REALM PROJECT
REopening Archives, Libraries and Museums

Systematic Literature Review of SARS-CoV-2: Spread, Environmental Attenuation, Prevention, and Decontamination

Phase 2 – Gap Analysis – Mid-May 2020 to August 14, 2020

Prepared for:

OCLC and Institute of Museum and Library Services (IMLS)

OCLC
6565 Kilgour Place
Dublin, OH 43017

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Submitted by:

Battelle
505 King Ave
Columbus, Ohio 43201-2696

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Executive Summary

As libraries, archives and museums (LAMs) work to resume operations in the midst of the continuing severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) pandemic, access to the latest scientific research on disease transmission and virus durability is critical. As part of the REALM project, Battelle has conducted two systematic literature reviews to provide LAMs with the informational support needed to make informed decisions about how to develop and implement protocols that can reduce risk of spreading the virus. The Battelle research team gathered, evaluated, and synthesized research literature published on SARS-CoV-2 as it relates to three key topics:

1. Virus spread through general building operations
2. Virus survival and decay on material surfaces over time
3. Effective prevention and decontamination measures that are readily available in the near term

The first literature review report was released in Phase 1 of REALM on June 17, 2020, and it presented a synthesis of relevant publications released through mid-May 2020. Due to the evolving nature of scientific research on SARS-CoV-2, a second literature review was conducted in Phase 2 of REALM to synthesize research that was published on the three key topics since the earlier review.

To be responsive to the needs of LAMs, several areas of interest within the three key topics were also identified to enhance the Phase 2 literature review, including impacts of heating, ventilation, and air conditioning (HVAC), air filtration, and fomites (contaminated objects) on the spread of the virus; impacts of environmental factors (e.g., humidity, temperature, surface pH, etc.) on how long the virus survives on surfaces and materials; and prevention and decontamination strategies known to create less impact on workplace environments. These interest areas were given additional consideration during the research process, to the extent they arose in the literature search results.

Using search terms similar to the Phase 1 literature review, Phase 2 identified relevant documents through a systematic search of four scientific databases: Scopus, Web of Science, SciTech, and MEDLINE, which were selected for their comprehensive coverage of the literature. The search results were scrutinized closely for their relevance to the three key topics, resulting in 203 relevant research articles considered for inclusion in the report.

Due to the novel and emerging nature of SARS-CoV-2, scientific research related to the virus continues to evolve. Similar to the Phase 1 literature review, the research literature identified in Phase 2 presents as a work in progress, with many of the articles being pre-prints, letters to the editor, and other types of publication that had not undergone the scholarly vetting process of peer review. However, compared to the search results of the Phase 1 literature review, many more documents were retrieved by the Phase 2 systematic search process, and a far greater proportion of those documents were peer-reviewed articles.

After reviewing the relevant research articles identified in the Phase 2 systematic literature search, the Battelle team identified several key themes:

- SARS-CoV-2 is generally understood to spread primarily through virus-containing water droplets expelled from sneezes, coughs, speaking, and other respiratory activities by infected persons. Evidence has also suggested that other pathways for spreading the virus may include:
    - Breathing air that the virus is suspended in, such as after an aerosolization event (e.g., a sneeze)
    - Touching surfaces of objects where the virus has been deposited (sometimes called fomites), which can occur through exhaling or otherwise depositing virus-containing droplets on the surface.
- Environmental factors, including temperature and humidity, have been identified as influential in the spread of SARS-CoV-2. Specifically, higher temperatures, higher humidity, and increased intensity of ultraviolet (UV) light (e.g., sunlight) seem to lead to SARS-CoV-2 decaying more quickly. However, additional research is needed to understand the complexities of these variables' impact on the virus and its transmission.
- Some evidence has suggested that HVAC systems and other air circulation mechanisms can contribute to spreading the virus through the air. On the other hand, poor ventilation may also lead to airborne virus remaining in indoor environments longer. However, the impact of these systems on people contracting the virus requires further study.
- A general observation was that, compared to the Phase 1 literature search, in Phase 2 fewer studies were found that conducted empirical research on how long SARS-CoV-2 survives on different surfaces and materials (i.e., key topic #2). This finding suggested that the scientific community's focus may have shifted more towards how the virus spreads and how it can be stopped from spreading and/or decontaminated.
- Prevention and decontamination tactics presented in the literature offered several feasible, low-cost options for reducing the presence of SARS-CoV-2 in environments, which may help prevent transmission of the virus among people in those environments. Tactics that showed efficacy included hand washing and hand sanitizing, wearing personal protective equipment (PPE) including masks, air ventilation and open spaces, applications of UV light and/or increased heat, applying disinfectants to decontaminate surfaces, and social distancing to prevent distribution of respiratory droplets between individuals. See the Table 3 in Section 4.1.3 for a list of noted tactics.

In general, additional rigorous research is needed to explore the impacts of diverse variables on the ability of SARS-CoV-2 to spread and persist. This includes closely evaluating the effects of changes in key factors such as temperature, humidity, fomites, and the presence of biological substances (e.g., saliva, feces). Furthermore, many studies conducted to date have tested for the presence of SARS-CoV-2 genetic material, ribonucleic acid (RNA), and not whether the virus is still viable and capable of transmission. Additional research is needed that employs tests capable of distinguishing when *viable* SARS-CoV-2 is present, as viability can have greater implications for humans contracting the virus. Relatedly, this literature review investigated findings about the spread of SARS-CoV-2, but additional research into the mechanisms of transmission and contraction of the virus, such as the minimum viral count leading to infection (i.e., the infectious dose), may provide key insight into exposure risks and prevention strategies that offer the highest impact. Such research will also help increase certainty about how long the virus remains infectious on surfaces, in the air, and by other potential means of transmission. To date, the infectious dose of this virus for humans remains unknown for all routes of exposure, according to the Department of Homeland Security's Master Question List for COVID-19 (the disease caused by SARS-CoV-2) (August 18, 2020). As these and other factors are further explored by the scientific community, LAMs will be able to refine their protocols and further reduce risk of exposure to SARS-CoV-2 for patrons, staff, and other stakeholders.

1. Introduction

The REopening Archives, Libraries, and Museums (REALM) project is conducting scientific research regarding SARS-CoV-2 and developing information, communications, and materials for LAMs as they plan to resume operations for the public. To help protect patrons, staff, and other stakeholders, LAMs that are resuming operations during the outbreak of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) require access to scientific research about how the virus can be spread through their operations. These institutions have unique operations, tactile surfaces, and a high volume of staff and patrons. Through a collaborative relationship, OCLC and Battelle merged their expertise to provide evidence-based information to the LAMs community that can support efforts to reduce the transmission of SARS-CoV-2 and Coronavirus Disease 2019 (COVID-19), the disease caused by SARS-CoV-2.

Battelle has conducted two systematic literature reviews for REALM in 2020. The first literature review report (Phase 1 - view the Phase 1 report here), released on June 17, 2020, presented a synthesis of relevant publications released through May 11 or May 18, with the cutoff date varying by search string (see Section 2.1.1 for more details). Due to the evolving nature of scientific research on SARS-CoV-2, the second literature review report (Phase 2) was conducted to synthesize relevant research that was published since the Phase 1 review.

1.1 Purpose of Literature Review

The purpose of this Phase 2 literature review was to perform a gap assessment that collected, curated, and disseminated information about relevant SARS-CoV-2 publications released after the Phase 1 literature review, which could be used by LAMs to inform ongoing decision making related to reopening of facilities and resuming operations. Like the Phase 1 literature review, the Phase 2 literature review focused on the following three research questions:

1. How could the virus spread through general building operations?
2. How long does the virus survive on material surfaces?
3. How effective are various prevention and decontamination measures that are readily available in the near term?

To be responsive to the needs of LAMs, additional areas of interest within these research questions were also considered, including impacts of HVAC, air filtration, and fomites on the spread of the virus; impacts of environmental factors (e.g., humidity, temperature, surface pH, etc.) on surface attenuation of the virus; and effective prevention and decontamination strategies known to create less impact on workplace environments. These interest areas were given additional consideration during the research process, to the extent they arose in the literature search results.

2. Methods

The literature review consisted of a systematic literature search, the methods of which are outlined in the sections that follow, including a description of the search process, abstraction process, and quality control (QC) processes. The overall process is visualized in Figure 1.

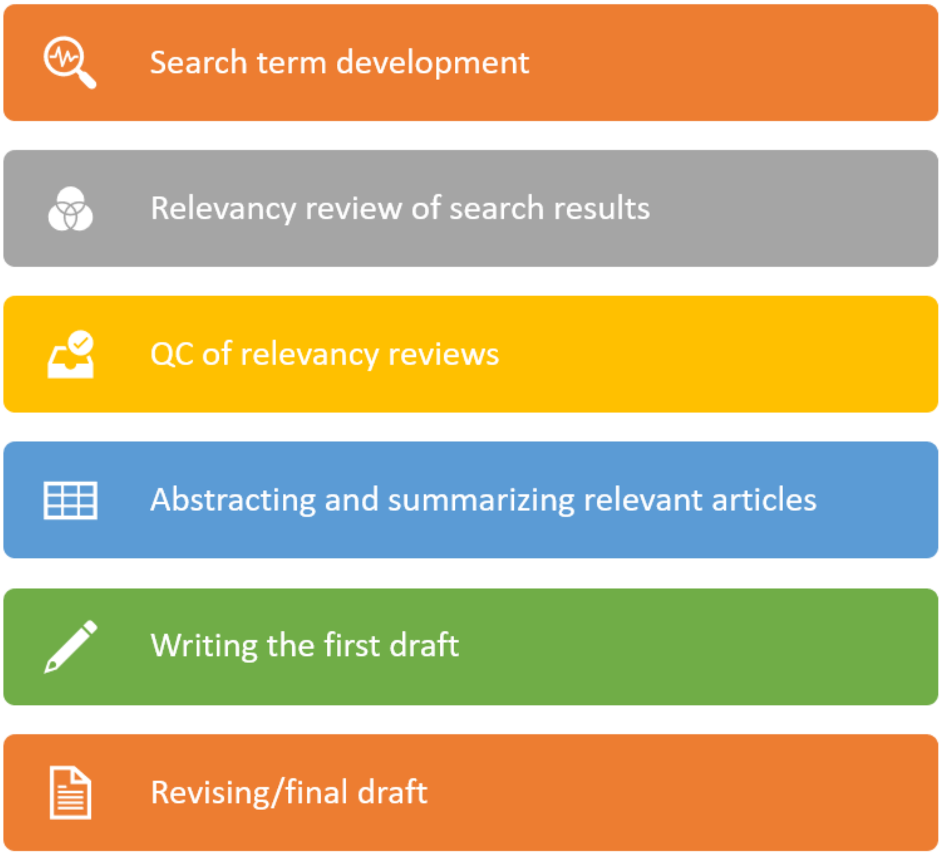


Figure 1. Systematic literature review process.

2.1 Systematic Literature Search

The systematic literature search was initiated after confirmation of the project objectives and research questions. It involved search string development, executing the searches, reviewing results for relevancy, abstracting key information from relevant articles, summarizing key findings, and conducting QC reviews.

2.1.1 Search String Development

To expand on the results identified in the Phase 1 literature review, the search strings used for the Phase 2 literature review involved similar syntax but were modified to collect only those articles published after the Phase 1 literature review concluded. As with the Phase 1 literature review, the search strings included variations of the term “SARS-CoV-2” and the research questions (e.g., spread/transmission routes, attenuation, and decontamination/prevention) using Boolean operators. The Boolean operator “AND” was used to separate SARS-CoV-2 and research question terms, while different variations of the virus name and verbs related to the research questions were grouped by category using parentheses and the Boolean operator “OR” [e.g., ("SARS-CoV-2" OR "2019-nCoV" OR "COVID-19") AND (decontam* OR attenuat*)]. Two different search strings were executed: one focused on decontamination and surface attenuation of the virus; another focused on avenues of indoor spread of the virus.

The virus name “SARS-CoV-2” and its variants were included in both searches to focus results on the virus of interest. The search string developed for indoor spread of the virus included an additional parenthetical to focus results on spread relevant to LAMs or other settings (e.g., “indoor” OR “aerosol”).

The Phase 2 search strings included a time criterion to capture articles published from June 1, 2020, through the date of search string execution (August 14, 2020). Furthermore, articles published in May after the cut-off dates for the Phase 1 literature review (May 11, 2020, for search string 1 and May 18, 2020, for search string 2) were gathered in early June by executing the search strings for publications in the month of May and removing all references that had appeared in the Phase 1 search results.

Before officially running the search strings (Appendix A), a Battelle librarian performed ad hoc testing of the search terms to confirm their continued efficacy and optimization.

Searches were conducted on August 14, 2020, using Scopus, SciTech, Web of Science, and MEDLINE databases. These databases were selected due to their ability to provide comprehensive search capacity, being inclusive of many smaller databases. Results from the four databases overlapped frequently, so duplicates were removed from the search results to produce a single results list. Ultimately, the searches produced 344 unique results from late May and 1,667 unique results for June 1 to August 14, totaling 2,001 articles that were then reviewed for relevancy.

2.1.2 Abstraction Process

Prior to beginning abstraction, Battelle staff were trained on the project, the research topics of interest, relevancy considerations, and the abstraction process. Battelle’s librarian conducted an initial review of the title and abstract of articles to identify non-relevant and potentially relevant articles, which then received a QC review by other members of the project team. The articles identified as potentially relevant were grouped in batches of approximately 80 articles and distributed to research team members, who reviewed the titles and abstracts closely to determine if the articles indicated relevancy to the literature review objectives and, for relevant articles, identified the research question for which the article was most relevant. For the subset of articles published in late May, a similar process was undertaken, except the initial relevancy review by the Battelle librarian was not needed.

Articles identified as relevant after these initial steps (n=502) were consolidated into a list for abstraction and summarizing. In this step, staff searched for the articles online and reviewed the full text of the articles to confirm relevancy. For articles that were confirmed to be relevant, the research team reviewed the research question category, indicated if the articles were relevant to either of the other research questions, indicated potential subcategories for the research questions addressed by the articles (e.g., a decontamination/prevention article focused on hand sanitizer), summarized relevant results, and identified limitations and qualifications for the articles.

Upon closer inspection of the full-text article during the abstraction and summarizing step, a total of 103 articles were identified as non-relevant. Additionally, before the abstraction and summarizing process, a subset of articles (n=168) were set aside as technically relevant but unlikely to be useful because they were articles that provided guidelines for mitigating risk of SARS-CoV-2 infection in specific clinical settings (e.g., guidelines for reducing COVID-19 risk in optometry practices). Although these articles presented prevention and decontamination strategies, they were often too site-specific to be relevant, rarely presented new scientific search, and/or provided guidance based on literature reviews of articles that were not always restricted to SARS-CoV-2. Because these articles were determined to be unlikely to contribute new information related to the research questions, the research team did not read, abstract, or summarize these articles. Another 16 articles were re-categorized to this list upon inspection of the full text, excluding them from further review. Lastly, 23 articles were later identified as duplicates of articles included in the Phase 1 literature review, and one article was found to be a duplicate of another article in the list of 502 relevant articles; accordingly, these 24 articles were excluded as well. In total, 311 articles were excluded from consideration.

