12-18                 | Milan and Turin, Italy             | [15]      |
| Wastewater                                              | 2020-03-05–2020-04-23      | Paris, France                      | [16]      |
| Non-potable water                                       | 2020-04                    | Paris, France                      | [17]      |
| Floor surfaces, door handles, sinks, lockers, tables, and windows | 2020-01-24–2020-02-04      | Singapore                          | [12]      |
| Packages and the inner wall of a container of frozen shrimp | 2020-07-03                 | Beijing, China                     | [18]      |
| Samples from seafood, meat, and the external environment | 2020-06                    | Beijing, China                     | [19]      |
| Human feces                                             | 2020-01–2020-02-17         | China                              | [20]      |
| Wastewater                                              | 2020-02                    | Schiphol Airport in Tilburg, the Netherlands | [13] |
| Soil and wastewater                                     | 2020-04                    | Wuhan, China                       | [22]      |

**Fig. 1.** The SARS-CoV-2 transmission pathway.
Virus survival times in environmental media [26–122].

1 year > t

Virus survival time (t) | Viruses
--- | ---
> 1 year | Reovirus [26], human adenooviruses [5], viral hemorraghic septicemia virus (VHSV) [33], feline calicivirus (FCV) [36], calf rotavirus [28], poliovirus [4], hepatitis A virus (HAV) [4], tomato mosaic virus (TMV) [46], scrapie virus [52], H5N1 [56], H5N2 [60], H7N3 [60], H11N1 [65], H9N2 [66], H7N1 [71], marek’s disease virus (MDV) [74], mouse hepatitis virus (MHV) [75], norwalk virus [5], granulosis virus [84], avian paramyxovirus-1 (APMV-1) [87], grapevine fanleaf virus (GFLV) [89], tomato ring spot virus (TmRSV) [92], human coronavirus 229E (HCoV-229E) [95], nuclear polyhedrosis virus (NPV) [96], African swine fever virus (ASFV) [98], swine vesicular disease virus (SVVD) [100], baculovirus midgut gland necrosis virus (BMNV) [102], granulosis viruses (Baculoviridae) [104], infectious hematopoietic necrosis virus (IHNV) [106], Mollivirus sibericum [23]

1 year > t > 1 month

Astrovirus (AstVs) [27], pigle fry rhabdovirus (PRFV) [30], spring viremia of carp virus (SVCV) [30], infectious pancreatic necrosis virus (IPNV) [30], rotavirus [39], echovirus [42], Tulane virus (TV) [45], coxsackievirus [49], murine norovirus (MNV) [53], Ebola virus [57], H12N5 [61], H10N7 [61], H9N2 [66], H4N6 [66], H9N2 [72], transmissible gastroenteritis virus (TGEV) [75], hand foot mouth virus (MMDV) [78], koi herpesvirus (KHV) [81], snow mountain virus (SMV) [85], the minute virus of mice (MVM) [35], beet necrotic yellow vein virus (BNYVV) [90], salmonid aliphavirus (SAV) [93], feline infectious peritonitis virus (FIPV) [95], variola virus [97], rhesus rotavirus (RRV) [99], frog virus 3 (FV3) [101], porcine teschovirus (FIV) [103], white spot spot virus (WSVSV) [105], lymphocystis disease virus (LCDV) [107], neurovaccine virus [108], potato spindle tuber viroid (PSTDV) [62], prion [109], turkey reovirus (TRVs) [110], bovine parvovirus [111], bovine enterovirus [112], hepatitis E virus (HEV) [113], channel catfish virus (CCV) [114], avian reovirus [115], infectious salmon anemia virus (ISAV) [116], infectious pancreatic necrosis virus [117], parovirus [118], duck plague herpesvirus [119], porcine parvovirus (PPV) [6], west Nile virus [120], H7N7 [121], hepatitis B virus (HBV) [122]

