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新冠病毒传播的可能路径：自然宿主—环境介质—人

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摘要

传统上，识别第一个感染病例（零号病人）是追溯病毒来源的关键，但是，常常很难找到零号病人。特别是如果零号病人无症状或症状非常轻微，无看医生或相关病情记录，可能永远也无法找到。因此，是否可以跳过零号病人追溯到病毒的来源？针对上述问题，研究中分析了人类历史上的病毒暴发以及病毒在环境中的存活时间等。发现很大比例的疫情事件都是由人类直接接触带有传染性病毒的环境介质而引起的，同时病毒可以在环境介质中长期保持活性。另一方面，随着人类活动能力不断增强，与动物等生存空间的逐渐重叠，人类与带病毒环境介质（我们称之为“环境准宿主”）之间的接触大大增加。因此，研究中提出了跳过零号病人在环境中追溯病毒来源的可能路径，即以携带SARS-CoV-2或RaTG3相关冠状病毒的环境介质为目标，基于自然宿主—环境介质（环境准宿主）—人的传播路径，进行新冠病毒溯源。

1. 引言

传统上，识别第一个感染病例（零号病人）是追溯病毒来源的关键，但是，常常很难找到零号病人。尽管科学家们做出了广泛的努力，但仍未确定1918年流感大流行、人类免疫缺陷病毒（HIV）或2009年H1N1流感的零号病人，而严重急性呼吸综合征冠状病毒2（SARS-CoV-2）的零号病人也很可能无法确定。目前，追溯SARS-CoV-2来源所面临的主要挑战是需要进行大量的跨学科研究，特别是如果零号病人无症状或症状非常轻微，他或她可能没有看医生或产生病历，那么我们可能永远也无法确定患者身份。因此，是否可以既跳过零号病人，又能追溯到病毒的来源呢？

基于此，我们跳过零号病人，以携带SARS-CoV-2或RaTG3相关的蝙蝠传播冠状病毒（Bat-CoV）等病毒的环境介质（以下称为“环境准宿主”）为中心，提出了一种新的病毒传播途径（图1）。并分析了环境准宿主可能成为识别SARS-CoV-2来源关键节点的理由。

病毒通过自然宿主-人接触或环境准宿主-人接触传染给人类，其中环境准宿主可能是被动物宿主的尿液、唾液、粪便或分泌物污染的水、土壤或食物等。尽管许多研究人员认为SARS-CoV-2可能来自野生动物市场，但他们还是把注意力集中在自然宿主-人的途径上[1–3]，而忽视了自然宿主-环境准宿主-人这一传播途径。

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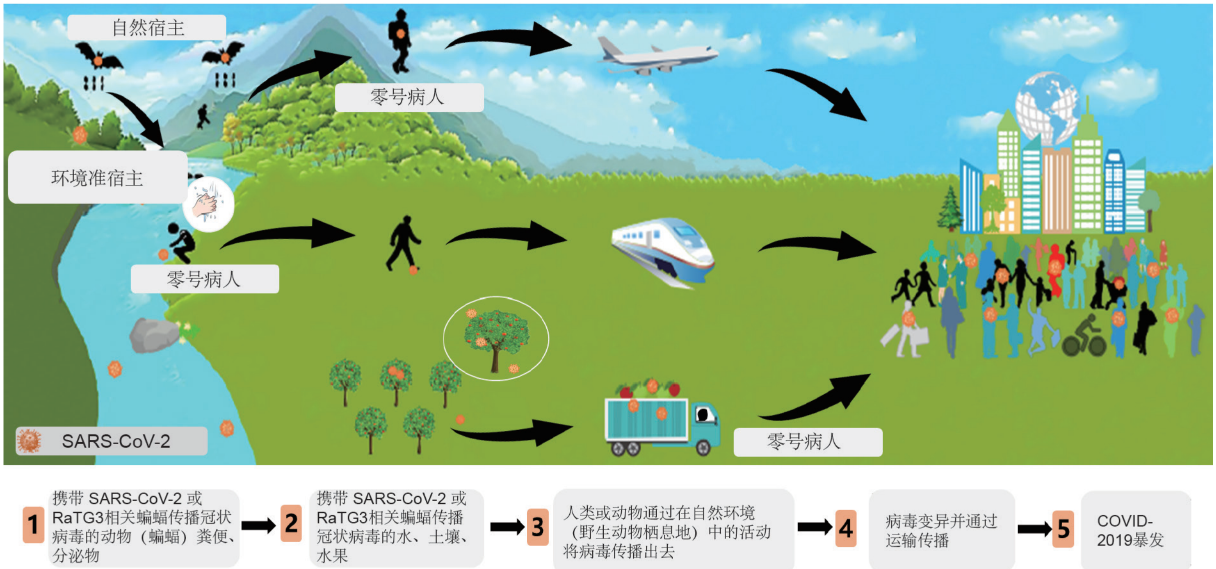