An important resource considered in the literature review was the U.S. Department of Homeland Security's Master Question List for COVID-19 (caused by SARS-CoV-2), a literature review updated on a weekly basis to provide up-to-date findings and guidance. (Note: the latest version available at approximately the same time the search strings were executed for the Phase 2 literature review was the August 18, 2020, edition.) Battelle cross-checked the systematic search results against the "Master Question List" and supplemented the relevant results list with any new articles found there.

The relevant articles and abstracted data were organized by research topic for the report writing team. In total, 203 relevant articles were identified through the search processes, including articles identified via the "Master Question List" mentioned above (see Table 1 for a summary of the number of articles under consideration at different phases of the systematic search process). Battelle synthesized the findings of 90 of these relevant documents in the Phase 2 literature review report. In addition, an EndNote database was created to house reference information for all relevant articles captured during this review, which was exported to Excel spreadsheet format. Additionally, a full reference list, including clickable links to the publisher websites, is included at the conclusion of this report.

Table 1. Summary of Article Count

Process Step	Articles Under Consideration After Process Step
Database Searches	2,001
Initial Relevancy Review by Battelle Library	1,211
Relevancy Reviews	502
Abstraction	191*
Additional Reference Reviews (e.g., DHS Master Question List)	203*
Final	**203***
*Count excludes 184 articles identified as technically relevant but too focused on specific clinical settings to contribute meaningfully to the literature review results.	

2.1.3 Inclusion/Exclusion Criteria

For inclusion in the literature review, articles needed to be written in or translated to English, include information specific to SARS-CoV-2, and address at least one of the three research questions. Published scholarly peer-reviewed research was prioritized, but other literature meeting the previously stated criteria was also included, such as “pre-prints,” letters to the editor, reports, and “articles in press.” Additionally, articles had to be published after the search string execution dates for the Phase 1 literature review (i.e., May 11, 2020, for the search string focused on decontamination and surface attenuation of the virus, and May 18, 2020, for the second search focused on avenues of indoor spread of the virus) and before search string execution for the Phase 2 literature review on August 14, 2020.

Articles published before or after the search period, in languages other than English, not about SARS-CoV-2, or that did not address at least one of the three research questions were excluded from the literature review. Literature reviews and reports were scrutinized closely to ascertain what findings were developed from SARS-CoV-2 research and what arose from research of other coronaviruses such as SARS-CoV-1 and Middle East Respiratory Syndrome (MERS). As mentioned above, articles that focused on providing guidance to clinical specialties for mitigating SARS-CoV-2 risk were categorized as relevant but were not considered for the Phase 2 literature review report.

2.1.4 Quality Control Process

Two sets of QC processes were implemented during the literature review project. One was a standard set of processes designed to minimize the risk of relevant articles being excluded and non-relevant articles being included. The other was implemented on an emergent basis when an insufficient number of articles related to the research question about surface attenuation were included in the final references list.

QC processes designed to verify if articles were appropriately identified as non-relevant and relevant during relevancy reviews involved Battelle staff performing QC at three levels:

- The first level involved reviewing the initial relevancy review conducted by Battelle's librarian to ensure articles were not excluded unnecessarily. Articles identified as non-relevant by the librarian were grouped in batches of approximately 130 articles, and QC staff randomly selected 20% of the articles from each batch to review the titles and abstracts and verify the relevancy determinations. Instances of disagreement were reviewed and reconciled by the project lead.
- The second level occurred after the second relevancy review step conducted by the full research team. QC staff reviewed batches of approximately 80 articles and randomly selected 20% of the articles to review the titles and abstracts and verify the relevancy determinations. If an incorrect determination was identified, QC staff conducted a full review of the articles marked non-relevant in the abstractor's batch and corrected determinations as needed (note: this occurred in the case of one batch), ensuring that relevant articles were not excluded unnecessarily.
- The third level occurred during the abstraction and summarizing stage, during which staff reviewed the full text of articles to confirm relevancy. Any articles that proved non-relevant during this review were excluded and not abstracted/summarized.

An additional need for QC reviews arose during the writing process for the portion of the report focused on surface attenuation of the virus. Upon reviewing the remaining articles categorized to this section after abstraction and summarizing, it became clear that very few articles addressed the research question in the form of presenting novel empirical evidence about the attenuation patterns of SARS-CoV-2 on diverse surfaces. To ensure that no relevant articles were excluded mistakenly, the research team and librarian conducted several QC processes, identifying in the process two additional articles to be considered for the report:

- Articles categorized to the other research questions (i.e., how the virus spreads and how the virus can be prevented/decontaminated) (n=175) were reviewed to verify if any showed relevance to the surface attenuation section as well.
- Articles categorized as non-relevant during the research team's relevancy review process (n=399 articles) were double-checked for relevancy to this topic.
- Narrowed search strings were executed in an ad hoc manner to target articles with an emphasis on key words, such as surfaces, survivability, attenuation, and persistence. Top results were reviewed for relevant articles.

Alert emails from the prior three months were examined by the Battelle librarian, who had requested weekly updates from the databases on articles that met the search string criteria.

3. Findings

The Phase 2 literature review search results yielded more than 200 relevant articles. Findings from the analysis of these articles were synthesized and presented in the following sections according to research topic:

- Virus spread through general building operations
- Virus survival and decay on material surfaces over time
- Effective prevention and decontamination measures that are readily available in the near term.

3.1 Spread of SARS-CoV-2 through General Building Operations

According to the Department of Homeland Security (DHS) Science and Technology Directorate (2020), SARS-CoV-2 is currently understood to spread most commonly between people in close contact to one another and through respiratory droplets. Transmission via aerosol and fomites was also reported as likely. SARS-CoV-2 can be transmitted by individuals who are in the incubation stage, symptomatic, or by individuals who are contagious but asymptomatic (DHS Science and Technology Directorate, 2020). Activities like breathing and talking produce aerosol particles of varied sizes that may contain the virus. Larger-sized droplets generally fall to the ground due to gravity; however, smaller-sized particles may remain suspended in the air long enough to be spread by wind or air conditioning and diffused in contact with other people, surfaces, or environments (Somsen, 2020).

Recent research on the spread of SARS-CoV-2 through person-to-person droplets (e.g., direct coughs), aerosol transmission, fomites (surfaces with active virus), and impact of environmental factors (e.g., humidity) are described below.

***Note**: No evidence specific to LAM settings and viral spread was found in the systematic search results.*

3.1.1 Person-to-Person Droplets

3.1.1.1 Manner of Droplet Spread

Transmission of SARS-CoV-2 due to close contact from person to person (e.g., coughing, sneezing, breathing, and/or talking) has been documented in a variety of settings, including hospitals.

In a peer-reviewed article, Rehman et al. (2020) reviewed existing literature and provided a synopsis of various aspects of SARS-CoV-2, including transmission. Based on their review of previous studies, the authors concluded that primary transmission of the virus is through inhaled respiratory droplets containing the virus or from touching surfaces contaminated by infected droplets. Similarly, Patel et al. (2020) summarized existing literature on various pathways of SARS-CoV-2 transmission in their peer-reviewed article. The authors concluded that the primary route of transmission is through direct contact or via droplets from an infected person. The authors reported that more research is needed to understand other routes of transmission.

Somsen et al. (2020) presented in a peer-reviewed comment the results from their analysis of droplets produced by coughing and speaking. The authors discussed size distribution, travel distance and velocity, and time airborne relative to ventilation. The authors used a laser diffraction spray droplet measurement system, which found that small droplets (1-10 µm in diameter) were more prevalent in coughs than large droplets (100-1,000 µm in diameter), and only small droplets were found during speech. The authors used a SprayScan laser sheet to track droplets and found that the largest droplets (500 µm in diameter) fall rapidly to the ground within one second from the start of the cough. The authors also found that in a well-ventilated room, the number of droplets dispersed into the air (a simulated effect of coughing) was halved after 30 seconds, while with no ventilation the quantity of airborne droplets was halved after about five minutes.

In their preprint article, Kumar et al. (2020) conducted a systematic experiment to investigate the evaporation characteristics of water droplets ranging from 5 to 100 µm generated using a nebulizer. Evaporation characteristics may have significance on the survivability of SARS-CoV-2 in droplets expelled during breathing and talking. The authors concluded that “these droplets do not disappear with evaporation, but instead shrink to a size of a few micrometers (referred to as residues), persist for more than 24 hours, and are highly durable against changes of environmental conditions” (p. 1). However, the authors cautioned that their results were dependent on specific environmental conditions.

Diverging evidence has also been presented, with some researchers suggesting that manner of viral spread remains unknown. In their peer-reviewed article, Jayaweeraa et al. (2020) conducted a literature review that examined existing research on the transmission of SARS-CoV-2-laden droplets produced by coughs from individuals with COVID-19 within confined spaces, including healthcare facilities, cars, and airplanes. Based on their review, the authors concluded that “droplet and aerosol laden transmission of COVID-19 are uncertain” and that “administrative, clinical, and physical best management practices are paramount in implementing, especially in confined spaces” to prevent the potential for transmission (p. 15).

In addition to respiratory droplets and fomites, samples collected from the Diamond Princess cruise ship indicated that the virus may be spread via other biological substances. In their peer-reviewed study, Yamagishi et al. (2020) conducted environmental sampling during the response to an outbreak on the Diamond Princess cruise ship from February 22-23, 2020. Sampling occurred with crew and some passengers on board and prior to widespread disinfection. The authors obtained 49 surface samples from 587 items in cabins with confirmed cases of COVID-19 and cabins with no confirmed cases using collection swabs moistened with viral transport medium, which were tested by the real-time reverse transcription polymerase chain reaction (RT-PCR) method, a method detecting the presence of virus particles. SARS-CoV-2 RNA was detected on multiple surfaces of cabins with cases. The authors concluded that the virus’ presence on bed pillows in particular “may have come from coughing, nasal drainage, or tears during sleep” and that positive samples from the floor around the toilet “may have come from stool or from respiratory secretions” (p.1100). See the “Case Study: Diamond Princess Cruise Ship” call-out box below for more details.

One of the more salient themes that has emerged in the literature is that the risk of contracting SARS-CoV-2 is higher indoors. In their preprint article, Chaudhuri et al. (2020) echoed this finding in their investigation of various transmission routes of SARS-CoV-2 using an *ab initio* SEIR model (additional information on the SEIR model can be found in Abou-Ismail, 2020). The authors concluded that the highest COVID-19 infection probability is from inhaled cough droplets (10-50 µm in diameter) in air-conditioned indoor spaces. Similarly, in their brief report published in the British Medical Journal, Dyer (2020) presented several published sources that concluded that respiratory droplets expelled during breathing, speaking, and singing, as well as coughing and sneezing, can remain airborne for “minutes or hours”; and, while the droplets may be capable of traveling greater than two meters, “most transmission happens in closed, indoor spaces where there is poor ventilation and crowding, and people are close together and talking loudly or singing without masks” (p. 1).

3.1.1.2 Physical Distancing

Over the course of the pandemic, there has been significant debate on the amount of distance individuals should maintain between themselves and others to mitigate the spread of SARS-CoV-2. In their letter to the editor, Chagla et al. (2020) asserted that “the epidemiologic data and clinical experience managing the pandemic continue to support that the main mode of transmission of SARS-CoV-2 is short range through droplets and close contact” (p. 1) based on review of existing literature. They further asserted that long-range airborne transmission of more than two meters from the source “seems rare at best” (p. 1).

There has been an increasing amount of research on physical distances to mitigate spread. In a peer-reviewed article, Borak (2020) discussed past examples and previous studies that suggest that SARS-CoV-2 may spread via fine aerosols; however, the method for literature review was not noted. Based on their review, the authors suggested that the two-meter recommendation for physical distancing may be inadequate to protect against actions that result in larger aerosolized emissions, such as shouting, singing, coughing, or sneezing. Similarly, in a peer-reviewed article by Simonds (2020), the author briefly discussed the potential for transmission of SARS-CoV-2 via cough. Based primarily on existing transmission models, the author concluded that distancing of more than two meters from an infected individual may be “insufficient in those with a paroxysmal, propulsive cough” (p. 206).

In another peer-reviewed study, Dbouk et al. (2020) used a modeled simulation based on fully coupled Eulerian–Lagrangian techniques to investigate the transmission dynamics of saliva droplets in air from a human cough. The authors also computationally investigated the impact of wind on the transmission of cough droplets. Based on the computational models, the authors found that in zero wind conditions, droplets expelled from a cough did not travel two meters. However, at wind speeds between 4-15 km/hour, the authors found that the droplets can travel up to six meters, although there was a decrease in concentration and droplet size at greater distances from the source. The authors concluded that “when a person coughs, the wind speed in an open space environment significantly influences the distance that airborne disease-carrier droplets travel” and that “airborne droplet carriers can travel significantly further than the 2 m recommended distance due to the wind speed” (p. 053310-9).

Conversely, lack of social distance is associated with SARS-CoV-2 spread. Wang, Tian, Zhang, et al. (2020) characterized transmission of SARS-CoV-2 within family units with at least one confirmed COVID-19 case residing in the same household. In this peer-reviewed study, the authors conducted a retrospective cohort study of 124 households containing 335 individuals to assess secondary person-to-person transmission of SARS-CoV-2. Preventative behaviors, existing health states, and demographics were self-reported and collected via survey. The secondary attack rate identified by the authors was 23%, meaning that 77 out of 335 individuals contracted COVID-19 from an infected family member. The authors concluded that “household transmission in the pre-symptomatic or early symptomatic period of COVID-19 is a driver of epidemic growth” (p. 8).

3.1.2 Aerosolization

In addition to spreading the virus via person-to-person contact with droplets, virus spread has thought to be possible from aerosolization of the virus, which may remain suspended in the air for extended periods of time. Research also sometimes refers to aerosol transmission as airborne transmission. The WHO defined airborne transmission as, “the spread of an infectious agent caused by the dissemination of droplet nuclei (aerosols) that remain infectious when suspended in air over long distances and time” (WHO, 2020, Airborne Transmission section, para. 5).