1 month > t > 1 week

H11N6 [28], human immunodeficiency virus (HIV) [31], equine herpesvirus type-1 (EHV-1) [34], porcine reproductive and respiratory syndrome virus (PRRSV) [37], human papillomavirus-16 (HPV16) [40], hepatitis C virus (HCV) [43], porcine sapovirus (SoV) [46], infectious bursal disease virus (IBDV) [50], Japanese encephalitis virus (JEV) [54], spumavirus [58], pepino mosaic virus (PepMV) [62], human parainfluenza viruses [63], lassa virus [67], venezuelan equine encephalitis virus (VEEV) [67], sindbis virus [67], taura syndrome virus (TSV) [76], severe acute respiratory syndrome coronavirus (SARS-CoV) [79], vesicular stomatitis virus (VSV) [82], nipah virus [86], hantavirus [88], severe fever with thrombocytopenia syndrome virus (SFTSV) [91], H1N2 [94]

< 1 week

Simian virus 40 (SV40) [29], lung-eye-trachea virus (LETV) [32], herpes simplex virus (HSV) [35], feline leukemia virus (FeLV) [38], invertebrate iridescent virus 6 (IV-6) [41], ostred herpesvirus-1 (OshHV-1) [44], lapinized rinderpest virus [47], mouse rotavirus (MRV) [51], infectious bronchitis virus (IBV) [55], human poliovirus (HPVs) [59], potato virus Y (PYY) [62], sud herpesvirus-1 (SuHV-1) [64], human rhinovirus (HRV) [68], cytomegalovirus (CMV) [70], marburg virus [73], severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) [77], measles virus [80], malle EAST respiratory syndrome coronavirus (MERS-CoV) [83]

Existing studies have confirmed that SARS-CoV-2 is likely to exist for a long time in septic tanks and other soil-containing solid media, as well as in the ground [22]. The Singapore National Center for Infectious Diseases and the Defense Science Organization (DSO) National Laboratories have detected the virus in the residence rooms of COVID-2019 patients; floor surfaces had the highest positive viral signal, exceeding those of toilets, door handles, sinks, lockers, tables, and windows [12]. SARS-CoV-2 was found to remain viable in aerosols throughout the experiment (3 h), with a reduction in infectious titer from 10^{3.5} to 10^{2} median tissue culture infective dose (TCID50) per liter of air [77]. Based on these findings, SARS-CoV-2 may exist and survive for a long time in habitat and activity place of wildlife, especially in places with low temperatures and low levels of light.

4. Viral outbreaks in humans caused by direct contact with environmental media rather than contact with a natural host

By analyzing the literature published in the past 120 years, we found at least 198 viral infection cases with 28 different strains of viruses that occurred through direct contact with environmental media (Table 3 [123–318]). Some of these cases were statistically derived from data in order to obtain a correlation between environmental media and viral transmission, and many were derived from investigations of environmental media that recognized the route or host of viral transmission. For example:

(1) A 44-year-old woman from Colorado, USA, suffered from Marburg disease in 2008 after returning home from a two-week tour in Uganda. This disease is caused by a virus that belongs to the same family as the Ebola virus, one of the deadliest pathogens to humans. Scientists sequenced the gene of an Egyptian fruit bat and believed that she was infected by the virus when she touched a rock covered with bat feces while visiting the python cave [8–10].

(2) The transmission route of the Ebola virus has been confirmed as the human consumption of fruit contaminated by bat feces [7].