图1. SARS-CoV-2的传播途径。

零号病人是否有可能是因为接触环境准宿主而感染了SARS-CoV-2呢？一方面，全球化和工业化进程的发展，使得人类的活动空间与动物的生活空间逐渐重叠，这导致人类与环境准宿主之间的接触大大增加。另一方面，病毒可以在某些环境介质中长期生存，人有很大的概率在接触这些环境介质时感染病毒[4–6]。研究发现，人类的许多病毒暴发都是由于人类直接接触了含有病毒的环境介质，如携带病毒的水和土壤岩土介质等，而不是直接接触自然宿主引起的[7–10]。

根据以下几条近期研究的证据和其他病毒的传播途径，我们认为SARS-CoV-2有可能是由环境准宿主传播的。

2. 在各种环境介质中检测出 SARS-CoV-2

SARS-CoV-2已在各种环境介质中被检测到，包括废水、土壤、地板表面、门把手、水槽、储物柜、桌子、窗户和包装等（表1 [11–22]）。2020年2—3月间，武汉大学的Liu及其同事[11]通过在两家医院及其周围设置气溶胶捕获装置，证明了空气中存在SARS-CoV-2 RNA。Ong的研究小组[12]在患者房间和厕所的环境表面检测到SARS-CoV-2。荷兰蒂尔堡史基浦机场的废水中也检测到了SARS-CoV-2 [13]。基于以上研究推测，SARS-CoV-2可能存在于其自然宿主的动物栖息地中，因此进一步检测自然栖息地环境介质中可能存在的SARS-CoV-2是有必要的。

3. 病毒在环境介质中的长期存活

目前已有研究显示，病毒能够在低温、相对封闭、受扰动较小、高度异质的环境介质中长时间保持活性。在适宜条件下，病毒在环境介质中可存活数百天乃至上千天，并且仍具有感染性。在永久冻土中保存了3万年的西伯利亚细小病毒，复苏后仍具有感染能力[23]。猪细小病毒在土壤中可存活43周以上[6]，脊髓灰质炎病毒在1 ℃下保存75天后依旧稳定并具有活性[24]。在地下水中，人诺如病毒存活1266天后仍有10%的活性[25]。甲型肝炎病毒和脊髓灰质炎病毒在4 ℃矿泉水中保存一年后的感染力仅有少量降低[4]。污水中的诺如病毒1343天后仍可被检测到[5]。

我们分析了近120年来发表的482篇学术论文（表2 [26–122]），这些论文研究了116种不同病毒株的生存时间。从统计学角度看，116种不同病毒株中，84%以上的病毒可以存活一周以上（图2 [26–122]）。而且随着全球交通的快速发展，环境介质中的病毒可以在几天或几周内从世界的一个地方被带到另一个地方，因此，病毒的起源地可能远离其暴发地。由于病毒的系统发育特征可能会在很大程度上影响其在环境介质中的存活时间，因此病毒的系统发育特征也值得进一步研究。

现有研究证实，SARS-CoV-2很可能长期存在于化粪池和其他含土壤的固体介质中[22]。新加坡国家传染病中心和国防科学组织（DSO）国家实验室在COVID-19患者的居室中检测到该病毒，其中地板表面的病

表1 环境介质中的SARS-CoV-2

编号	环境介质	收集时间	地点或国家	参考文献
1	气溶胶	2020年2–3月	中国武汉	[11]
2	污水	2019年11月27日	巴西南部的弗洛里亚诺波利斯	[14]
3	污水	2019年12月18日	意大利米兰和都灵	[15]
4	污水	2020年3月5日至4月23日	法国巴黎	[16]
5	非饮用水	2020年4月	法国巴黎	[17]
6	地面、门把手、水槽、储物柜、桌子和窗户等	2020年1月24日至2月4日	新加坡	[12]
7	冻虾的包装和容器的内壁	2020年7月3日	中国北京	[18]
8	从海产品、肉类和外部环境中提取的样品	2020年6月	中国北京	[19]
9	粪便	2020年1月1日至2月17日	中国	[20]
10	粪便	2020年	中国	[21]
11	污水	2020年2月	荷兰蒂尔堡史基浦机场	[13]
12	土壤、污水	2020年4月	中国武汉	[22]