Researchers appear to disagree about whether SARS-CoV-2 is spread via aerosol particles, although some evidence suggests that aerosol transmission is possible. Zhang et al. (2020) analyzed trends in global COVID-19 infections between January 23 to May 9, 2020. The goal of their peer-reviewed research was to infer potential routes of SARS-CoV-2 transmission. Based on their evaluation of infection data in concert with mandatory mitigation measures, the authors determined that airborne transmission of SARS-CoV-2 was the leading contributor to the linear increase in COVID-19 prior to mandated mask order in Italy and New York City. The authors concluded that “airborne transmission, particularly via nascent aerosols from human atomization, is highly virulent and represents the dominant route for the transmission” of SARS-CoV-2 (p. 7). However, conclusions of systematic literature reviews, primarily on aerosol transmission, have taken a less strong stance, reporting, “air should be considered a major route of transmission,” yet “COVID-19 airborne transmission has not been yet demonstrated” (Carraturo et al. 2020, p. 2-5). Additional systematic reviews on aerosol transmission of SARS-CoV-2 have agreed with this sentiment noting airborne transmission of SARS-CoV-2 is possible but “still far from proven”, and that challenges associated with detecting infectious SARS-CoV-2 have made it difficult to verify viability of the virus in air samples (Jiang et al. 2020, p. 866; Carducci et al. 2020).

3.1.2.1 Air Sampling in Indoor and Outdoor Settings

To better understand the extent of SARS-CoV-2’s presence in the air, researchers have conducted air sampling studies in spaces where people infected with the virus have been. In a peer-reviewed article, Santarpia et al. (2020) presented results from air sampling conducted in two hospitals and nine isolation rooms housing patients with confirmed COVID-19. In-room high-volume air samples were collected from three patient rooms in various areas, including a window ledge, near the patient, and by a door located more than two meters from the bed. The air was also sampled in hallways outside of patient rooms. Airborne concentration of SARS-CoV-2 RNA was calculated, as the sampling time and flow rate were known. Results were positive for the presence of SARS-CoV-2 RNA in 63.2% of the in-room air samples, with the highest concentration noted in the sample closest to the patient (4.07 copies of RNA/L of air). Of the hallway air samples, 58.3% were positive for SARS-CoV-2; the mean concentration of hallway air samples was calculated to be 2.51 copies of RNA/L of air. In addition, two study personnel responsible for conducting the air sampling each wore a low-volume personal air sampling device, both of which revealed positive results indicating the presence of viral SARS-CoV-2 RNA. All air sampling results were determined by RT-PCR. Comparing air sampling results with surface sampling results in the same general areas, the authors concluded that airflow may strongly influence the dispersion of SARS-CoV-2. Although the size of particles and droplets was not evaluated in this study, “the data is suggestive that viral aerosol particles are produced by individuals that have the COVID-19 disease, even in the absence of cough” (p. 5).

Case Study: Diamond Princess Cruise Ship

Aerosol transmission of SARS-CoV-2 continues to be debated among scientists. An example of this debate is borne out in analysis of the February 2020 COVID-19 outbreak on the Diamond Princess cruise ship. Azimi et al. (2020) used data from the ship to predict transmission routes using an adapted version of the Reed-Frost epidemic model. The authors concluded that the primary transmission route was long-range via aerosol. The ventilation rate in the cruise ship was 9-12 changes an hour with no recirculated air. They further noted that when looking at short- and long-range distances, aerosol contributed to over 70% of transmission. The average contribution of droplets versus aerosols was 41% and 59%, respectively.

In their peer-reviewed study, Yamagishi et al. (2020) conducted air and surface sampling during the outbreak response on the Diamond Princess cruise ship from February 22-23, 2020. Sampling occurred with crew and some passengers on board and prior to widespread disinfection. The authors obtained air samples from the bed and toilet seat areas in seven random cabins (four cabins with confirmed cases of COVID-19 and three cabins with no confirmed cases) using two samplers equipped with a gelatin filter. The air in these areas were sampled at 50 L/minute for 20 minutes and was tested using RT-PCR. No SARS-CoV-2 RNA was detected in any of the air samples. However, the authors attributed the detection of viral RNA in a surface sample from an air vent in the ceiling of a corridor to a projectile droplet, and thus concluded that this result “suggests that the virus could flow beyond 1 m in a condition with limited airflow” (p. 1101). The authors noted several study limitations, including the relatively short sampling time and that sampling was conducted after infected individuals left the cabins. The authors also noted that air recirculation was stopped on the ship, which may have prevented airborne transmission.

In a preprint study, Hu et al. (2020) assessed airborne transmission of SARS-CoV-2 by obtaining 123 indoor and outdoor air samples from three hospitals, two colleges, hotels, residential communities, and greenspace located in Wuhan, China, between February 16, 2020, and March 14, 2020. The air samples were collected using a centrifugal aerosol-to-hydrosol sampler (30 minutes at 400 L/min) and were tested using RT-PCR. Intensive care units and computerized tomography rooms in hospitals frequented by patients had the highest virus SARS-CoV-2 RNA detection rates (21.1% and 16.7%, respectively), which the authors noted were consistent with results from another study. Air samples from other areas were negative, which the authors attributed to good ventilation. Viral RNA was detected in outdoor air samples collected ten meters from an inpatient and outpatient building. Based on positive samples, the authors estimated that “close-range infection risk by airborne droplet transmission may reach 30–50%” and that the “positive percentage of virus in the indoor environments with poor ventilation was ~20%” (p. 6). Viral nucleic acid tests determined that none of the detected viral RNA was viable (infectious) in any of the positive air samples, which led the authors to conclude that “SARS-CoV-2 has a relatively short survival time in the aerosol” (p. 4). However, the authors also noted that “airborne transmission and infection risk for the virus mainly occurs in closed environments where infected patients are present” (p. 6). The authors provided limited data on sampling locations and results.

In another hospital-based, peer-reviewed study, Razzini et al. (2020) conducted air sampling in the COVID-19 ward of an Italian hospital to assess the airborne presence of SARS-CoV-2. Five air samples were collected using a portable air sampler with gelatin membrane filters. Samples were collected from a corridor that housed COVID-19 patients, a clean area designated for non-contaminated items, and a semi-contaminated area located between patient rooms and the clean area. Sample results were obtained using real time RT-PCR. SARS-CoV-2 RNA was detected in all of the air samples taken from the patient corridor but was not detected in the semi-contaminated or clean areas, which suggests isolation precautions were adequate. The authors compared their results with previous studies and concluded that although there is conflicting evidence, airborne transmission of SARS-CoV-2 could be possible. The authors also noted that “the WHO recommends a ventilation rate of at least 288 m^3 per hour per person for control of opportunistic airborne transmission”; however, this guidance primarily applies to health care settings where aerosol generating procedures may occur (p. 5).

Some researchers believe that SARS-CoV-2 is likely not spread via aerosol. In their peer-reviewed study, Cheng et al. (2020) performed air sampling inside the hospital isolation rooms of patients with confirmed SARS-CoV-2 infection using sampling devices containing sterile gelatin filters. The device that gathered the air samples was placed 10 cm away from the patient’s chin. Samples were taken with or without patients’ wearing a surgical mask. The authors analyzed the potential connection between patient viral loads and air samples, as well as surface samples (separately). Minimal SARS-CoV-2 was found in air samples from patients’ isolation rooms, and the authors speculated that airborne transmission may not be the main transport mode for SARS-CoV-2; however, the authors noted other studies that had conflicting results.

Bays et al. (2020) also reported uncertainty of airborne transmission. In their peer-reviewed article, the researchers used contact investigations to study the transmission of SARS-CoV-2 within a community hospital and university medical center. Two asymptomatic patients with no known COVID-19 infection underwent multiple aerosol-generating procedures, to which 421 health care workers were exposed. The contact investigations revealed that eight of the workers contracted COVID-19 and had been in close contact with the patients without adequate PPE. The authors concluded that in a health care setting “a majority of SARS-CoV-2 transmission is likely to take place during close contact with infected patients through respiratory droplets, rather than by long-distance airborne transmission” (p. 1).

Rahmani et al. (2020) discussed potential limitations of air sampling studies in their peer-reviewed literature review. The authors evaluated air sampling studies conducted in the rooms of patients with confirmed COVID-19 infections, as well as other hospital areas. The authors summarized different studies' methods including sampling procedure, sampling time and flow rate, sampling culture medium, preparation, storage and transferring conditions, and identification methods. The review concluded that airborne transmission of SARS-CoV-2 is possible; however, because most air sampling was conducted within patient rooms, the authors noted that it was difficult to discern whether positive results were due to airborne transmission or respiratory droplets. Other factors were noted to have potentially interfered with air sampling results, such as patient distance from the sampler, patient coughing or sneezing during sampling, air circulation, patient activities, and other environmental conditions. Zhang (2020) echoes these findings in his brief peer-reviewed article. The author presented findings from previous studies on SARS-CoV-2 transmission pathways and concluded that evidence of airborne or aerosol transmission is inconsistent and that additional studies are needed.

3.1.2.2 Aerosol Travel and Infectivity

Some research has modeled the capacity of SARS-CoV-2 to travel via aerosol pathways. In a preprint article, Gorbunov (2020) conducted two-dimensional (2D) and three-dimensional (3D) modeling of aerosol clouds using Comsol Multiphysics v5.5 software and a Gaussian model to assess potential transmission routes of SARS-CoV-2 via exhalation in open unobstructed spaces, street canyons, and indoor settings. Based on modeling, the author concluded that aerosol particles loaded with SARS-CoV-2 could “travel over 30 m and sometimes 100 m depending on the atmospheric conditions” (p. 15). Modeling also suggested that aerosol particles could build up inside public places. Other findings have reported lesser distances, with Klompas et al. (2020) suggesting SARS-CoV-2 aerosols can travel 27 feet .In an invited commentary, Morawska and Milton (2020) concluded that there is “significant potential for inhalation exposure to viruses in microscopic respiratory droplets (microdroplets) at short to medium distances (up to several meters, or room scale)” based on evidence from previous studies (p. 1). However, the authors also noted that while evidence for airborne transmission of SARS-CoV-2 is incomplete, so is that of large droplet and fomite transmission. The authors assert that although airborne transmission of SARS-CoV-2 is not widely accepted, a precautionary approach should be taken.

In another peer-reviewed study, Fears et al. (2020) studied the infectivity of SARS-CoV-2 via short-term aerosol studies that analyzed three strains of SARS-CoV-2, as well as SARS-CoV-1 and MERS. The authors concluded that, based on their results, SARS-CoV-2 “generally maintains infectivity at a respirable particle size over short distances” and “is resilient in aerosol form” (p. 2170). A limitation of this study is that the authors reported only one measurement at a 16-hour time point.

3.1.2.3 Aerosolization of SARS-CoV-2 in Human Waste

Despite conflicting evidence on the potential for aerosol transmission of SARS-CoV-2, it is important to know what activities may generate aerosols, especially those that may take place in a public setting such as restrooms.

In their letter to the editor, Meng et al. (2020) cited evidence that SARS-CoV-2 has been detected in the feces and urine of individuals with confirmed COVID-19, including asymptomatic carriers. The authors suggest that toilet flushing, which generates aerosols, could be a transmission pathway. Furthermore, the authors suggest that feces-laden aerosols may build up in bathroom areas. Mitigation measures, such as closing the toilet lid before flushing and cleaning the toilet with an appropriate disinfectant after use, were recommended.

In their letter to the editor, Yang et al. (2020) asserted that, based on previous studies and the characteristics of aerosols, SARS-CoV-2 may remain infectious and transmittable even after physical decay in an aerosol plume and thus could be deposited onto fomites through an airborne pathway.

3.1.3 Biological Substances and SARS-CoV-2 Transmission

The spread of SARS-CoV-2 through the media of biological substances has been identified in some cases, but the use of RT-PCR testing in these studies contributes to limited understanding of the risk for exposure to viable virus via biological substances of infected persons. Xing et al. (2020) assessed viral shedding of SARS-CoV-2 in feces of three children. Children were also tested for COVID-19 via daily throat swabs using RT-PCR tests. The authors found that the presence of SARS-CoV-2 RNA in fecal samples occurred well after the respiratory tests were undetectable (8-20 days after).

A preprint review by Jones et al. (2020) reported that fecal shedding of SARS-CoV-2 is the highest during the symptomatic period. It was also noted that viral/infectious SARS-CoV-2 has been found in feces, however, the genetic material of the virus in feces is lower than nasopharyngeal fluid samples. The authors conclude that fecal-oral transmission risk is very low except in cases of direct person-to-person contact. Handwashing and disinfection of sanitation facilities were suggested to prevent risk for fecal-oral transmission. Jones et al. (2020) also discussed the presence of SARS-CoV-2 in urine and vomit. Findings on urine revealed that SARS-CoV-2 RNA is found in urine but less frequently compared to fecal matter. Research reported in this review indicated the viral virus has been reported in urine, but like fecal matter, to a lesser degree compared to nasopharyngeal fluids. Liu et al. (2020) also studied the presence of SARS-CoV-2 in urine in three participants. The authors found the infectious virus in urine for 3-4 days.

Research on vomit was limited, but it is thought that vomit can contain the virus from both nasopharyngeal fluids and the gastrointestinal tract (Jones et al., 2020). However, vomit was suggested to have lower infectivity due to low pH levels.

3.1.4 Fomites

Fomites, or objects with which people come into contact and that are contaminated with the virus (e.g., doorknobs), are another likely contributor to the spread of SARS-CoV-2, as infected people spread the virus to fomites through respiratory secretions (World Health Organization [WHO], 2020). Although fomite transmission of SARS-CoV-2 is likely, the WHO explains research determining if SARS-CoV-2 is transmitted via droplets versus fomites is challenging, noting, “people who come into contact with potentially infectious surfaces often also have close contact with the infectious person.” (WHO, 2020, Fomite section, para. 2).

The Department of Homeland Security Science and Technology Directorate (August 18, 2020) published their literature review titled Master Question List for COVID-19 (caused by SARS-CoV-2), which concluded that, "SARS-CoV-2 can persist on surfaces for at least 3 days and on the surface of a surgical mask for up to 7 days depending on conditions" (p.13). It was also noted that further study is needed "to quantify the duration of infectivity of SARS-CoV-2 on surfaces, not simply the presence of RNA." (p. 13). In other words, understanding how long the virus remains infective on surfaces will help clarify the extent to which people can contract SARS-CoV-2 through fomites.

Further information about persistence of SARS-CoV-2 on surfaces can be found in Section 3.2.

In a report by Santarpia et al. (2020), surfaces were sampled in rooms of 13 people diagnosed with COVID-19. The authors sampled residential isolation and hospital rooms between days 5 and 10 of patient occupancy. One additional sample was taken on the day 18. Using RT-PCR targeting, approximately 72% of samples tested positive for SARS-CoV-2 RNA. Cell phones, toilets, bedside tables, bed rails, window ledges, and ventilation grates were positive for SARS-CoV-2 RNA over 70% of the time. All floor samples (n = 5) tested positive. Of all patients, around 58% had a fever over 99 ºF and approximately 58% reported other symptoms such as a cough. The authors found that presence of fever in patients and the quantity of infected surfaces were not strongly associated. The other symptoms measured were not included in the analysis.