(3) No less than five infectious disease incidents have occurred in China since 2009 due to drinking groundwater containing a virus that ended up affecting thousands of people. For example, an outbreak of gastroenteritis occurred in Hebei, China, in the winter of 2014–2015. The nucleotide sequence of the norovirus extracted from clinical and water samples had 99% homology with...
Table 3
Cases of virus infection caused by direct human contact with environmental media [123–318].

| Virus                        | The relevant environmental media | Site, region, or country              | Date          | Reference |
|------------------------------|----------------------------------|---------------------------------------|---------------|-----------|
| Hepatitis E virus            | Water                             | Kanpur, India                         | 1991          | [123]     |
|                              | Water                             | Hyderabad, India                      | 2005          | [124]     |
|                              | Water                             | Shimla, India                         | 2015–2016     | [125]     |
|                              | Water                             | Am Timan, Chad                        | 2016-09–2017  | [126]     |
|                              | Water                             | Hyderabad, India                      | 2005-03–2005-08 | [127]     |
| Norovirus (Norwalk virus, a small round structured virus) | Water                             | Zhejiang, China                       | 2003          | [128]     |
|                              | Water                             | Guatemala                             | 2006          | [129]     |
|                              | Water                             | Western Norway                        | 2002-07–2003-07 | [140]     |
|                              | Water                             | Western Finland                       | 2014-07–2015  | [141]     |
|                              | Drinking water                    | Northern Italy                        | 2009-06–2010-06 | [142]     |
|                              | Drinking water                    | Iceland                               | 2004          | [143]     |
|                              | Drinking water                    | Wisconsin, USA                        | 2007-06–2008  | [144]     |
|                              | Drinking water                    | Switzerland                           | 2008          | [145]     |
|                              | Drinking water                    | The Netherlands                       | 2001-11–2001-12 | [136]     |
|                              | Drinking water                    | China                                 | 2010-10-31–2011-12 | [146]     |
|                              | Drinking water                    | Maine, USA                            | 2018          | [147]     |
|                              | Drinking water                    | Colorado, USA                         | 2019          | [148]     |
|                              | Drinking water                    | A hospital and an attached long-term care facility (LTFC), Japan | 2007 | [149]     |
|                              | Drinking water                    | Taiwan, China                        | 2015-02–2015-03 | [150]     |
|                              | Drinking water                    | A cruise ship sailing along the Yangtze River, China | 2014-04–2015-05 | [151]     |
|                              | Sandwich                          | Hamilton County, Ohio, USA            | 1997          | [152]     |
|                              | Drinking water                    | Wuhan, China                          | 2017-04-28–2017-05-08 | [153]     |
|                              | Drinking water                    | Northwest University of China, China  | 2014-06–2014-11 | [154]     |
|                              | Drinking water                    | Salzburg, Austria                     | 2005-05–2005-06 | [155]     |
|                              | Drinking water                    | Jiaxing, China                        | 2014-02–2014-06 | [156]     |
|                              | Drinking water                    | South Africa                          | 2017-01–2017-02 | [157]     |
|                              | Drinking water                    | Catalonia, Spain                      | 2016-04-11–2016-04-25 | [158]     |
|                              | Drinking water                    | Shanghai, China                       | 2012-12–2012-13 | [159]     |
|                              | Drinking water                    | Netherlands                           | 2002-06–2002-06 | [160]     |
|                              | Drinking water                    | Northeast Greece                      | 2006-06–2009 | [161]     |
|                              | Drinking water                    | Xanthi, Northern Greece               | 2005          | [162]     |
|                              | Drinking water                    | Jeju Island, Republic of Korea        | 2004-05–2015-05 | [163]     |
|                              | Drinking water                    | Quebec, Canada                        | 2011-01–2011-02 | [164]     |
|                              | Drinking water                    | Nagasaki, Japan                       | 2003-01-2003-11 | [165]     |
|                              | Swimming pool water              | Southeast England                     | 2016-01–2016-02 | [166]     |
|                              | Swimming pool water              | Vermont, USA                          | 2004-02–2012-02 | [167]     |
|                              | Swimming pool water              | Galveston County, Texas, USA          | 2013          | [168]     |
|                              | Swimming pool water              | Puerto Rico                           | 2009          | [169]     |
|                              | Swimming pool water              | Southern Sweden                       | 2017-01–2018-02 | [170]     |
|                              | Swimming pool water              | Lianyungang, China                    | 2017          | [171]     |
|                              | Swimming pool water              | Taiwan, China                         | 2015          | [172]     |
|                              | Swimming pool water              | Zhejiang, China                       | 2011          | [173]     |
|                              | Swimming pool water              | Beijing, China                        | 2017-12–2017-12 | [174]     |
|                              | Swimming pool water              | Wuhan, China                          | 2014-12-11–2015-04 | [175]     |
|                              | Swimming pool water              | Hebei, China                          | 2014-12–2015-05 | [174]     |
|                              | Swimming pool water              | Shanghai, China                       | 2013-12–2014-12 | [176]     |
|                              | Swimming pool water              | Beijing, China                        | 2018-09-04–2019-05 | [177]     |
|                              | Swimming pool water              | Seven-day holiday cruise from Florida, USA to the Caribbean | 2002-11–2003-05 | [178]     |
|                              | Environmental surface            | France                                | 2003-01–2004 | [179]     |
|                              | Environmental surface            | A 240-bed veterans LTCF, USA          | 2003-01–2003-02 | [180]     |
| Water                        | Well water                        | Sweden                                | 2011-03–2012-11 | [181]     |
| Well water                   | Well water                        | Santo Stefano Quisquina, Sicily, Italy | 2007-11–2007-12 | [182]     |
| Well water                   | Well water                        | Delaware, USA                         | 1987-09-19–1987-09-27 | [183]     |