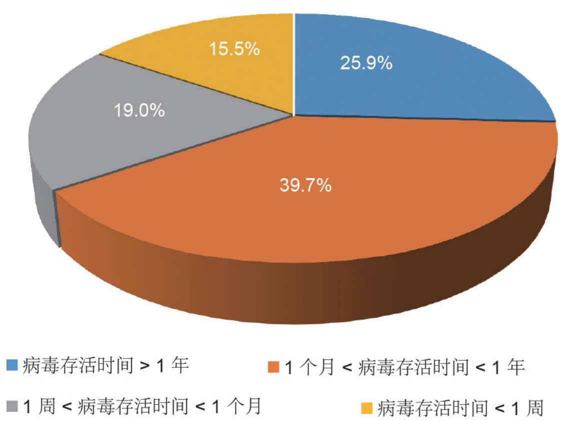

图2. 研究的116病毒的存活时间比较[26–122]。

毒阳性信号最高，超过马桶、门把手、水槽、储物柜、桌子和窗户等地方的信号[12]。SARS-CoV-2被发现可以在气溶胶中保持长期活性，研究者们发现在实验3 h后每升空气中的感染性滴度（TCID50）仅从$10^{3.5}$降至$10^{2.7}$ [77]。基于这些研究结果推测，SARS-CoV-2可能在野生动物的栖息地和活动场所存在并长期保持活性，特别是在气温低、光照少的地方。

4. 因直接接触环境介质而非自然宿主所引起的人类病毒暴发

通过分析过去120年发表的文献，我们发现至少198例病毒感染病例，涉及 28种不同的病毒株，是通过直接接触环境介质而引起的（表3 [123–318]）。其中有些病例是从数据统计中获得了环境介质与病毒传播之间的相关性，大多数病例是通过对环境介质的调查，从而认识到了病毒传播的途径或宿主。例如：

（1）2008年，一名44岁的美国妇女在乌干达旅游时参观了一个有蝙蝠群栖息的蟒蛇洞，她在回国后不久就出现了马尔堡病的症状。这种疾病是由一种与埃博拉病毒同属一个家族的病毒引起的。科学家对乌干达一个山洞中的埃及果蝠进行了基因测序，认为她是在参观蟒蛇洞时接触了一块布满蝙蝠粪便的岩石而感染了该病毒[8–10]。

（2）埃博拉病毒传播途径也被确认是由于人类误食了果蝠粪便污染的水果[7]。

（3）自2009年以来，我国已累计发生不少于5起因饮用病毒污染地下水而引发的传染疾病，受影响人数合计上千人。例如，2014—2015年冬季，中国河北发生了一起胃肠炎疫情。从临床和水样中提取的诺如病毒核苷酸序列与Beijing/CHN/2015年的毒株同源性达99%，证实了此次疫情是由水传播引起的。这是通过调查环境介质找到病毒传播途径的一个很好的例子[154,176,194,244,319]。

（4）空气传播是病毒传播的一种重要方式，目前已经报道了至少6种不同的病毒通过空气传播感染人类的病例。Alsved及其同事从诺如病毒感染患者的周围环境中采集空气样本，通过逆转录聚合酶链反应（RT-PCR）分析样本中的诺如病毒RNA。他们在部分空气样本中检测到诺如病毒RNA，提示呕吐造成的空气污染是诺如病毒的重要来源[170,265,273,276,292,295]。