A peer-reviewed study by Cheng et al. (2020) researched surface sampling inside hospital isolation rooms of 21 patients with COVID-19. High-touch surfaces were swabbed prior to daily disinfection with sodium hypochlorite. The authors analyzed the potential connection between patient viral loads and environmental samples. Viral loads were measured using RT-PCR tests conducted on the same day as surface sampling. Only 5% of the surface samples were RT-PCR positive, and the most contaminated object were patients' mobile phones (approximately 8%). The authors concluded that higher viral load correlates with greater likelihood of environmental contamination.

In the peer-reviewed investigation of the COVID-19 Outbreak on the Diamond Princess cruise ship (Yamagishi et al., 2020), researchers collected 601 environmental samples on the cruise ship over a two-day span prior to disinfection. Samples were tested for the presence of SARS-CoV-2 RNA using RT-PCR. Results showed SARS-CoV-2 RNA on surfaces of cabins previously occupied by people with COVID-19 up to 17 days after the cabins had been vacated. Specifically, in cabins of people with COVID-19, the floor near the toilet (39%) and bed pillows (34%) were most frequently positive for SARS-CoV-2 RNA followed by phones (24%), tables (24%), remotes (21%), chair arm (12%), toilet flush and seat (6%), light switch (3%), and doorknobs (3%). In cabins of those without COVID-19, all samples were negative. Further, nearly all shared areas (e.g., restaurants, medical clinic) tested negative for SARS-CoV-2 RNA except for one hood of an air outlet that was located in a corridor. The study concluded transmission via fomites was possible and that the lower occurrence of SARS-CoV-2 on high-touch surfaces (e.g., doorknobs) may be attributed to improved hygiene and disinfection.

These three studies sampled the same types of fomites (i.e., cell phones, toilets, and tables) in areas occupied by individuals with COVID-19 (Santarpia et al., 2020; Cheng et al., 2020; Yamagishi et al., 2020). Rates of positive samples varied significantly, with percentages ranging from 4% to 81%. These mixed results may be attributed to different SARS-CoV-2 sampling procedures or various cleaning procedures implemented by the facility. Figure 2 depicts these results for comparison.

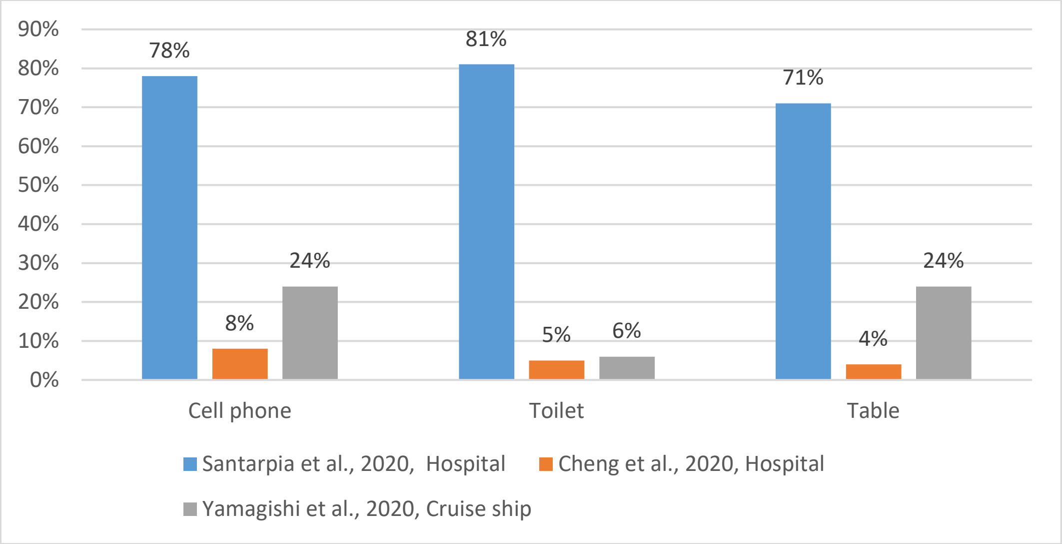


Figure 2. **Percent of fomites tested positive for SARS-CoV-2.**

Several other studies measured the presence of SARS-CoV-2 on a variety of surfaces in a hospital setting. A peer-reviewed study by Razzini et al. (2020) examined SARS-CoV-2 RNA in an isolation ward of a hospital in Italy. The researchers swabbed 37 different surfaces prior to the daily cleaning process. The surfaces were in areas categorized as contaminated, semi-contaminated, or clean. For example, a semi-contaminated area was described as either an area for medical staff to pass through or an undressing room. Overall, using RT-PCR, SARS-CoV-2 RNA was found on 35% of contaminated surfaces and 50% of semi-contaminated areas. SARS-CoV-2 RNA was not found in the areas identified as clean (i.e., dressing room). The fomites that tested positive at least once for SARS-CoV-2 RNA included door handles, bedrails, hand sanitizer dispensers, medical equipment, medical equipment shelves, and medical equipment touch screens. SARS-CoV-2 RNA was not found on staff lockers, walls, waste containers, water taps, windows, glove boxes, benches, nor computer keyboards. The results highlighted the need for stricter disinfection protocols and stringent hand hygiene.

Wang, Qiao, Zhou, et al. (2020) examined 66 surface samples in a hospital isolation ward and intensive care unit (ICU). Using a fluorescence PCR instrument, approximately 3% of the samples tested positive for SARS-CoV-2. In the ICU, a nurse's hands and a nurse station were weakly positive, although the authors did not describe what 'weakly positive' meant. All samples in the general ward were negative. The authors attributed the low rates to the disinfecting and cleaning procedures used, including air disinfection using a mobile air disinfector four times a day, UV lamps, surface cleaning and disinfection four times a day, equipment disinfection, and hand hygiene.

A peer-reviewed study by Lee at al. (2020) examined the presence of SARS-CoV-2 on fomites in facilities with COVID-19 patients including hospitals, a rehabilitation center, and an apartment complex. The areas varied in disinfectant procedures prior to sampling. Samples were tested for SARS-CoV-2

RNA using real time RT-PCR. Out of the 80 samples taken, the hospital and apartment samples were negative for SARS-CoV-2 RNA. At the rehabilitation center, two of twelve samples were positive, each taken from door handles in the patient's room.

As seen in this section, multiple studies have reported the presence of SARS-CoV-2 on surfaces in the spaces inhabited by people infected with the virus, but at present, no research has proven human transmission directly via fomites (WHO, 2020), so the risk of contracting the virus through fomites remains unknown.

3.1.5 Environmental Factors Affecting Transmission

Several researchers have investigated climate-related factors that may affect the spread of SARS-CoV-2. In particular, humidity, temperature, and air quality have been reported to have some impact.

3.1.5.1 Temperature

There has been some research examining the impact of temperature on the spread of SARS-CoV-2; however, more work needs to be done to better understand its role on virus transmission in both indoor and outdoor environments.

Xie and Zhu (2020) examined whether temperature affected the transmission and survival of SARS-CoV-2. Using a generalized additive model (GAM), the authors assessed whether there was a non-linear relationship between mean temperature and COVID-19 cases, based on data collected on daily confirmed cases and meteorological factors in 122 cities in China between January 23, 2020, and February 29, 2020. Findings indicated that there was a significant positive relationship between mean temperature and COVID-19, such that 1°C (33.8°F) rise in the mean temperature was associated with a 4.86% increase in the daily confirmed COVID-19 cases. The authors concluded that there is no evidence to support the idea that warmer weather results in a decline in COVID-19 cases.

Del Rio and Camacho-Ortiz (2020) investigated how temperature might impact the course of COVID-19. The authors analyzed climate temperature from different regions against ongoing human-to-human transmission status. Results showed that regions which did not have ongoing human-to-human transmissions had higher temperatures compared to regions which did. Additionally, average rainfall was significantly higher in regions without ongoing human-to-human transmissions compared to those which saw active transmission of SARS-CoV-2. These findings suggest that both temperature and humidity have the potential to impact SARS-CoV-2 transmissions.

3.1.5.2 Humidity

Some authors have explored the links between humidity levels in an area and spread of SARS-CoV-2. In a peer-reviewed article, Fareed et al. (2020) assessed the impact of outdoor air quality and average humidity on daily new deaths due to COVID-19 in Wuhan between January 21, 2020, and March 31, 2020. The authors employed the wavelet methodology, which enabled them to analyze non-normal and non-stationary time series. Results showed that a rise in average humidity was associated with a decrease in COVID-19 related deaths. Additionally, poor air quality was linked to more COVID-19 deaths. The authors determined the relationship between bad environmental conditions and COVID-19 was indirect. These findings highlight the significance of varying environmental conditions on the spread and containment of COVID-19. The authors noted the need for subsequent studies using larger datasets with varying weather conditions since these results may be limited to cities with similar weather conditions and containment measures as Wuhan.

Similarly, in their peer-reviewed article, Harmooshi et al. (2020) reviewed the extant literature on the impact of humidity and temperature on the stability and transmission of SARS-CoV-2. Overall, the literature suggests that increases in temperature and humidity are associated with reduced transmission of SARS-CoV-2. The authors concluded that despite these findings, it is important to consider that the magnitude of change in the transmission of the virus in cooler, less humid conditions is moderate and will not stop the transmission of SARS-CoV-2.

Furthermore, humidity's impact on virus attenuation may be impacted by the medium in which the virus is suspended as well. In a letter to the editor, Smither et al. (2020) described their study in which they assessed the ability of SARS-CoV-2 in aerosols and within artificial saliva to survive in the dark at two different humidity values. Findings of this study showed that in the aerosol sample, SARS-CoV-2 was more stable at medium relative humidity compared to higher relative humidity. The converse is true of SARS-CoV-2 in artificial saliva; the virus was more stable at a higher relative humidity.

3.1.5.3 Other Environmental Factors

Various other factors may play a role in the proliferation of virus in an area or region. In a peer-reviewed article, Schuit et al. (2020) examined the stability of aerosolized SARS-CoV-2 under various controlled or simulated experimental conditions using rotating aerosol chambers that contained the virus. They exposed viral suspensions to varying regulated relative humidity (20%, 45%, and 70%) and simulated sunlight intensities (darkness, mid-intensity, and high intensity) and assessed the decay rate of the aerosolized virus. Findings showed all simulated sunlight levels inactivated SARS-CoV-2. Sunlight conditions representative of late winter/early fall resulted in a 90% decay of the virus at 19 minutes while conditions representative of summer resulted in a 90% decay at 8 minutes. On the other hand, relative humidity alone made minimal impact in decay rate of SARS-CoV-2 (90% decay at 286 minutes). Based on these results, the authors concluded that the aerosol transmission of SARS-CoV-2 may be dependent on sunlight in particular.

In a review article, Domingo et al. (2020) reviewed the association between pollution (including PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, and O_3 levels) and COVID-19/SARS-CoV-2. Findings of several studies suggested that, similar to other respiratory diseases, chronic exposure to air pollutants may result in "more severe and lethal forms of COVID-19" (p. 4) and impede recovery from the disease. The authors also examined the relationship because air pollution and the transmission of SARS-CoV-2. Studies across the world suggested that air pollution are positively associated with transmission such that higher levels of air pollution was related to increases in COVID-19 cases and deaths.

In a preprint article, Asher et al. (2020) used surrogate data tests to assess whether climate attributes including temperature, humidity, and UV radiation are related to the global spread of COVID-19 as assessed by number of confirmed cases, number of active cases, number of severe cases, and number of deaths. Results showed that COVID-19 is significantly more common when the temperature is approximately 10°C, the specific humidity is approximately, 5 g/kg, and the UV radiation is approximately 80 kJ/m^2. In other words, low temperature, low humidity, and low UV radiation are associated with an increased spread of COVID-19.

3.1.6 HVAC and Air Exchange

Some research has focused on HVAC systems as a potential transmission pathway for SARS-CoV-2, particularly with regards to air recirculation and ventilation in indoor environments.

Evans (2020) presented a novel mathematical model that assessed aerosol transmission of SARS-CoV-2 in his preprinted research. Based on their calculations, the author provided a brief discussion on the impact of HVAC systems on viral transmission and noted that HVAC systems may contain "significant viral load" (p. 6) and that decreased air exchange rates and recirculation in HVAC systems can contribute to the spread of SARS-CoV-2.

In their peer-reviewed article, Rezaei et al. (2020) primarily discussed an ideal setup for an HVAC system to reduce the presence of SARS-CoV-2 in exhaust air. However, the authors also noted that "recirculating air in ventilation systems of hospitals with infected patients can contribute to virus spreading" (p. 085308-1) throughout a facility and that "HVAC systems when not appropriately used may contribute to the spreading of SARS-CoV-2" (p. 085308-2). Furthermore, the authors established that HVAC systems, in general, do not account for outdoor air quality and may be responsible for the spread of virus-laden droplets outside of hospitals through HVAC exhaust.

In their peer-reviewed research, Aroul Raj V et al. (2020) analyzed state-wide data on the number of persons with COVID-19, mortality, and climatic conditions in India during March and April 2020 by comparing the data with select parameters, including population density, relative humidity and temperature, volume of indoor spaces, and air conditioning usage. The authors performed statistical analyses to obtain correlations. Major spread of SARS-CoV-2 was noted in areas with high usage of air conditioning systems and low spread was noted in areas where air conditioning is less used due to more moderate climates. The authors concluded that the rate of spread was directly proportional to energy usage (i.e., higher rates of air conditioning usage) and that recirculation of air may cause the virus to spread easily in an indoor environment. The authors noted that there may have been unknown parameters influencing transmission of SARS-CoV-2 that were not considered in their analysis.

Ventilation can also impact transmission of SARS-CoV-2. In a peer-reviewed short report, Aggarwal et al. (2020) discussed the potential correlation between high viral load and poor ventilation. The authors hypothesized that repeated exposure to centrally heated or air-conditioned environments would result in increased exposure to viral content. Consequently, this might lead to the persistence of the virus in droplets or in the environment which puts people at a higher risk of mortality from COVID-19. The authors concluded that open air ventilation would contribute to a lower viral load and ultimately, lower mortality from the disease.

In their preprint, Shao et al. (2020) quantitatively assessed the impact of ventilation on transmission risk of SARS-CoV-2 in different settings, including an elevator, small classroom, and supermarket, through in situ measurements and numerical simulations. The study included eight participants who provided the average flow field of exhaled gas, the concentration, size, and shape distributions of aerosols ranging from 0.5-50 µm. This data was then used during a simulation of aerosol transport in the different settings to assess the effect of ventilation. The authors also considered evaporation, drag, gravity, and residence lifetime of each aerosol produced by a simulated asymptomatic person. The authors concluded that inappropriate ventilation design “can significantly limit the efficiency of aerosol removal, create local hot spots with orders of magnitude higher risks, and enhance aerosol deposition causing surface contamination” (p. 1).