(continued on next page)
| Virus                        | The relevant environmental media                                                                 | Site, region, or country                          | Date             | Reference |
|-----------------------------|--------------------------------------------------------------------------------------------------|-------------------------------------------------|------------------|-----------|
| Food                        | Hamburg, Germany                                                                                 | 2005-08                                         | [185]            |
| Tap water                   | Hemiksem, Belgium                                                                                 | 2010-12                                         | [186]            |
| Environmental surface       | An international cruise ship                                                                      | 2008                                            | [187]            |
| Public toilet environment   | Cruise ships                                                                                     | 2005–2008                                       | [188]            |
| Water, environmental surface| A cruise ship, Europe                                                                            | Summer of 2006                                  | [189]            |
| Dirty computer equipment (i.e., keyboard and mouse) | District of Columbia, USA                                                                      | 2007-02-08                                      | [190]            |
| Environmental surface       | Shanghai, China                                                                                  | 2014-12-7–2014-12-18                           | [191]            |
| Food                        | A football game in the University of Florida, USA                                                 | 1998-09                                         | [192]            |
| Food                        | West Virginia, USA                                                                                | 2006-01                                         | [193]            |
| Water                       | Shenzhen, China                                                                                   | 2009-09-17–2009-10-03                          | [194]            |
| Food                        | Stockholm County, Sweden                                                                          | 2007-11                                         | [195]            |
| Tap water                   | Taranto Bay, Southern Italy                                                                       | 2000-07                                         | [196]            |
| Swimming pool water         | Ohio, USA                                                                                         | 1977-06                                         | [197]            |
| Tap water                   | Heinävesi, Finland                                                                               | 1998-03                                         | [198]            |
| Food                        | New York, USA                                                                                     | 2000-02                                         | [199]            |
| Drinking water              | Northern Georgia, USA                                                                             | 1980-08                                         | [200]            |
| Food                        | A hotel in Virginia, USA                                                                          | 2000-11                                         | [201]            |
| Food                        | Virginia, USA                                                                                     | 1999-05–1999-06                                | [202]            |
| Environment                 | Southern Finland                                                                                 | 1999-12–2000-02                                | [203]            |
| Well water                  | Arizona, USA                                                                                      | 1989-04-17–1989-05-01                          | [204]            |
| Water                       | Pennsylvania, USA                                                                                 | 1978-07                                         | [205]            |
| Aerosol                     | A primary school and nursery                                                                      | 2001-06                                         | [206]            |
| Water                       | A ski resort in Sweden                                                                            | 2002-02–2002-03                                | [207]            |
| Food                        | Southern Sweden                                                                                  | 2000-05-02–2000-05-03                          | [208]            |
| Food                        | Fort Bliss, El Paso, Texas USA                                                                    | 1998-08-27–1998-09-01                          | [209]            |
| Aerosol                     | A large hotel, Canada                                                                             | 1998-12                                         | [210]            |