从统计学角度的研究也为环境与流行病之间的联系提供了证据：

（1）首次报道的11例人类埃博拉病例中，有8例发生在森林破坏严重的地区，而森林是携带埃博拉病毒的蝙蝠的栖息地[320]。

表2 病毒在环境介质中的存活时间

病毒存活时间（t）	病毒
$t > 1$年	呼肠孤病毒[26]、腺病毒[5]、病毒性出血败血症病毒[33]、猫杯状病毒[36]、小牛轮状病毒[26]、脊髓灰质炎病毒[4]、甲型肝炎病毒[4]、番茄花叶病毒[48]、瘙痒病毒[52]、H5N1 [56]、H5N2 [60]、H7N3 [60]、H1N1 [65]、H6N2 [69]、H7N1 [71]、马立克氏病病毒[74]、小鼠肝炎病毒[75]、诺瓦克病毒[5]、颗粒病毒[84]、禽副黏病毒-1 [87]、葡萄扇叶病毒[89]、茄环斑病毒[92]、人冠状病毒229E [95]、核多角体病病毒[96]、非洲猪瘟病毒[98]、猪水泡病病毒[100]、中肠腺坏死杆状病毒[102]、肉芽肿病毒（杆状病毒科）[104]、传染性造血坏死病毒[106]、西伯利亚细小病毒[23]
1个月＜ t ＜1年	星状病毒[27]、梭鱼苗横纹肌病毒[30]、鲤鱼春季病毒血症[30]、传染性胰腺坏死病毒[30]、轮状病毒[39]、艾柯病毒[42]、图兰病毒[45]、柯萨奇病毒[49]、鼠诺如病毒[53]、埃博拉病毒[57]、H12N5 [61]、H10N7 [61]、H3N8 [66]、H4N6 [66]、H9N2 [72]、传染性胃肠炎病毒[75]、口蹄疫病毒[78]、鲤鱼疱疹病毒[81]、雪山病毒[85]、小鼠微小病毒[35]、甜菜坏死黄脉病毒[90]、鲑鱼α病毒[93]、猫传染性腹膜炎病毒[95]、天花病毒[97]、猴轮状病毒[99]、蛙病毒3 [101]、猪捷申病毒[103]、白斑综合征病毒[105]、淋巴囊肿病病毒[107]、神经疫苗病毒[108]、马铃薯纺锤块茎类病毒[62]、朊病毒[109]、火鸡呼肠孤病毒[110]、牛细小病毒[111]、牛肠道病毒[112]、戊型肝炎病毒[113]、斑点叉尾鮰病毒[114]、禽呼肠孤病毒[115]、传染性鲑鱼贫血病毒[116]、传染性胰腺坏死病毒[117]、细小病毒[118]、鸭瘟疱疹病毒[119]、猪细小病毒[6]、西尼罗河病毒[120]、H7N7 [121]、乙型肝炎病毒[122]
1周＜ t ＜1个月	H11N6 [28]、人体免疫缺陷病毒[31]、马疱疹病毒1型[34]、猪繁殖与呼吸综合征病毒[37]、人乳头瘤病毒16型[40]、丙型肝炎病毒[43]、猪札如病毒[46]、传染性法氏囊病病毒[50]、乙型脑炎病毒[54]、水痘病毒[58]、佩皮诺花叶病毒[62]、人副流感病毒[63]、拉沙病毒[67]、委内瑞拉马脑炎病毒[67]、辛德毕斯病毒[67]、陶拉综合征病毒[76]、严重急性呼吸综合征相关冠状病毒[79]、水泡性口炎病毒[82]、尼帕病毒[86]、汉坦病毒[88]、发热伴血小板减少综合征病毒[91]、H3N2 [94]
$t < 1$周	猴病毒40 [29]、肺眼气管病毒[32]、单纯疱疹病毒[35]、猫白血病病毒[38]、无脊椎动物虹彩病毒6 [41]、鸵鸟疱疹病毒-1 [44]、牛瘟病毒[47]、小鼠轮状病毒[51]、传染性支气管炎病毒[55]、人类多瘤病毒[59]、马铃薯Y病毒[62]、猪瘟病毒[64]、人类鼻病毒[68]、巨细胞病毒[70]、马尔堡病毒[73]、新型冠状病毒[77]、麻疹病毒[80]、中东呼吸综合征冠状病毒[83]

（2）受损林区蜱虫的迁徙轨迹与科萨努尔森林病[321]和莱姆病[322]的分布以及发病情况有显著的相关性。此外，研究表明，栖息地的破坏既增加了野生动物的生存压力，也增加了尿液和唾液分泌物的病毒量[323]。