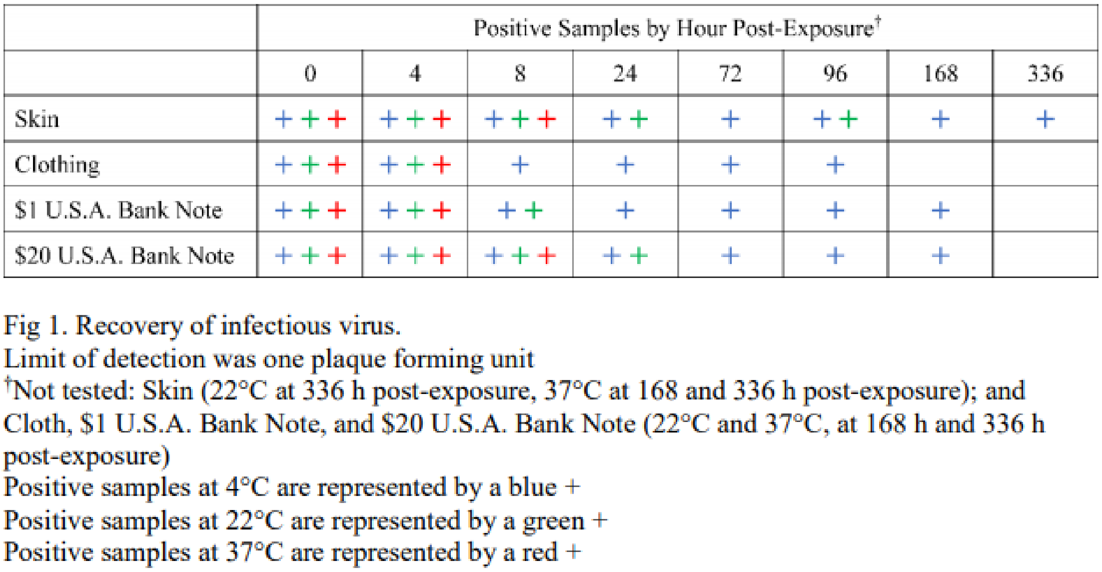
3.2 Survival of SARS-CoV-2 on Material Surfaces Through Environmental Attenuation

From March to May 2020, there was a growing body of evidence suggesting that it may be possible for SARS-CoV-2 to be spread via contact with surfaces and materials containing active virus (DHS Science and Technology Directorate, 2020). Since May 2020, the focus of the research has shifted to environmental factors and methods to deactivate the virus. Multiple recent review articles cited the same previous research that was discussed in the Phase 1 literature review, including that SARS-CoV-2 can persist on many surfaces for at least three days (Aboubakr et al., 2020; Akram, 2020; Rizou, 2020; Zhang, 2020).

However, in some cases, surface attenuation has been studied further. For example, one preprint article by Harbourt et al. (2020) tested skin (swine), currency, and clothing samples under laboratory conditions using a plaque assay to determine if these surfaces contribute to fomite transmission. Samples were incubated at 4°C (39.2°F), 22°C (71.6°F), and 37°C (98.6°F) and kept at 40-50% humidity. SARS-CoV-2 remained viable (infectious) on skin the entire 14 days of the experiment at 4°C; but stability decreased at higher temperatures, with the virus remaining stable for at least 96 hours at 22°C and 8 hours at 37°C. Banknotes and clothing were less hospitable to SARS-CoV-2 and had similar results: the virus was stable on both surfaces for 96 hours at 4°C, and stability steadily decreased as temperatures increased. See Figure 3 for all positive sample limits of detection.

Another preprint article by Liu et al. (2020) tested the stability of SARS-CoV-2 on nine objects: stainless steel, plastic, glass, ceramics, paper, cotton clothes, wood, latex gloves, and surgical masks. Fifty microliters of virus stock (infectious titer 10^6 fifty-percent tissue culture infectious dose ($TCID_{50}$) per milliliter) was deposited on each surface. Samples were left at room temperature (25-27°C; 77-80.6°F) at a relative humidity of 35%. SARS-CoV-2 was stable and remained viable for seven days on plastic, stainless steel, glass, ceramics, wood, latex gloves, and surgical masks. Cotton and paper were not found to have active virus after 4 and 5 days, respectively.

Lastly, in a short communication article, Zhou et al. (2020) found that 28 days after discharge, SARS-CoV-2 RNA could still be detected on the surfaces of employees’ pagers and in drawers in isolation wards. They detected the presence of SARS-CoV-2 RNA using real-time RT-PCR. However, the authors noted that their study detected gene fragments of the virus, not necessarily active virus.



	Positive Samples by Hour Post-Exposure†							
	0	4	8	24	72	96	168	336
Skin	+ + +	+ + +	+ + +	+ +	+	+ +	+	+
Clothing	+ + +	+ + +	+	+	+	+		
$1 U.S.A. Bank Note	+ + +	+ + +	+ +	+	+	+	+	
$20 U.S.A. Bank Note	+ + +	+ + +	+ + +	+ +	+	+	+	

Fig 1. Recovery of infectious virus.
Limit of detection was one plaque forming unit
†Not tested: Skin (22°C at 336 h post-exposure, 37°C at 168 and 336 h post-exposure); and Cloth, $1 U.S.A. Bank Note, and $20 U.S.A. Bank Note (22°C and 37°C, at 168 h and 336 h post-exposure)
Positive samples at 4°C are represented by a blue +
Positive samples at 22°C are represented by a green +
Positive samples at 37°C are represented by a red +

Figure 3. Recovery of infectious virus (Harbourt et al., 2020).

Virus Inactivation Using Copper, Nickel, Silicon Nitride, and Aluminum Nitride

Four recent articles looked at copper as a way to inactivate the virus. In an editorial, Scully (2020) reviewed copper's antimicrobial capabilities and concluded that although more research needs to be done, copper alloy surfaces may be capable of reducing virus transmission. Behzadinasab et al. (2020) tested a copper and polyurethane substance that adheres to materials like glass and stainless steel. SARS-CoV-2 was tested on this substance to assess for inactivation. After one hour, the coating on glass and stainless-steel reduced SARS-CoV-2 by 99.98% and 99.90%, respectively. Mantlo et al. (2020) tested Luminore CopperTouch™ copper and copper-nickel surfaces, which inactivated 99% of SARS-CoV-2 titers in two hours.

In a pre-printed article, Pezzotti et al. (2020) tested SARS-CoV-2 virions in 15 wt.% aqueous suspensions of silicon nitride, aluminum nitride, and copper particles. These materials all had 99% or greater viral inactivation at one and ten minutes of exposure. High RNA fragmentation (i.e., RNA breaking apart to the point of inactivation) was observed for copper at one minute, followed by aluminum nitride, and to a lesser extent silicon nitride. However, after ten minutes substantial RNA fragmentation was found in all three substances, first by copper, followed by silicon nitride and to a lesser extent aluminum nitride.

3.2.1 Environmental Factors Affecting Attenuation

Researchers have also investigated how environmental factors (e.g., temperature, relative humidity, etc.) impact the survival of SARS-CoV-2 on surfaces and materials. In a perspective article, Joonaki et al. (2020) called for more research "on the role of surface-active moieties of the viral proteins, hydrophilic or hydrophobic characteristic of the solid surface, pH of the bulk fluid, relative humidity, and temperature of the environment" (p. 2142).

Recently, a model was developed by the DHS Science and Technology Directorate (n.d.) for SARS-CoV-2 decay on stainless steel, ABS plastic, and nitrile rubber at varying temperatures and relative humidity. This model can be used to estimate virus decay in the absence of exposure to direct sunlight. Users can input temperature (74-95°F) and relative humidity (20-60%) and the model determines how many hours or days until 50->99.9% of the virus is inactive. It should be noted that the model does not take into account the infectious dose or viral shedding. In addition, the model is designed for conditions absent of sunlight; however, some evidence suggests that SARS-CoV-2 decays more quickly when exposed to sunlight (Schuit et al., 2020). The most salient feature of the model is that as temperature and relative humidity increase, the decay time decreases (Department of Homeland Security, 2020).

Temperature and Humidity

Changes in temperature and humidity have been demonstrated to affect virus stability. For example, a recent study by Biryukov et al. (2020) tested the stability of SARS-CoV-2 on surfaces by using simulated saliva and depositing it onto stainless steel, acrylonitrile butadiene styrene (ABS) plastic, and nitrile rubber gloves. These were specifically chosen to represent common types of fomite transmission, such as doorknobs, electronics, and PPE. Virus stability was measured in combinations ranging from approximately 20 to 80% relative humidity from 24°C (75.2°F) to 35°C (95°F). In this study, there were no significant differences in the virus decay rate on stainless steel, ABS plastic, or nitrile gloves; and droplet size was not a significant factor influencing virus half-life. Higher temperatures resulted in faster virus decay and shorter half-life at 20%, 40%, and 60% relative humidity. Pairwise comparisons of mean half-life results between 24 and 35°C under each set of humidity conditions showed that these results were significant. Overall, this article found that higher temperatures and higher relative humidity lead to quicker inactivation of SARS-CoV-2 on surfaces. This study also found that relative humidity was a significant factor influencing virus decay. At ambient indoor temperatures, the virus is most stable at a lower relative humidity.

Additionally, a peer-reviewed article by Chan et al. (2020) used virus strain SARS-CoV-2 HKU-001a and SARS-CoV HKU39849 to compare the stability of SARS CoV-2 to SARS-CoV-1. They found that dried SARS-CoV-2 on glass retained viability for 3 to 5 days at room temperature (22–25°C; 71.6–77°F) and for 14 days at cold temperatures (4°C; 39.2°F). However, SARS-CoV-2 lost viability rapidly within 1 day at hotter temperatures (37°C; 98.6°F).

In a letter to the editor, Kratzel, Steiner, Todt, et al. (2020) tested SARS-CoV-2 stability at 4°C (39.2°F) and 30°C (80°F) to understand how seasonal changes impacted the virus. Tests were done on metal discs at 4 hours, 8 hours, 24 hours, and then after 24 more hours, up to 9 days. All tests were done at a humidity of 30-40%. SARS-CoV-2 remained stable for several days regardless of tested temperature changes. These results challenged theories that surface stability changes due to the seasons changing; however, this study did not include other environmental factors such as viral load and humidity.

Wet vs. Dry Conditions

Others have sought to test if there was a difference in viral stability in a wet versus dry environment, such as in the correspondence article by Sun et al. (2020). The investigators used a plaque-purified strain (nCoV-SH01) isolated from a patient in Shanghai. Ultimately, they found that SARS-CoV-2 can survive for 3 days in liquid medium or on dry filter paper. At room temperature, the 3-day incubation in liquid medium left 1.35 $\text{Log}_{10}\text{TCID}_{50}$ (initial titer was 3.75) of viable virus. For dry filter paper under the same conditions, the virus also remained viable for 3days, but the researchers were unable to determine the TCID_{50} titer at the 3-day mark. Cytopathic effects were observed at the 3-day timepoint on the filter paper, but the researchers did not detail what these effects were.

Furthermore, one notable finding by Chan et al. (2020) was that SARS-CoV-2 suspended in solution remained viable longer than dried SARS-CoV-2 under the same temperature conditions. Dried SARS-CoV-2 retained viability for 3-5 days at room temperature and more than 14 days at cold temperatures, but it lost viability within 1 day at hotter temperatures. SARS-CoV-2 in solution retained viability for 7 days at room temperature, remained viable for up to 14 days at cold temperatures, and retained viability for 1-2 days in hotter temperatures. This finding conflicts with Sun et al. (2020), who found that SARS-CoV-2 suspended in a liquid medium at room temperature remained viable for 3 days, not 7.

Surface pH

The pH of surfaces has also been found to impact the ability of SARS-CoV-2 to survive on surfaces. For example, Sun et al. (2020) found that SARS-CoV-2 at a high titer can survive under acidic conditions that mimic the stomach. Specifically, when 1.2 × 103 plaque-forming units (PFU) of virus was treated with acidic saline (pH 2.2) for 30 or 60 minutes, virus survival could be observed as manifested by cytopathic effects (CPE), but was not quantified. There was no virus survival detected with lower virus titers (<1.0 × 103 PFU) treated under the same condition.

Chan et al. (2020) also tested the effect of pH on viability. The investigators created viral transport medium (VTM) at pHs ranging from 2 to 13. They found that “the virus remained viable for up to six days but lost between 2.9 and 5.33 logs of infectivity” for pH levels between 5 (e.g. coffee) and 9 (e.g. baking soda) (p. 229). Finally, at pH extremes (pH 2 - 3 (e.g. lemon juice) and pH 11 - 12 (e.g. household ammonia)), the virus’ viability was lost in less than a day.

3.3 Effectiveness of Prevention and Decontamination Measures for SARS-CoV-2

The research literature explored the efficacy of a variety of prevention and decontamination measures to eliminate the presence of SARS-CoV-2, including UV light treatments, PPE, hand hygiene, ventilation and open space, surface cleaners and disinfectants, as well as other strategies. Findings showed the most effective methods include the following:

- Handwashing for 20 seconds from fingertip to forearm with soap and warm water
- Rubbing hands with 60-80% ethanol hand sanitizer for 30 seconds
- Utilizing triple-layer cotton and surgical face masks
- Use of UV-C energy and filters with HVAC systems
- Mixed ventilation through mixing fresh outdoor air with existing air
- Intermittent occupancy
- Ethanol-based cleaners

Numerous studies investigated these interventions and reported on effectiveness against SARS-CoV-2. These results have been organized into subsections below by treatment type: UV light, PPE, hand hygiene, ventilation and open space, and surface cleaners and disinfectants.

In addition to studies that investigated specific interventions, several articles provided general guidelines and recommendations for mitigating the presence of SARS-CoV-2. For example, Sun and Zhai (2020) suggested that social distancing requirements should be at least 5.2 feet, extending up to 9.8 feet to consider aerosol transmission of large droplets, and to 26 feet to account for all droplets. Additionally, in a peer-reviewed article authored by Wang, Tian, Zhang, et al. (2020), various disinfection and prevention methods were studied in a home-based setting where at least one family member tested positive for SARS-CoV-2. Findings showed that use of ethanol- and chlorine-based surface cleaners, social distancing, and closing the toilet seat lid while flushing were proven effective and decreased transmission within the household. Furthermore, the Central Disaster and Safety Countermeasure Headquarters of the Republic of Korea (2020) outlined guidance from the Korean government regarding prevention and decontamination. Specifically, the guidelines promoted social distancing (at a distance of 1 to 2 meters between others and seating), availability of soap and hand sanitizer, keeping windows open for air flow, cleaning frequently touched areas at least once a day, using 70% ethanol (or household bleach) to disinfect, and properly wearing face masks and coverings.