| Water vapor                 | Ontinyent (Valencia), Spain                                                                       | 1992-01                                         | [211]            |
| Recreational water          | The Netherlands                                                                                  | 2012-08                                         | [212]            |
| Drinking water              | Finland                                                                                          | 1994-04                                         | [213]            |
| Food (made from drinking water) | South Dakota, USA                                                                                 | 1986-08-30–1986-08-31                          | [214]            |
| Water                       | North Georgia, USA                                                                                | 1982-01                                         | [215]            |
| Water, food                 | Two Caribbean cruise ships                                                                        | 1986-04-26–1986-05-01                          | [216]            |
| Lake water                  | Markham County, Michigan                                                                          | 1979-07-13–1979-07-16                          | [217]            |
| Food (exposure to non-drinking water) | The US Air Force Academy, USA                                                                   | 2002-09                                         | [218]            |
| Fomite                      | Sydney, Australia                                                                                 | 1996-01–1996-05                                | [219]            |
| Environment                 | North West England                                                                                | 1999-01–1996-05                                | [220]            |
| Food                        | Metropolitan Concert Hall, UK                                                                     | 1995-01–1995-05                                | [221]            |
| Food                        | Toyota City, Japan                                                                                | 1989-03                                         | [222]            |
| Food                        | A Massachusetts university, USA                                                                   | 1994-12                                         | [223]            |
| Air                         | Los Angeles, USA                                                                                  | 1988-12–1989-01                                | [224]            |
| Well water                  | A restaurant in the Yukon territory in Canada                                                    | 1995                                            | [225]            |
| Groundwater                 | La Neuveville, Switzerland                                                                        | 1998                                            | [226]            |
| Tap water                   | A re-education ward                                                                              | 1999-01                                         | [227]            |
| Food made from contaminated water | South Wales and Bristol, UK                                                                       | 1994-08                                         | [228]            |
| Air                         | A British registered cruise ship                                                                  | 1988-01-13                                      | [229]            |
| River water                 | Southern New South Wales, Australia                                                                | Christmas holiday period of 1989                | [230]            |
| Raw oysters                 | Southwest Scotland                                                                                | Christmas holiday period of 1993                | [231]            |
| Aerosol                     | An elderly care unit, UK                                                                          | 1992-11                                         | [232]            |
| Environment                 | A hospital for the mentally infirm, UK                                                            | 1994-05                                         | [233]            |
| Food                        | A large hotel, UK                                                                                 | 1985-11                                         | [234]            |
| Hepatitis A virus           | Drinking water                                                                                   | Mead County, Kentucky, USA                       | 1982-11           | [235]      |
| Well water                  | A trailer park in Bartow County, Georgia, USA                                                     | 1982                                            | [236]            |
| Lake water                  | Waterway Lake, USA                                                                                | 1969-09                                         | [237]            |
| Water                       | Albania                                                                                          | 2002-11–2003-01                                | [238]            |
| Bread                       | A village in South Cambridgeshire, England                                                        | The late spring and summer of 1989              | [239]            |