5. 动物身上的病毒可能通过多种途径传播给人类

巢病毒目（Nidovirales）冠状病毒科（Coronaviridae）正冠状病毒亚科（Orthocoronavirinae）由四个属组成：α-冠状病毒、β-冠状病毒、γ-冠状病毒和δ-冠状病毒。SARS-CoV-2属于β-冠状病毒属的*Sarbecovirus*亚属，SARS-CoV和MERS-CoV也属于该属。冠状病毒（CoV）既能感染人类，也能感染家畜和野生动物，在大多数情况下，感染仍处于亚临床状态[324–326]。α-冠状病毒和β-冠状病毒通常可以感染哺乳动物，可能宿主是蝙蝠，而γ-冠状病毒和δ-冠状病毒主要感染鸟类，有时也可以感染哺乳动物，可能宿主是猪[327–329]。据报道，有许多动物物种是病毒的中间宿主，如狗、猫、牛、马、骆驼、啮齿动物、兔子、穿山甲、水貂、蛇、青蛙、土拨鼠、刺猬和雪貂等[324,330–336]。因此，不同动物对人的病毒传播途径可能有多种。中国的三个冠状病毒暴发点，即2003年广东的畜禽市场、2019年年底的武汉华南海鲜市场和2020年6月的北京新发地海鲜市场，都与动物市场有关。果子狸和骆驼已经被证明可以将SARS-CoV或MERS-CoV传播给人类，这为病毒直接从动物身上传播给人类提供了重要提示。然而，目前尚不清楚哪种动物可能是SARS-CoV-2的主要中间宿主，尽管在海鲜市场和三文鱼的砧板上检测到了阳性的病毒RNA信号。1983年，Lidgerding和Hetrick [337]首次报道了冠状病毒在鱼类细胞系中的复制。此外，Sano等[338]于1988年成功地从普通鲤鱼（*Cyprinus carpio*）中分离出一种冠状病毒，该病毒能导致实验感染鱼的肝脏、肾脏和肠道坏死。Miyazaki等[339]于2000年在彩鲤（*Cyprinus carpio*）身上发现了一种冠状病毒，该病毒可引起皮肤病变和内脏坏死。

基于上述证据，我们认为SARS-CoV-2可以也有可能通过环境准宿主感染人类，可能的传播途径有两种：

（1）自然宿主（携带病毒的动物）—环境准宿主（动物粪便/被动物尿液、唾液、粪便污染的水、土壤和食物，以及分泌物）—零号病人（在野外旅行或工作时与环境准宿主接触的感染者或病毒携带者）—回到家中或人类居住地—暴发COVID-19；

表3 人与环境介质直接接触引起的病毒感染病例

编号	病毒	相关环境介质	地点、区域或国家	时间	参考文献
1	戊型肝炎病毒	水	印度坎普尔	1991	[123]
		水	印度海得拉巴	2005	[124]
		水	印度希姆拉	2015–2016	[125]
		水	乍得安提曼	2016-09–2017-04	[126]
		水	印度海得拉巴	2005-03–2005-08	[127]
		水	中国浙江	2014	[128]
		地表水	苏丹达尔富尔	2004	[129]
		水	巴基斯坦阿伯塔巴德	1988	[130]
		饮用水	尼泊尔	1995	[131]
2	诺如病毒（诺沃克病毒、小圆结构病毒）	地下水、海水	意大利	2003	[132]
		水	危地马拉	2009	[133]
		井水	美国威斯康星州东北部	2007-06	[134]
		水	瑞士	2008	[135]
		饮用水	荷兰	2001-11–2001-12	[136]
		饮用水	冰岛	2004	[137]
		水	新西兰的滑雪胜地	2006	[138]
		水	希腊北部基尔基斯	2012	[139]
		饮用水和淋浴水	挪威西部	2002-07	[140]
		湖水	芬兰西部	2014-07	[141]
		饮用水	意大利北部	2009-06	[142]
		水	比利时	2007-07	[143]
		水	希腊查尔基迪基	2015-08	[144]
		饮用水	黑山波德戈里察	2008-08	[145]
		自来水	中国	2010-10-31–2010-11-12	[146]
		湖水	美国缅因州海滩	2018	[147]
		环境表面	美国科罗拉多州	2019	[148]
		食物	日本一家医院和一个附属的长期护理机构（LTCF）	2007	[149]
		猪肝和羊排	中国台湾	2015-02	[150]
		水或被水污染的食物	中国沿着长江航行的游船	2014-04	[151]
		三明治	美国俄亥俄州汉密尔顿县	1997	[152]
		水	中国武汉	2017-04-28–2017-05-08	[153]
		井水	中国西北大学	2014-06	[154]
		水	奥地利萨尔茨堡	2005-05–2005-06	[155]
		桶装水	中国嘉兴	2014-02	[156]
		水	南非	2017-01	[157]
		瓶装水	西班牙加泰罗尼亚	2016-04-11–2016-04-25	[158]
		食物	中国上海	2012-12	[159]
		娱乐用水	荷兰	2002-06	[160]
		饮用水	希腊东北部	2006-06	[161]
		井水	希腊北部赞西	2005	[162]
		地下水	韩国济州岛	2004-05	[163]
		食物	加拿大魁北克省	2011-01	[164]
		食物	日本长崎	2003-11-18–2003-11-19	[165]
		游泳池水	英格兰东南部	2016-01	[166]
		娱乐用水	美国佛蒙特州	2004-02	[167]