Also, García de Abajo et al. (2020) published a peer-reviewed article of their review of literature and decontamination practices. The authors noted that social distancing guidelines involving school, restaurant, and workplace shutdowns have been shown to be effective in mitigating the spread of SARS-CoV-2. However, costs (e.g., economic and social) were vast and unsustainable. In indoor settings, efficacy of measures such as frequent handwashing, mask wearing, and physical barriers may be limited, due in part to the airborne transmission of SARS-CoV-2 and the presence of shared surfaces (e.g., handles, handrails). Relatedly, UV-C light can be used on frequently touched surfaces (e.g., elevator buttons, toilets). Further, inserting a UV-C light into air filtration systems has been recommended to inactivate virus particles transmitted in the air circulation system. Lastly, the authors asserted that due to its rapid decontamination abilities, easy employment, and minimal cost, use of UV-C was found to be a preferable alternative decontamination strategy. However, implementation was said to be limited by production constraints that require industry and government support.

Dietzel et al. (2020) published a peer-reviewed article compiling recommendations from a facilitated discussion of SARS-CoV-2 safety procedures among facility managers. To investigate, facility managers who were members of German Bioimaging discussed the sharing of equipment (e.g., microscopes) and how equipment could be operated with minimal risk of spreading SARS-CoV-2 between users and staff. The resulting guidelines focus on separating users physically as well as distancing time of use, providing protective face masks, and keeping surfaces virus-free. Specifically, findings indicated that key strategies included limiting the number of staff in the facility, promoting distance between staff, conducting team rotations every 14 days, clearly displaying social distancing requirements with tape, ensuring the occupation of a space involved a break prior to another staff member entering, use of high-density cotton face masks, and disinfecting surfaces and equipment with ethanol or 2-propanol to deactivate the virus. Further, disinfectants containing ethanol and 2-propano in formulations were shown to sanitize within 30 seconds.

3.3.1 Ultraviolet Light Treatments

Types of UV light have been demonstrated to have efficacy in destroying SARS-CoV-2. For example, Heilingloh et al. (2020) drafted a peer-reviewed article exploring the susceptibility of SARS-CoV-2 to irradiation with UV light. The virus was treated with UVA and/or UV-C light and with samples taken after every 3 minutes across 15 minutes for UVA or UV-C irradiation alone, and across 30 minutes for combined UVA and UV-C irradiation. Findings indicated that SARS-CoV-2 was highly susceptible to UV-C irradiation at high viral titers, such that a high infectious titer of 5×10^6 $TCID_{50}$/milliliter was completely inactivated after 9 minutes of exposure. In contrast, UVA irradiation had a weak effect on virus inactivation across 15 minutes.

A peer-reviewed study by Simmons et al. (2020) tested the effectiveness of pulsed-xenon ultraviolet (PX-UV) exposure on a hard surface (8-well chamber slides) containing infectious SARS-CoV-2 virus. The authors found PX-UV significantly reduced the viral load by 99.97% within 1 minute of exposure. Results should not be generalized, as UV light from PX-UV differs from other UV light sources.

Marcelo (2020) provide insights into the transmission and strategies to control spread. In addition to PPE, findings indicated that UV light can be an efficient decontamination strategy for surfaces and equipment. However, the authors noted that UV technology requires substantial space, of which hospitals are currently lacking due to the large volume of patients. Further, UV germicidal irradiation protocols have not yet been established (see Food and Drug Administration's Q and A related to UV lights and lamp online for more information).

3.3.2 Personal Protective Equipment

Personal protective equipment continued to have demonstrated efficacy in preventing spread of the virus among people. Zhang et al. (2020) published a peer-reviewed article that determined the efficacy of face masks in reducing the number of new infection cases of SARS-CoV-2. Researchers analyzed prevention strategies in three epicenters: Wuhan, China; Italy; and New York City (NYC). China implemented mandated masks early in January 2020, compared to Italy and NYC who mandated masks in April 2020. To determine if this lapse in mandated masks contributed to the sharp increase in cases, a linear regression was applied to infection number and date (April-May) in NYC and the U.S. overall. The data show the new infection rate in NYC decreased after the mandated masks policy along with the stay at home orders, compared to the U.S. that only enforced stay at home orders. The authors suggested NYC's decision to enforce the combination of measures (i.e., face masks along with stay at home orders) prevented at least 66,000 new infections between April and May 2020. In conclusion, the early implementation of a mask mandate helped China flatten the infection curve (compared to Italy and the U.S.).

In a peer-reviewed article by Ho et al. (2020), the authors investigated differences between medical and cotton masks with regard to preventing droplet transmission. Participants with suspected SARS-CoV-2 and confirmed influenza wore both masks in a regular size bedroom and vehicle. The mean particle size was collected and coughs/sneezes per hour were documented. Findings showed there were no significant differences in number of droplets detected between a medical and a triple-layer cotton mask. Thus, results indicated that cotton masks (which are also washable) are as efficient at preventing droplet/virus transmission as medical masks. However, this study was conducted on suspected (i.e., not confirmed) SARS-CoV-2 cases, which is a major study limitation.

Furthermore, in a peer-reviewed article, Hendrix et al. (2020) presented a case study of a hair salon in which two stylists worked closely with clients before being diagnosed with COVID-19. Both stylists and the majority of their clients followed company policy and city ordinance requiring the use of face masks. None of the clients developed COVID-19 symptoms and those tested were negative for the virus, which supports the mitigation measure of using face masks in public spaces where physical distancing may not be possible.

Amendola et al. (2020) published a rapid screening method for testing the efficiency of masks in breaking down aerosols. Authors created laboratory environment to mock inhalation and exhalation to test performance of seven masks in meeting essential requirements outlined in European Standard EN 14683:2019, and Standard EN 149:2009. The ability of each mask to block particles larger than 0.28 µm was tested at least eight times. The presence of aerosol in two chambers (separated by a mask) provided evidence as to the efficacy of this strategy. Results showed that “the medical face mask is characterized by values higher than 97%, while only the face masks fabricated with three layers mainly constituted by non-woven fabric material (TNT) are able to reach values higher than 95%.” (p.2).

3.3.3 Hand Hygiene

Hand hygiene has been found to be imperative to curbing the spread of SARS-CoV-2. In their peer-reviewed article, Hillier (2020) examined effective handwashing practices, including utilizing hand sanitizer, in healthcare settings. The article instructed that effective handwashing involved washing from fingertip to forearm for at least 20 seconds with warm water, which opens the pores on the skin; and the hands and arms should be dried with a disposable paper towel to remove any excess moisture, followed by using the paper towel to turn off the faucet. The author noted that lack of access to sinks and restrooms impose a barrier to handwashing. Commentary by Roshan et al. (2020) noted that other barriers included time constraints and lack of easy access to hand sanitizers. They went on to state that hand sanitizer efficacy is dependent on the alcohol concentration and type, with ethanol concentrations of 60%-70% proven effective in health care settings, and with 70% concentration being more effective than cleansing with soap and water. However, the authors noted, some cultural and religious beliefs regarding alcohol may lead some to opt out of using hand sanitizer.

In their correspondence letter, Kratzel, Todt, V’Kovski, et al. (2020) investigated the effectiveness of WHO-recommended hand sanitizing formulations on SARS-CoV-2. They applied WHO formulation I (80% ethanol), WHO formulation II (75% 2-propanol), slightly modified versions (with lower glycerol concentrations), and various dilutions of ethanol and 2-propanol. The authors found that both WHO formulations and the modified versions were effective virucides for SARS-CoV-2. Dilutions of ethanol and 2-propanol were effective at viral inactivation all the way down to a 30% concentration level. However, authors noted a key limitation in the specificity of an exact 30-second application of virucides used in the study, since typical application of sanitizing agent in routine practice is less than 30 seconds. The authors concluded, "We found that SARS-CoV-2 was efficiently inactivated by WHO-recommended formulations, supporting their use in healthcare systems and viral outbreaks. Of note, both the original and modified formulations were able to reduce viral titers to background level within 30 s. In addition, ethanol and 2-propanol were efficient in inactivating the virus in 30 s at a concentration of >30% (vol/vol)" (p. 1594).

3.3.4 Ventilation and Air Filtration

Several researchers have explored opportunities to adjust variables and features in air ventilation and filtration in indoor environments to reduce the risk for transmission of SARS-CoV-2 among occupants.

In their peer-reviewed study, Sun and Zhai (2020) introduced two indices, social distance probability and ventilation effectiveness, into a model predicting airborne virus-related infection probability. Findings showed that 1.6−3.0 meters (5.2–9.8 feet) was the safe social distance when considering aerosol transmission of exhaled large droplets from talking, with 8.2 meters (26 feet) being the maximum potential distance for transmission, accounting for all droplets in a calm air environment. The authors found that increased exposure time in confined spaces (e.g., public transport, office spaces) increased risk for infection. However, modifications, such as increasing ventilation rate to bring in more outside air and decreasing occupancy to enable social distancing, could be applied to maintain a low infection rate. Of note, the modeling showed that social distancing was useful, but increased ventilation was needed to maximize infection risk reduction in indoor environments: “Although social distancing is effective in reducing the risk of infection, to control the [probability of infection] to a lower level (for example, 2 %) requires adequate ventilation rate to dilute the contaminants from infectors” (p. 7). The model was calibrated using data from an actual pandemic case and verified using data for additional cases in different scenarios. However, limitations and assumptions included a model that only considered droplet transmission and not other methods (e.g., contact with infected fomites) and a use of a hypothesized initial infection rate.

Melikov et al. (2020) conducted modeling of infection risk based on occupancy, ventilation practices, room volume, and time spent in an enclosed room. Results showed that ventilation systems operating at the maximum airflow rate (versus demand control ventilation (i.e., airflow rate linked to the number of occupants)) help reduce the risk of virus exposure for people in a space, and that employing ventilation continuously would provide increased efficiency. The authors recommended several practices to reduce exposure risk in indoor environments: ventilation systems should be operated continuously and should be initiated before people enter a space; people should be asked to leave the space periodically; shorten occupation times and increase empty times (i.e., “a shorter occupation time prevents the room concentration from building up to the highest level, and a longer break between periods of occupation allows the room concentration to decrease as much as possible and allows the use of additional high-noise ventilation equipment” (p. 6)); ventilation should be increased if occupancy increases, though occupancy should remain low to reduce the number of asymptomatic infected people in a space at once; use stand-alone air units (e.g., window AC or fan units) during breaks if possible to reduce disruption and increase ventilation (or the alternative: “a stand-alone room air cleaner, efficient filtration of air recirculation, and air disinfection” (p. 6); and increases in room height to increase volume, in cases of new construction.

In a peer-reviewed study, Zhang (2020) described indoor air quality control strategies that can be used to mitigate the spread of SARS-CoV-2 indoors. The strategies included source control, ventilation, and air cleaning. Local air exhaust was described as a source control strategy similar to a vacuum that can reduce cross-contamination by removing impurities and contaminants from the air. Maximized ventilation was recommended for the circulation of fresh air, which could be achieved through utilization of high-efficacy particulate air (HEPA) and minimum efficiency reporting value (MERV) 14 filters; promoting mixed ventilation by mixing fresh outdoor air with existing air; and applying displacement ventilation by ensuring cool air enters the room at floor level and exhausts at ceiling level. Air cleaning was recommended through face masks, stand-alone air purifiers, and use of UV-C energy at a 254-nanometer wavelength to disinfect within HVAC systems.

Yu et al. (2020) published a peer-reviewed article related to the application of a heated air disinfection system that implemented a heated nickel (Ni) component in the air filtration system to destroy aerosolized SARS-CoV-2 through the air circulation process. The authors “designed and fabricated a filter device consisting of folded pieces of Ni foam in multiple compartments connected electrically in series to efficiently increase the resistance to a manageable level so that a temperature up to 250 °C was able to be achieved” (p. 2). Testing of this device involved “using aerosolized actual SARS-CoV-2, isolated from humans…[to test] viral load reduction from upstream to downstream in the device using a single passthrough when the filters were heated up to 200°C (temperature optimization is currently being studied)” (p. 4). Results showed that 99.8% of SARS-CoV-2 virus was able to be captured and destroyed in the air passed through a filtration system equipped with the disinfection system. This intervention, due to its production of high temperatures, was also demonstrated not to negatively impact the ability of air conditioning systems to cool indoor spaces.

Additionally, in a peer-reviewed brief report, Lane et al. (2020) collected and analyzed bioaerosol samples from an isolation room, bathroom, and anteroom of a ventilated patient with confirmed COVID-19. Out of the 30 collected samples, 28 samples were found to be negative for SARS-CoV-2 and two samples were unable to be tested due to equipment failure. The authors postulated that the samples were negative “possibly due to the patient being on a closed-circuit ventilator or the efficiency of the air exchanges in the room” (p. 1). Various limitations were noted by the authors, including that the sampling may have been too diluted to detect SARS-CoV-2 RNA in the samples and potentially insufficient sampling time.

In a report by Romano Spica et al. (2020), the Working Group on Movement Sciences for Health of the Italian Society of Hygiene Preventive Medicine and Public Health established recommendations regarding indoor and outdoor swimming pool prevention and safety. Their recommendations for indoor facilities included a call for regular ventilation of indoor air by introducing outdoor air, rather than re-circulating indoor air or circulating air from another indoor environment; however, no empirical analyses were conducted by the working group as part of this publication.

3.3.5 Surface Cleaners and Disinfectants

To reduce the presence of SARS-CoV-2 in indoor environments, surface cleaners and other disinfectants have been investigated to understand their capacity to destroy the virus, with many types showing efficacy. For example, in a preprint article, Pezzotti et al. (2020) tested the ability of silicon nitride, copper, and aluminum nitride to disinfect SARS-CoV-2 on surfaces. The virus was exposed to 15 wt.% of each aqueous solution, and all of the suspensions showed over 99% virus deactivation in 1 to 10 minutes.

In this letter of correspondence, Scully (2020) presents literature on the effectiveness of copper deactivation of SARS-CoV-2. Of importance, copper naturally has antimicrobial properties due to aqueous corrosion. In the presence of copper, viral levels of SARS-CoV-2 decreased. Further, Scully provide the following in his final thoughts, "Fomites that are high-touch objects pose a threat to disease transmission and novel host infection by viruses and perhaps COVID-19. Copper alloy surfaces may be capable of suppressing virus transmission through inherent lethality with respect to viable viruses on these fomite surfaces. This is enabled by natural corrosion processes on copper triggered by oxidation in relatively “dry” or humid air, as well as in an infected droplet or aerosol excretion that has settled on fomite surfaces. This process is intrinsic to copper in many environments and can occur without regular human interventions such as daily cleaning."