(continued on next page)
| Virus                      | The relevant environmental media              | Site, region, or country                          | Date               | Reference |
|---------------------------|-----------------------------------------------|-------------------------------------------------|--------------------|-----------|
| Groundwater               | USA                                           | 1971–2017                                       | [240]              |
| Food                      | The Netherlands                               | 2017                                            | [241]              |
| Food                      | Italy                                         | 1996                                            | [242]              |
| Shellfish                 | Shanghai, China                               | 1988                                            | [243]              |
| Well water                | Guangxi, China                                | 2012-05                                         | [244]              |
| Food                      | Southern Italy                                | 2002                                            | [245]              |
| Groundwater               | Thailand                                       | 2000                                            | [246]              |
| Water                     | Rudraprayag District of Uttarakhand State, India | 2013-05                                         | [247]              |
| Water                     | Georgetown, Texas, USA                        | 1980-06                                         | [248]              |
| Frozen berries            | Northern Italy                                | 2013                                            | [249]              |
| Clams                     | Valencia, Spain                               | 1999                                            | [250]              |
| Water                     | Orleans Island in the St. Lawrence River, Canada | Summer of 1995                             | [251]              |
| Swimming pool water       | USA                                           | 1989                                            | [252]              |
| Spa pool                  | Victoria, USA                                 | 1997                                            | [253]              |
| Water                     | Republic of Korea                             | 2015-04                                         | [254]              |
| Water                     | Arapiles 62 camp located in Castellciutat, near Seo de Urgel, Spain | 1987-09                                       | [255]              |
| Drinking water            | A medical college student's hostel, New Delhi, India | 2014-01                                         | [256]              |
| Orange juice              | Europe                                        | 2004                                            | [257]              |
| Frozen strawberries       | Nordic countries                              | 2012-10–2013-06-27                              | [258]              |
| Frozen mixed berries      | Northern Italy                                | 2013-01–2013-05                                 | [259]              |
| Semi-dried tomato         | The Netherlands                               | 2010                                            | [260]              |
| Pomegranate               | USA                                           | 2013-05                                         | [261]              |
| Hepatitis C virus         | Water                                         | Medea, Algeria                                  | 1980–1981          | [262]     |
|                          | Wastewater                                    | Sewage treatment plant, Algeria                 | 1991               | [263]     |
| Parvovirus                | Drinking water                                | USA                                             | 1971–1978          | [264]     |
| Measles virus             | Air                                           | The Minneapolis–St. Paul metropolitan area, USA | 1991-07            | [265]     |
| Poliovirus                | Milk                                          | West coast of USA                               | 1943-09            | [266]     |
|                          | Lake water                                    | Oakland County, Michigan, USA                   | 1993-06-11–1993-06-13 | [267] |
|                          | Droplet                                       | Middlesex Hospital, London, UK                  | Late summer of 1952 | [268] |
| H5N1                      | Chicken manure                                | Indonesia                                       | 2005-06–2008-06    | [269]     |
| Rotavirus                 | Tap water                                     | Isere region, France                            | 1994               | [270]     |
|                          | Well water                                    | India                                           | 2009-04–2009-05    | [271]     |
|                          | Water                                         | Eagle-Vail, Colorado, USA                       | 1981-03            | [272]     |
|                          | Aerosol                                       | A primary school                                |                    | [273]     |
| Adenovirus                | Swimming pool water                           | Oklahoma, USA                                   | 1982-07            | [274]     |
|                          | Environment                                   | The marine corps recruit training command, San Diego, USA | 2004               | [275]     |
|                          | Air                                           | Wuhan, China                                    | 2014               | [276]     |
|                          | Swimming pool water                           | Georgia, USA                                    | 1977               | [277]     |
|                          | Swimming pool water                           | Beijing, China                                  | 2013               | [278]     |
|                          | Swimming facilities                           | Taiwan, China                                   | 2011-09            | [279]     |
| Hantavirus                | Animal feces                                  | North Dakota, USA                               | 2016               | [280]     |
|                          | Deer mouse excreta                            | California, USA                                 | 2017               | [281]     |
|                          | Animal secretions                             | North Wales                                     | 2013               | [282]     |
|                          | Rat                                           | Illinois and Wisconsin, USA                     | 2017               | [283]     |
| SARS-CoV-2                | Saliva                                        | Hong Kong, China                                | 2020               | [284]     |
| MERS-CoV                  | Camel                                         | The United Arab Emirates                        | 2019               | [285]     |
|                          | Droplet                                       | Saudi Arabia                                    | 2013-03–2013-04    | [286]     |
| Severe fever with         | Cat                                           | Japan                                           |                    | [287]     |
| thrombocytopenia syndrome virus |                                    |                                                  |                    |           |
| Herpes simplex virus      | Saliva                                        | England                                         | 2019               | [288]     |
| SARS-CoV-1                | Rat                                           | Yunnan, China                                   | 2015               | [289]     |
|                          | Aerosol                                       | Canada                                          | 2003               | [290]     |
|                          | Aerosol                                       | Hong Kong, China                                | 2003               | [291]     |
|                          | Air                                           | Canada                                          | 2003               | [292]     |
|                          | Air                                           | Hong Kong, China                                | 2003               | [293]     |
| West Nile virus           | Mosquito-controlled pool                      | California                                      | 2007               | [294]     |
| H3N2                      | Pig                                           | Ohio, USA                                       | 2012               | [295]     |
|                          | Air, droplets                                 | Alaska, USA                                     | 1977               | [296]     |
| H1N1                      | Droplet                                       | Sichuan, China                                  | 2009               | [297]     |
| H7N7                      | Poultry, human                                | The Netherlands                                 | 2003-02            | [298]     |