（续表）

编号	病毒	相关环境介质	地点、区域或国家	时间	参考文献
		游泳池水	美国得克萨斯州加尔维斯顿县	2013	[168]
		娱乐用水	波多黎各	2009	[169]
		空气	瑞典南部	2017–2018	[170]
		空气	中国连云港	2017	[171]
		冰	中国台湾	2015	[172]
		食物	中国珠海	2011	[173]
		食物	中国北京	2017-12	[174]
		水	中国无锡	2014-12-11	[175]
		井水	中国河北	2014–2015	[176]
		食物	中国上海	2013-12	[177]
		食物	中国北京	2018-09-04	[178]
		食物	从美国佛罗里达州到加勒比海的七天假期游轮	2002-11	[179]
		环境表面	美国有240张床位的退伍军人长期护理机构（LTCF）	2003-01–2003-02	[180]
		井水	瑞典	Easter 2009	[181]
		井水	意大利西西里岛圣斯特凡诺·奎斯奎纳	2011-03	[182]
		水	芬兰诺基亚城	2007-11	[183]
		冰	美国特拉华州	1987-09-19–1987-09-27	[184]
		食物	德国汉堡	2005-08	[185]
		自来水	比利时海米克塞姆	2010-12	[186]
		环境表面	国际游轮	2008	[187]
		公共卫生间环境	游船	2005–2008	[188]
		水、环境表面	欧洲	Summer of 2006	[189]
		未清洁的计算机设备（即键盘和鼠标）	美国哥伦比亚特区	2007-02-08	[190]
		受污染的环境表面	中国上海	2014-12-7–2014-12-18	[191]
		食物	美国佛罗里达大学的一场足球赛	1998-09	[192]
		食物	美国西弗吉尼亚州	2006-01	[193]
		水	中国深圳	2009-09-17–2009-10-03	[194]
		食物	瑞典斯德哥尔摩	2007-11	[195]
		自来水	意大利南部塔兰托湾	2000-07	[196]
		游泳池水	美国俄亥俄州	1977-06	[197]
		自来水	芬兰海因维斯	1998-03	[198]
		食物	美国纽约	2000-02	[199]
		饮用水	美国北乔治亚州	1980-08	[200]
		食物	美国弗吉尼亚州的一家酒店	2000-11	[201]
		食物	美国弗吉尼亚州	1999-05–1999-06	[202]
		环境	芬兰南部	1999-12–2000-02	[203]
		井水	美国亚利桑那州	1989-04-17–1989-05-01	[204]
		水	美国宾夕法尼亚州	1978-07	[205]
		气溶胶	小学和托儿所	2001-06	[206]
		水	瑞典的滑雪胜地	2002-02–2002-03	[207]
		食物	瑞典南部	2000-05-02–2000-05-03	[208]
		食物	美国得克萨斯州埃尔帕索的布利斯堡	1998-08-27–1998-09-01	[209]
		气溶胶	加拿大一家大酒店	1998-12	[210]
		水气	西班牙翁蒂涅恩特（瓦伦西亚）	1992-01	[211]