A peer-reviewed article by Welch et al. (2020) presented findings of various disinfection methods against SARS-CoV-2 and other viruses. The viruses were tested on surgical face masks under 50-70° C against the following disinfectants: 10% bleach, quaternary ammonium sanitizer, 3% hydrogen peroxide, and 70% isopropanol. Results showed that bleach, ammonia, and hydrogen peroxide deactivated SARS-CoV-2 and other viruses with a single application by wiping, but the 70% alcohol performed significantly less effectively.

A peer-reviewed article by Wang, Tian, Zhang, et al. (2020) explored various disinfection and prevention methods in a home-based setting with at least one family member tested positive for SARS-CoV-2. Data was collected on household hygiene routines before, during, and after symptoms. Findings showed that ethanol and chlorine-based surface cleaners decreased transmission by 77%. Closing the toilet seat lid during flushing to prevent aerosol transmission was another effective prevention strategy. Limitations of this study included recall bias and inability to measure the concentration of disinfectant products.

In a preprint, Castaño et. al (2020) outlined various disinfectant strategies against SARS-CoV-2. A known virus titer was evaluated after the use of a disinfectant. Findings showed that the following surface cleaners were successful in deactivating SARS-CoV-2: 0.1% benzalkonium chloride; 0.05% chlorhexidine; 7.5% povidone iodine; 0.05% chloroxylenol; 70% ethanol; and 1% and 2% household bleach. Heating the surface to 70˚C was also proven effective. It is important to keep in mind that some disinfectants may stain or otherwise damage some surfaces, are heat sensitive, and alcohols may evaporate more quickly than the required contact time before viral inactivation.

A peer-reviewed article by Takeda et al. (2020) mixed virus strains with electrolyzed water test solutions and found acidic electrolyzed water potently inactivates SARS-CoV-2 (depending on the amount of free available chlorine in contact with the virus). Acidic electrolyzed water (EW) with a high concentration of free available chlorine (FAC) shows strong antimicrobial activity against bacteria, fungi, and viruses. Here, authors assessed the SARS-CoV-2-inactivating efficacy of acidic EW for use as an alternative disinfectant. The quick virucidal effect of acidic EW depended on the concentrations of contained FAC. The effect completely disappeared in acidic EW in which FAC was lost owing to long-time storage after generation. In addition, the virucidal activity increased proportionately with the volume of acidic EW mixed with the virus solution when the FAC concentration in EW was same. Using a 1:9 test solution, SARS-CoV-2 was deactivated in 1 minute. These findings suggest that the virucidal activity of acidic EW against SARS-CoV-2 depends on the amount of FAC contacting the virus.

The literature review identified numerous disinfectants and surface cleaners by active ingredients that have been proven to deactivate SARS-CoV-2. Table 2 provides common household products that include those active ingredients. Asterisks in the right column indicate Environmental Protection Agency (EPA) approval of a cleaner against SARS-CoV-2 (U.S. Environmental Protection Agency, 2020; see full list of EPA-approved cleaners).

Table 2. Common Names for Disinfectants and Surface Cleaners

Active Ingredient	Common Product Name
Quaternary Ammonium Sanitizer	• Pine-Sol Cleaner and Antibacterial • Fantastik All Purpose Cleaner* • Clorox Disinfecting Wipes* • Lysol Disinfecting Wipes*
0.1% Benzalkonium Chloride	• Noviruclean • Bin Buddy Spray Citrus • Calfarme FOAMCARE Spray & Wipe All Purpose Surface Sanitizer • FairPrice Anti-Bacterial Wet Wipes • G3Tech Disinfectant • Sanitiser Guard • Spray Nine Heavy Duty Cleaner / Degreaser / Disinfectant • Vsafe Multi-Purpose Sanitiser
7.5% Povidone Iodine	• Betadine Surgical Scrub
0.05% Chloroxylenol	• Shopkins Hand Sanitizer • Kung Fu Panda Hand Sanitizer

3.3.5.1 Improper Use of Cleaners

Increased use of surface cleaners to prevent the spread of SARS-CoV-2 may also have contributed to accidents and harm when used improperly. A recent report by Gharpure et al. (2020) described a sharp increase in calls to poison centers related to exposures to cleaners and disinfectants since the onset COVID-19 pandemic. Since, U.S. data within household settings are limited, an opt-in Internet panel survey of 502 U.S. adults was conducted in May 2020 to characterize knowledge and practices regarding household cleaning and disinfection. Knowledge gaps related to safe preparation of cleaning and disinfectant solutions, use of recommended PPE when using cleaners and disinfectants, and safe storage of hand sanitizers, cleaners, and disinfectants were identified. Findings showed 39% of respondents reported engaging in improper high-risk practices with the intent of preventing SARS-CoV-

2 transmission (e.g., improper or harmful use of cleaning and disinfecting agents, such as washing produce with bleach, wiping hands with ineffective household cleaners, gargling with soap or bleach, or mixing bleach with ammonia or vinegar). Respondents who engaged in high-risk practices more frequently reported an adverse health effect that they believed was a result of using cleaners or disinfectants than did those who did not report engaging in these practices. To reduce transmission of SARS-CoV-2, authors suggested that public messaging continue to emphasize evidence-based, safe practices such as hand hygiene and recommended cleaning and disinfection of high-touch surfaces. Further, messaging should emphasize avoidance of high-risk practices (e.g., unsafe preparation of cleaning and disinfectant solutions, use of bleach on food products, application of household cleaning and disinfectant products to skin, and inhalation or ingestion of cleaners and disinfectants).

4. Discussion, Gaps, and Recommendations for Future Research

4.1 Discussion

Scientific research about SARS-CoV-2 has continued to evolve since the Phase 1 literature review, and although the literature remains a work in progress, the results of the Phase 2 literature review indicated that scientific publication on the three topics of interest had grown in quantity and specifically the number of peer-reviewed publications. Syntheses of these findings are described in this section.

4.1.1 Spread of SARS-CoV-2 through General Building Operations

The findings presented in this study were consistent with guidance from the Centers for Disease Control and Prevention (CDC; 2020) that SARS-CoV-2 is thought to spread between people in close contact to one another, primarily through respiratory droplets passed from person to person. The literature suggested that the virus may most commonly be spread from an infected person to someone else during respiratory actions like coughing, sneezing, speaking, and breathing. Other indirect means may also contribute, such as when the virus becomes deposited on high-touch objects (i.e., fomites) or suspended in the air. Research has been conducted on these other means of transmission, such as studies that reported positive tests for SARS-CoV-2 RNA in samples taken from high-touch surfaces (e.g., doorknobs, bathroom floors, toilets) near people infected with the virus. However, additional research is needed to clarify the extent of transmission, particularly since much of the research used methods such as RT-PCR to detect for the presence of virus (past or present) but not the viability of the virus in these other indirect means of transmission.

Furthermore, environmental factors such as humidity, temperature, UV light, and air movement and ventilation have been found to impact the spread of the virus. Specifically, lower temperatures, humidity, and sunlight intensity are associated with slower decay of SARS-CoV-2. Additionally, the use of HVAC systems may facilitate the spread of the virus, and poor ventilation may lead the virus to remain in indoor environments.

Overall, the primary means of viral spread are thought to have been identified, but further research is needed to confirm the relative risks of exposure to the virus via droplets, aerosols, fomites, and other pathways, in addition to the complex interactions of environmental factors on spread of SARS-CoV-2.

4.1.2 Survival of SARS-CoV-2 on Material Surfaces through Environmental Attenuation

For the Phase 1 literature review, there was a growing body of evidence about the extent to which SARS-CoV-2 survived on surfaces before environmental attenuation. In fact, multiple review articles published after the Phase 1 literature review cited the same environmental attenuation studies that were discussed in the Phase 1 report, including that SARS-CoV-2 can persist on many surfaces for at least three days (Aboubakr et al., 2020; Akram, 2020; Rizou, 2020; Zhang, 2020).

Since then, however, the research has shifted towards environmental factors affecting attenuation and methods to deactivate the virus on surfaces. Environmental factors continue to be highly studied, focusing primarily on temperature and humidity. Overall, the research showed that higher temperatures (Biryukov et al. 2020; Chan et al. 2020; Harbourt et al. 2020) as well as higher humidity (Biryukov et al. 2020) result in faster virus decay. The virus also appeared to remain stable longer in solution than in dry conditions (Chan et al. 2020) and can survive in acidic environments that mimic the conditions of the stomach, which has implications in research on transmission via biological substances. Though newer literature on this topic is limited, the implication of studies like Biryukov et al. (2020) and Harbourt et al. (2020) showed that virus stability on surfaces, especially high-touch surfaces, illustrate the importance of decontamination and hand hygiene practices in public spaces.

4.1.3 Effectiveness of Prevention and Decontamination Measures for SARS-CoV-2

The literature review identified a number of measures that have been reported to be effective in eliminating the presence of SARS-CoV-2 (for summary, see Table 3 below). One of the most effective strategies reported was handwashing and wearing face masks. It was recommended that handwashing should occur for 20 seconds with soap and warm water, and hand sanitizer should be thoroughly rubbed for 30 seconds (Hillier, 2020). Studies also showed that triple-layer cotton and surgical masks were equally effective in protecting against SARS-CoV-2 (Ho et al., 2020).

Additionally, air circulation and filtration interventions were also discussed in the literature. For example, incorporating nickel and UV-C energy within HVAC systems was proven to deactivate viral particles, ensuring that any aerosolized virus would be not be re-circulated within an enclosed space (Yu et al., 2020; Heilingloh et al., 2020). Ventilation strategies that promote air renewal with outdoor air and air purifiers were also identified as useful in decreasing aerosol concentration of SARS-CoV-2 in enclosed spaces (Spica et al., 2020; Zhang, 2020).

Some studies noted the potential for UV light treatments to deactivate SARS-CoV-2. For example, combining UV-A and UV-C light was shown to inactivate the virus within nine minutes (Heilingloh et al., 2020), while exposure to PX-UV diminished the virus in one minute (Simmons et al., 2020). Further study may identify low-cost, high impact means to implement UV light interventions to destroy the virus in indoor environments.

Finally, several surface cleaners and disinfectants were found to kill SAR-CoV-2. For example, Pezzotti et al. (2020) asserted successful decontamination with application for 1-10 minutes of 15 wt% of each aqueous solution: silicon nitride, copper, and aluminum nitride. Welch et al. (2020) found that 10% bleach, quaternary ammonium sanitizer, and 3% hydrogen peroxide were each successful in deactivating the virus after one wipe. Ethanol-based cleaners (Wang, Tian, Zhang, et al., 2020), 0.1% benzalkonium chloride (Castaño et al., 2020), 0.05% chlorhexidine (Castaño et al., 2020), 7.5% povidone iodine (Castaño et al., 2020), and 0.05% chloroxylenol (Castaño et al., 2020) were also cited as successful disinfectants. Lastly, acidic electrolyzed water with a high concentration of free available chlorine (i.e., 1:9 solution) deactivated SARS-CoV-2 in one minute (Takeda et al., 2020). Accordingly, it has been found that a wide range of disinfectants are effective at reducing the presence of the virus in indoor environments.

Table 3 lists the decontamination and prevention strategies that were presented as effective against SARS-CoV-2 in the Phase 2 literature review.

Table 3. Decontamination/Prevention Strategies

Strategy	Details
Handwashing	• Handwashing for 20 seconds from fingertip to forearm with soap and warm water (Hillier, 2020) • Rubbing hands with 60-80% ethanol hand sanitizer for 30 seconds (Hillier, 2020) • Rubbing hands with 75% 2-propanol hand sanitizer for 30 seconds (Kratzel, Todt, V'Kovski, et al., 2020)
PPE	• Face masks (Zhang et al., 2020) • Medical masks (Ho et al., 2020) • Triple-layer cotton masks (Ho et al., 2020) • Providing PPE to all guests and staff (Spica et al., 2020)
HVAC	• Continuous air renewal from fresh outdoor air (Spica et al., 2020) • Use of UV-C energy with HVAC systems (Heilingloh et al., 2020) • Use of nickel filters with HVAC systems (Yu et al., 2020)
Ventilation and Open Space	• Maintaining a physical distance of at least 5.2–9.8 ft (Sun & Zhai, 2020) • Local air exhaust (Zhang, 2020) • Utilizing high efficacy particulate air (HEPA) and MERV 14 filters (Zhang, 2020) • Mixed ventilation through mixing fresh outdoor air with existing air (Zhang, 2020) • Displacement ventilation by ensuring cool air enters the room at floor level and exhausts at ceiling level (Zhang, 2020) • Stand-alone air purifiers (Zhang, 2020) • Intermittent occupancy (Melikov et al., 2020) • Scheduling reservations (Spica et al., 2020)
UV Light	• Complete deactivation after exposure to combined UVA and UVC light for 9 minutes (Heilingloh et al., 2020) • Exposure to pulsed-xenon UV for 1 minute (Simmons et al., 2020)

Technology	• Long-distance learning (Madurai Elavarasan et al., 2020) • Work from home (Madurai Elavarasan et al., 2020)
Surface Cleaners and Disinfectants	• 15 wt% of each aqueous solution: silicon nitride, copper, and aluminum nitride for 1-10 minutes (Pezzotti et al., 2020) • 10% bleach, quaternary ammonium sanitizer, and 3% hydrogen peroxide deactivated the virus with one wipe (Welch et al., 2020) • Copper (Scully, 2020) • Ethanol-based cleaners (Wang, Tian, Zhang, et al., 2020) • 0.1% benzalkonium chloride (Castaño et al., 2020) • 0.05% chlorhexidine (Castaño et al., 2020) • 7.5% povidone iodine (Castaño et al., 2020) • 0.05% chloroxylenol (Castaño et al., 2020) • 1:9 acidic electrolyzed water test solution, SARS-CoV-2 was deactivated in 1 minute (Takeda et al., 2020)
Other	• Enforcing penalties for violations (e.g., not wearing a mask) (Spica et al., 2020) • Closing the toilet seat lid while flushing (Wang, Tian, Zhang, et al., 2020)

4.2 Gaps and Recommendations

4.2.1 Gaps in the SARS-CoV-2 Literature

Given the emerging and evolving nature of SARS-CoV-2 and its impact on humans, researchers are actively working to produce new data and develop a comprehensive understanding of the virus, especially how it spreads, its transmissibility, how long it persists on surfaces, effective means to mitigate transmission and spread, and effective means to destroy the virus in the environment. At the time of this report, the scientific community's understanding of the virus has evolved considerably since publication of the Phase 1 literature review, as demonstrated by the sizable increase in peer-reviewed publications related to the research questions. In general, additional rigorous experimental research is needed that focuses specifically on SARS-CoV-2 to (1) replicate and verify (or challenge) the findings of the experiments released to date, (2) resolve discrepancies in the current literature, and (3) explore the diverse variables that could affect the virus' ability to spread in LAMs and other similar environments. Some of the gaps in the literature that may prove useful to understanding the research questions of this literature review include:

- Comprehensive studies employing experimental research methods to investigate the relative risks for airborne spread of the virus, including testing the dispersion of SARS-CoV-2 specifically through talking, breathing, coughing, sneezing, and other respiratory activities. Furthermore, when the virus is spread from an infected individual to fomites in the environment, further research may clarify the potential for transmission to other people who make contact with those fomites over time.