(continued on next page)
the strain of Beijing/CHN/2015, which confirmed that the outbreak was waterborne. This is an excellent example of finding the route of virus transmission by investigating environmental media [154,176,194,244,319].

(4) Airborne transmission is an important mode of virus transmission, and at least six different cases of viruses infecting humans through airborne transmission have been reported. Alsved and colleagues took air samples from the surrounding environment of patients with norovirus infection and analyzed the norovirus RNA in the samples by reverse transcription polymerase chain reaction (RT-PCR). They detected norovirus RNA in some air samples, suggesting that air pollution from vomiting is an important route of virus transmission directly from animals. However, it remains unclear which animal could be the main intermediate host of SARS-CoV-2, although positive viral RNA signals were detected in seafood markets and on the chopping boards of salmon. In 1983, Lidgerding and Hetrick [337] first reported the replication of a coronavirus in a fish cell line. Furthermore, Sano et al. [338] successfully isolated a coronavirus from common carp (Cyprinus carpio) in 1988, which induced hepatic, renal, and intestinal necrosis in experimentally infected fish. Miyazaki et al. [339] found a corona-like virus in color carp (Cyprinus carpio) in 2000, which caused dermal lesion and necrosis in internal organs. Based on the aforementioned pieces of evidence, we propose that an environmental quasi-host can infect a human, and that there are two transmission routes of SARS-CoV-2:

(1) Natural hosts (animals with the virus)–environmental quasi-host (animal feces/water, soil and food contaminated by animals’ urine, saliva, feces, and secretions)–patient zero (infected or virus-carrying human who came into contact with the environment while traveling or working in the wild)–back to home or human habitations–outbreak of COVID-19.

(2) Natural host (animals with the virus)–environmental quasi-host (fruit, food, or meat contaminated by animals’ urine, saliva,
feces, and secretions)—transported to different regions or countries—patient zero (infected or virus-carrying human who came into contact with or ate the environmental quasi-host)—outbreak of COVID-19.

To summarize, it is imperative to investigate environmental quasi-hosts in order to source track the origin of SARS-CoV-2 through our two suggested transmission routes. Given the need to trace the virus around the world to prevent further pandemics, global collaboration is required not only to identify the origin of the virus, but also to fundamentally protect the existence and development of species. Doing so will proactively conserve and restore habitats for species, and serve as a key strategy for preempting the next pandemic.

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Compliance with ethics guidelines

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