（续表）

编号	病毒	相关环境介质	地点、区域或国家	时间	参考文献
		娱乐用水	荷兰	2012-08	[212]
		饮用水	芬兰	1994-04	[213]
		食物（饮用水制成）	美国南达科他州	1986-08-30–1986-08-31	[214]
		水	美国北乔治亚州	1982-01	[215]
		水、食物	两艘加勒比游轮	1986-04-26–1986-05-10	[216]
		湖水	美国密歇根州马克姆县	1979-07-13–1979-07-16	[217]
		食物(暴露于非饮用水中)	美国空军学院		[218]
		媒介物	澳大利亚悉尼	2002-09	[219]
		环境污染	英格兰西北部	1996-01–1996-05	[220]
		食物	英国大都会音乐厅	1999-01	[221]
		食物	日本丰田城	1989-03	[222]
		食物	美国麻省大学	1994-12	[223]
		空气	美国洛杉矶	1988-12–1989-01	[224]
		井水	加拿大育空地区的一家餐馆	1995	[225]
		地下水	瑞士拉纽维尔	1998	[226]
		自来水	再教育病房	1999-01	[227]
		污染水制出的食物	英国南威尔士和布里斯托尔	1994-08	[228]
		空气	英国注册的游轮	1988-01-13	[229]
		河水	澳大利亚新南威尔士州南部	Christmas holiday period of 1989	[230]
		生牡蛎	苏格兰西南部	Christmas holiday period of 1993	[231]
		呕吐物的雾化，气溶胶	英国老年护理机构	1992-11	[232]
		环境污染	英国精神病医院	1994-05	[233]
		食物	英国一家大酒店	1985-11	[234]
3	甲型肝炎病毒	饮用水	美国肯塔基州米德县	1982-11	[235]
		井水	美国佐治亚州巴托县的拖车停车场	1982	[236]
		湖水	美国沃特利湖	1969-09	[237]
		水	阿尔巴尼亚	2002-11–2003-01	[238]
		面包	英国南剑桥郡的一个村庄	The late spring and summer of 1989	[239]
		地下水	美国	1971–2017	[240]
		食物	荷兰	2017	[241]
		食物	意大利	1996	[242]
		贝类	中国上海	1988	[243]
		井水	中国广西	2012-05	[244]
		食物	意大利南部	2002	[245]
		地下水	泰国	2000	[246]
		水	印度鲁德拉普拉耶格	2013-05	[247]
		水	美国得克萨斯州乔治敦	1980-06	[248]
		冷冻的浆果	意大利北部	2013	[249]
		蛤蜊	西班牙瓦伦西亚	1999	[250]
		水	加拿大圣劳伦斯河上的奥尔良岛	Summer of 1995	[251]
		游泳池水	美国	1989	[252]
		水疗池	美国维多利亚州	1997	[253]
		供水	韩国	2015-04	[254]
		水	西班牙卡斯特利尤特	1987-09	[255]