- Further study using viability assays as opposed to RT-PCR testing is needed to help clarify the extent of the virus' ability to spread intact in environments (note: RT-PCR detects virus particles, but does not distinguish between presence of just genetic material versus viable virus, which can impact transmission to humans).
- Expansion of rigorous laboratory testing of SARS-CoV-2 surface attenuation patterns across surface types, especially those most relevant to LAMs. Such studies could also further scrutinize the effects of the environmental variables that have been found to impact survivability of the virus, especially temperature, humidity, and surface pH.
- Effectiveness of thermal, UV light, and ventilation interventions to destroy the virus, especially those means that are cost effective and practical for diverse indoor environments. Long-term use of these interventions on organisms (including people), materials, and environments should also be better explored.
- Investigations of the virus' infectious dose for humans (i.e., the minimum viral load that results in infection in humans), including variations introduced by individual differences (e.g., immunological capabilities), to clarify what end point(s) for attenuation and decontamination are necessary to prevent spread of the virus and/or transmission to other people. Note: direct investigation of the clinical research on this topic is beyond the scope of this literature review, but knowledge about this topic could be used to promote clear guidelines for prevention and spread of the virus by providing a metric for maximum tolerance of the virus in environments where humans gather.
- Further clarification of the relative risks of secondary modes of transmission beyond expelled droplets containing the virus, including transmission via aerosols, fomites, and biological substances unrelated to respiration (e.g., urine, feces, vomit, etc.). Of note, further understanding of the infectious dose and laboratory testing with viability assays can support efforts to quantify how long the virus remains viable on surfaces, in the air, and by other potential means of transmission. This approach may provide additional insight beyond current research where the majority of studies only detect for the presence of SARS-CoV-2 RNA and not whether virus particles are infectious
- There is little research on the survival of SARS-CoV-2 on fomites sampled in public settings, and research on the survival of SARS-CoV-2 on surfaces (e.g., metal, plastic) is not always reflective of fomite materials in the natural environment. More information is needed on the survival of the virus on common fomites such as floors, shoes, ventilation grates, and cell phones to better understand risk of transmission.

4.2.2 Recommendations for Specific Research to Inform Building Operations

Recommendations for additional research include those items listed in the gaps above, and novel research on these topics should be conducted with SARS-CoV-2 in particular (where safe and feasible) to avoid errors arising from assumptions of similarity between this virus and other coronaviruses. Additional testing is recommended to gather data on the impacts of ambient environmental conditions (temperature and humidity) on SARS-CoV-2 located on surfaces and materials representative of those found in LAMs. Battelle's laboratory science work in this area will help fill some of these gaps in the field's understanding of attenuation patterns. Further, rigorous scientific experiments that expand the scientific community's understanding of how SARS-CoV-2 is spread indoors through air and fomites are needed, as are studies of how people can contract the virus through these avenues. These findings could help inform how building operations can be modified to protect staff, patrons, and visitors by reducing the risks of viral transmission. Lastly, the body of peer-reviewed scientific publications about SARS-CoV-2 only continues to grow as researchers explore these questions and develop scientific consensus on key questions. As such, ongoing monitoring and periodic reviews of updates to the literature are recommended to ensure operations are informed by the latest, highest-quality, and most significant research findings.

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Appendix A. Search Strings

Focus Area	Database	Search String	Search Date	Results Yielded*
Decontamination and Attenuation	Scopus	(TITLE-ABS (coronavir* OR "SARS-CoV-2" OR "2019-nCoV" OR "COVID-19") AND TITLE-ABS (sanitiz* OR decontam* OR steriliz* OR disinfect* OR inactivat* OR "half life" OR attenuat* OR persist* OR stabil*) AND NOT TITLE-ABS (peptide OR cytokine OR pregnancy OR aperture OR iron OR cancer OR vaccine OR glycoprotein OR protease OR antibod* OR intravascular OR clinical OR opioid OR pollution OR mental OR therap* OR recept* OR protein OR immun*)) AND ((PUBDATETXT ("June 2020" OR "July 2020" OR "August 2020" OR "September 2020" OR "October 2020" OR "November 2020" OR "December 2020") OR PUBYEAR > 2020))	14-Aug-2020	1,247
	SciTech	(noft(coronavir* OR "SARS-CoV-2" OR "2019-nCoV" OR "COVID-19") AND noft(sanitiz* OR decontam* OR steriliz* OR disinfect* OR inactivat* OR "half life" OR attenuat* OR persist* OR stabil*)) NOT noft(peptide OR cytokine OR pregnancy OR aperture OR iron OR cancer OR vaccine OR glycoprotein OR protease OR antibod* OR intravascular OR clinical OR opioid OR pollution OR mental OR therap* OR recept* OR protein OR immun*) Additional limits - Date: After June 01 2020 Scholarly Journals OR Working Papers OR Other Sources OR Reports OR Conference Papers & Proceedings		
	Web of Science	(TS=(coronavir* OR "SARS-CoV-2" OR "2019-nCoV" OR "COVID-19") AND TS=(sanitiz* OR decontam* OR steriliz* OR disinfect* OR inactivat* OR "half life" OR attenuat* OR persist* OR stabil*)) NOT TS=(peptide OR cytokine OR pregnancy OR aperture OR iron OR cancer OR vaccine OR glycoprotein OR protease OR antibod* OR intravascular OR clinical OR opioid OR pollution OR mental OR therap* OR recept* OR protein OR immun*) Refined by: [excluding] DOCUMENT TYPES: (PATENT) Timespan: Year to date. (Filtered June-current) Databases: WOS, BCI, CCC, DRCI, DIIDW, KJD, MEDLINE, RSCI, SCIELO, ZOOREC. Search language=Auto		
	MED-LINE	AB (coronavir* OR "SARS-CoV-2" OR "2019-nCoV" OR "COVID-19") AND AB (sanitiz* OR decontam* OR steriliz* OR disinfect* OR inactivat* OR "half life" OR attenuat* OR persist* OR stabil*) AND AB (peptide OR cytokine OR pregnancy OR aperture OR iron OR cancer OR vaccine OR glycoprotein OR protease OR antibod* OR intravascular OR clinical OR opioid OR pollution OR mental OR therap* OR recept* OR protein OR immun*) Limiters - Date of Publication: 20200601-; Publication Type: Adaptive Clinical Trial, Case Reports, Case Study, Clinical Study, Clinical Trial, Clinical Trial Protocol, Clinical Trial, Phase I, Clinical Trial, Phase II, Clinical Trial, Phase III, Clinical Trial, Phase IV, Comment, Commentary,		

		Comparative Study, Conference, Congress, Dataset, Editorial, Evaluation Study, Government Document, Guideline, Journal Article, Lecture, Letter, Observational Study, Practice Guideline, Randomized Controlled Trial, Report, Research, Review, Systematic Review, Technical Report, Validation Study		

***Articles duplicated across the 4 databases were removed from these counts**

Focus Area	Database	Search String	Search Date	Results Yielded*
Transmission	Scopus	((TITLE-ABS ((coronavir* OR covid OR "COVID-19" OR "SARS-CoV-2" OR "2019-nCoV")) AND TITLE-ABS (spread* OR transfer* OR transmi* OR persist* OR surviv*) AND TITLE (indoor OR office OR "climate controlled" OR ambient OR environment* OR air OR airborne OR aerosol* OR hvac OR merv OR filter* OR filtrat* OR ventilat*)) AND (PUBDATETXT ("June 2020" OR "July 2020" OR "August 2020" OR "September 2020" OR "October 2020" OR "November 2020" OR "December 2020") OR PUBYEAR > 2020))	14-Aug-2020	420
	SciTech	ti,ab(coronavir* OR covid OR "COVID-19" OR "SARS-CoV-2" OR "2019-nCoV") AND ti,ab(spread* OR transfer* OR transmi* OR persist* OR surviv*) AND ti(indoor OR office OR "climate controlled" OR ambient OR environment* OR air OR airborne OR aerosol* OR hvac OR merv OR filter* OR filtrat* OR ventilat*)		
	Web of Science	TS=(coronavir* OR covid OR "COVID-19" OR "SARS-CoV-2" OR "2019-nCoV") AND TS=(spread* OR transfer* OR transmi* OR persist* OR surviv*) AND TI=(indoor OR office OR "climate controlled" OR ambient OR environment* OR air OR airborne OR aerosol* OR hvac OR merv OR filter* OR filtrat* OR ventilat*) Refined by: [excluding] DOCUMENT TYPES: (PATENT) Databases= WOS, BCI, CCC, DRCI, DIIDW, KJD, MEDLINE, RSCI, SCIELO, ZOOREC Timespan=Year to date, Filtered June 2020-current; Search language=Auto		
	MED-LINE	AB ((coronavir* OR covid OR "COVID-19" OR "SARS-CoV-2" OR "2019-nCoV") AND AB (spread* OR transfer* OR transmi* OR persist* OR surviv*) AND TI (indoor OR office OR "climate controlled" OR ambient OR environment* OR air OR airborne OR aerosol* OR hvac OR merv OR filter* OR filtrat* OR ventilat*) OR TI ((coronavir* OR covid OR "COVID-19" OR "SARS-CoV-2" OR "2019-nCoV") AND TI (spread* OR transfer* OR transmi* OR persist* OR surviv*) AND TI (indoor OR office OR "climate controlled" OR ambient OR environment* OR air OR airborne OR aerosol* OR hvac OR merv OR filter* OR filtrat* OR ventilat*) Pub Date: June 2020- current		

Search Strings Conducted to Identify Publications in Late May 2020

Focus Area	Database	Search String	Search Date	Results Yielded*
Decontamination and Attenuation	Scopus	(TITLE-ABS (coronavir* OR "SARS-CoV-2" OR "2019-nCoV" OR "COVID-19" OR hcov) AND TITLE-ABS (sanitiz* OR decontam* OR steriliz* OR disinfect* OR inactivat* OR "half life" OR attenuat* OR persist*) AND NOT TITLE-ABS (peptide OR cytokine OR pregnancy OR aperture OR iron OR cancer OR vaccine OR glycoprotein OR protease OR antibod* OR intravascular OR clinical OR opioid OR pollution OR mental)) AND RECENT (30)	01-June-2020	262
	SciTech	TOPIC:(coronavir* OR "SARS-CoV-2" OR "2019-nCoV" OR "COVID-19" OR hcov) AND TOPIC: (sanitiz* OR decontam* OR steriliz* OR disinfect* OR inactivat* OR "half life" OR attenuat* OR persist*) NOT TOPIC: (peptide OR cytokine OR pregnancy OR aperture OR iron OR cancer OR vaccine OR glycoprotein OR protease OR antibod* OR intravascular OR clinical OR opioid OR pollution OR mental) Databases= WOS, BCI, CCC, DRCI, DIIDW, KJD, MEDLINE, RSCI, SCIELO, ZOOREC Timespan=Last 4 weeks Search language=Auto		
	Web of Science	noft(coronavir* OR "SARS-CoV-2" OR "2019-nCoV" OR "COVID-19" OR hcov) AND noft(sanitiz* OR decontam* OR steriliz* OR disinfect* OR inactivat* OR "half life" OR attenuat* OR persist*) NOT noft(peptide OR cytokine OR pregnancy OR aperture OR iron OR cancer OR vaccine OR glycoprotein OR protease OR antibod* OR intravascular OR clinical OR opioid OR pollution OR mental) Databases: Coronavirus Research Database, Ebook Central, NTIS Database (National Technical Information Service), SciTech Premium Collection, These databases are searched for part of your query. Limited by: Date: After May 10 2020 Narrowed by:Source type: Scholarly Journals; Working Papers; Reports (No results for Conference Papers & Proceedings, Dissertations & Theses, Evidence-Based Medical Resources, Government & Official Publications, Standards & Practice Guidelines)		
	MED-LINE	AB (coronavir* OR "SARS-CoV-2" OR "2019-nCoV" OR "COVID-19" OR hcov) AND AB (sanitiz* OR decontam* OR steriliz* OR disinfect* OR inactivat* OR "half life" OR attenuat* OR persist*) NOT AB (peptide OR cytokine OR pregnancy OR aperture OR iron OR cancer OR vaccine OR glycoprotein OR protease OR antibod* OR intravascular OR clinical OR opioid OR pollution OR mental) Limiters - Date of Publication: 20200501-		

Focus Area	Database	Search String	Search Date	Results Yielded*
Transmission	Scopus	(TITLE-ABS (coronavir* OR covid OR "COVID-19" OR cov OR hcov OR "SARS-CoV-2" OR "2019-nCoV") AND TITLE-ABS (spread* OR transfer* OR transmi* OR persist* OR surviv*) AND TITLE (indoor OR office OR "climate controlled" OR ambient OR environment* OR air OR airborne OR aerosol*)) AND RECENT (30)	02-June-2020	131
	SciTech	noft((coronavir* OR covid OR "COVID-19" OR cov OR hcov OR "SARS-CoV-2" OR "2019-nCoV")) AND noft((spread* OR transfer* OR transmi* OR persist* OR surviv*)) AND ti((indoor OR office OR "climate controlled" OR ambient OR environment* OR air OR airborne OR aerosol*))Databases: Coronavirus Research Database, Ebook Central, NTIS Database (National Technical Information Service), SciTech Premium Collection. Limited by: Date: After May 10 2020. Narrowed by: Source type: Scholarly Journals; Working Papers; Reports		
	Web of Science	TOPIC: ((coronavir* OR covid OR "COVID-19" OR cov OR hcov OR "SARS-CoV-2" OR "2019-nCoV")) AND TOPIC: ((spread* OR transfer* OR transmi* OR persist* OR surviv*)) AND TITLE: ((indoor OR office OR "climate controlled" OR ambient OR environment* OR air OR airborne OR aerosol*)) Databases= WOS, BCI, CCC, DRCI, DIIDW, KJD, MEDLINE, RSCI, SCIELO, ZOOREC Timespan=Last 4 weeks Search language=Auto		
	MED-LINE	(AB (coronavir* OR covid OR "COVID-19" OR cov OR hcov OR "SARS-CoV-2" OR "2019-nCoV") AND AB (spread* OR transfer* OR transmi* OR persist* OR surviv*) AND TI (indoor OR office OR "climate controlled" OR ambient OR environment* OR air OR airborne OR aerosol*)) OR (TI (coronavir* OR covid OR "COVID-19" OR cov OR hcov OR "SARS-CoV-2" OR "2019-nCoV") AND TI (spread* OR transfer* OR transmi* OR persist* OR surviv*) AND TI (indoor OR office OR "climate controlled" OR ambient OR environment* OR air OR airborne OR aerosol*))		