（续表）

编号	病毒	相关环境介质	地点、区域或国家	时间	参考文献
		饮用水	印度新德里，医学院学生宿舍	2014-01	[256]
		橙汁	欧洲	2004	[257]
		冷冻草莓	北欧国家	2012-10–2013-06-27	[258]
		冷冻混合浆果	意大利北部	2013-01–2013-05	[259]
		半干西红柿	荷兰	2010	[260]
		石榴	美国	2013-05	[261]
4	丙型肝炎病毒	水	阿尔及利亚美迪亚	1980–1981	[262]
		污水	阿尔及利亚污水处理厂	1991	[263]
5	细小病毒	饮用水	美国	1971–1978	[264]
6	麻疹病毒	空气	美国明尼阿波利斯-圣保罗大都会区	1991-07	[265]
7	脊髓灰质炎病毒	牛奶	美国西海岸	1943-09	[266]
		湖水	美国密歇根州奥克兰县	1993-06-11–1993-06-13	[267]
		飞沫	英国伦敦米德尔塞克斯医院	Late summer of 1952	[268]
8	H5N1	鸡粪	印度尼西亚	2005-06–2008-06	[269]
9	轮状病毒	自来水	法国伊塞尔地区	1994	[270]
		井水	印度	2009-04–2009-05	[271]
		水	美国科罗拉多州伊格尔维尔	1981-03	[272]
		气溶胶	小学		[273]
10	腺病毒	游泳池水	美国俄克拉荷马州	1982-07	[274]
		环境	美国圣地亚哥海军陆战队新兵训练司令部	2004	[275]
		空气	中国武汉	2014	[276]
		游泳池水	美国乔治亚州	1977	[277]
		游泳池水	中国北京	2013	[278]
		游泳设施	中国台湾	2011-09	[279]
11	汉坦病毒	动物粪便	美国北达科他州	2016	[280]
		鹿鼠排泄物	美国加利福尼亚州	2017	[281]
		动物分泌物	北威尔士	2013	[282]
		老鼠	美国伊利诺伊州和威斯康星州	2017	[283]
12	新型冠状病毒	唾液	中国香港	2020	[284]
13	中东呼吸综合征冠状病毒	骆驼	阿拉伯联合酋长国	2019	[285]
		飞沫	沙特阿拉伯	2013-03–2013-04	[286]
14	发热伴血小板减少综合征病毒	猫	日本		[287]
15	单纯疱疹病毒	唾液	英格兰	2019	[288]
16	严重急性呼吸综合征相关冠状病毒	蝙蝠	中国云南	2015	[289]
		气溶胶	加拿大	2003	[290]
		气溶胶	中国香港	2003	[291]
		空气	加拿大	2003	[292]
		空气	中国香港	2003	[293]
17	西尼罗河病毒	蚊虫控制池	美国加利福尼亚州	2007	[294]
18	H3N2	猪	美国俄亥俄州	2012	[295]
		空气、液滴	美国阿拉斯加	1977	[296]
19	H1N1	飞沫	中国四川	2009	[297]
20	H7N7	家禽，人	荷兰	2003-02	[298]
21	尼帕病毒	鲜枣椰汁	孟加拉国坦格尔区	2004–2005	[299]
22	乙型肝炎病毒	足部护理	美国洛杉矶	2008	[300]

（续表）

编号	病毒	相关环境介质	地点、区域或国家	时间	参考文献
23	人类杯状病毒	井水	美国怀俄明州	2001-01	[301]
24	艾柯病毒	游泳池水	德国卡塞尔	2001-07–2001-10	[302]
		游泳池水	意大利罗马	1997	[303]
25	埃博拉病毒	体液	刚果	1995	[304]
		体液	刚果	1995	[305]
26	马尔堡病毒	蝙蝠或蝙蝠分泌物	乌干达	2007-06–2007-09	[306]
		蝙蝠或蝙蝠分泌物	荷兰	2008	[307]
		蝙蝠分泌物	美国	2008	[308]
		洞穴、矿井或类似的栖息地	刚果	1998-10	[309]
		病人尸体或分泌物	乌干达	2012-09–2012-12	[310]
27	肠道病毒	灌溉废水	以色列	1980–1981	[311]
		饮用水	瑞士	1998-08	[312]
		海水	美国康涅狄格州	2004	[313]
		食物	英格兰	2003-04	[314]
		井水	美国密苏里州南部和阿肯色州	1978-05-07–1978-05-26	[315]
		饮用水	美国科罗拉多州	1976-12	[316]
28	肝炎病毒	水	奥地利	1952	[317]
		水	法国	1957-09-08–1957-10-05	[318]

（2）自然宿主（携带病毒的动物）—环境准宿主（被动物尿液、唾液、粪便和分泌物污染的水果、食品或肉类）—运输到不同的地区或国家—零号病人（接触或吃掉环境准宿主的感染者或病毒携带者）—暴发COVID-19。

综上所述，环境中的溯源的核心是调查寻找环境准宿主，可以通过以上建议的两种传播途径追溯SARS-CoV-2的起源。由于目前人类的活动范围非常广泛，跨区域或跨国活动非常频繁，目前还很难确定新冠病毒的最初来源地，新冠病毒可能来源于地球上任一人类能接近的动物栖息地或栖息地环境显著改变地区。另一方面，也说明溯源工作任重道远，实施难度大、周期长、复杂程度高，需要在全球尺度上开展溯源研究，更需要多学科和多国家合作。长远来说，我们必须从根本上保护各级物种的生存和发展，积极主动地保护和恢复物种的生存环境，才能从根本上预防下一次大流行病的暴发。

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Compliance with ethics guidelines

Miao Li, Yunfeng Yang, Yun Lu, Dayi Zhang, Yi Liu, Xiaofeng Cui, Lei Yang, Ruiping Liu, Jianguo Liu, Guanghe Li, and Jiuhui Qu declare that they have no conflict of interest or financial conflicts to disclose.

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