

RESEARCH ARTICLE

Decontamination of *Geobacillus Stearothermophilus* using the Arca Aerosolized Hydrogen Peroxide decontamination system

Loren Benjamin Mead ^{1,2*}, Tanner Mathison¹, Garry Osborne¹, Anne Marie Richards¹

1 Abaton, Board of Directors, Washington, D.C, United States of America, **2** Department of Emergency Medicine, University of Texas Health Science Center at Houston, Houston, TX, United States of America

* lmead@abaton.care

Abstract

Introduction

In response to the limited supply of personal protective equipment during the pandemic caused by SARS-CoV-2, recent studies demonstrate that gaseous H_2O_2 is an effective decontaminant of N95 filtering facepiece respirators to enable reuse of these items in a clinical setting. This paper evaluates the efficacy of the Arca Aerosolized Hydrogen Peroxide Decontamination System (Arca), a novel aerosolized H_2O_2 decontamination system, using biologic indicator testing.

Materials and methods

The Arca produces and circulates H_2O_2 aerosol inside of a sealed stainless steel chamber. The Arca's decontamination efficacy was evaluated in 8 decontamination trials with 2 H_2O_2 concentrations (3% and 12%) and 4 decontamination cycle durations (45, 60, 90, and 120 minutes). Efficacy was evaluated by testing: 1) the concentration in parts per million (ppm) of H_2O_2 produced inside the chamber and the concentration in ppm of H_2O_2 vented from the chamber, and 2) the decontamination of Mesa Biologic Indicator filter strips (BI) inoculated with *Geobacillus Stearothermophilus*. Control tests were conducted by submerging BI strips in 3mL of 3% and 12% H_2O_2 for 120 minutes (negative controls) and by not exposing one BI strip to H_2O_2 (positive control).

Results

Greater than 5000 ppm of H_2O_2 was detected on the concentration strips inside the chamber for each of the eight decontamination trials. No vented H_2O_2 was detected on the external concentration strips after any decontamination trial. No growth was observed for any of the negative controls after seven days. The positive control was positive for growth.

Conclusion

The Arca Aerosolized Hydrogen Peroxide Decontamination System is effective at decontaminating bacterial *G. Stearothermophilus* at a cycle time of 45 minutes utilizing 6mL of 3% H_2O_2 solution.

OPEN ACCESS

Citation: Mead LB, Mathison T, Osborne G, Richards AM (2022) Decontamination of *Geobacillus Stearothermophilus* using the Arca Aerosolized Hydrogen Peroxide decontamination system. PLoS ONE 17(9): e0273937. <https://doi.org/10.1371/journal.pone.0273937>

Editor: Peter Setlow, University of Connecticut, UNITED STATES

Received: May 1, 2022

Accepted: August 17, 2022

Published: September 20, 2022

Peer Review History: PLOS recognizes the benefits of transparency in the peer review process; therefore, we enable the publication of all of the content of peer review and author responses alongside final, published articles. The editorial history of this article is available here: <https://doi.org/10.1371/journal.pone.0273937>

Copyright: This is an open access article, free of all copyright, and may be freely reproduced, distributed, transmitted, modified, built upon, or otherwise used by anyone for any lawful purpose. The work is made available under the [Creative Commons CC0](https://creativecommons.org/licenses/by/4.0/) public domain dedication.

Data Availability Statement: The testing results have been published on Dryad at <https://datadryad.org/stash/share/prBqllz7DDyStlxHEBmpo6TWigdv8OyjTi9oViQJqY>

Funding: The Booz Allen Foundation Innovation Fund contributed \$25,000 to Abaton, a non profit corporation for the development and testing of the Arca device, including the research published in this paper. The Booz Allen Foundation is a separate legal entity from Booz Allen Hamilton and it exists as a 501(c)3 with the mission "To be a convening force for the social sector, bringing together thought leaders and diverse perspectives to use innovation and technology advancements to help solve challenging social issues and build community resilience from the ground up". No authors directly received funding from any source, including the Innovation Fund. The Innovation Fund website can be reached at <https://boozallenfoundation.org/innovationfund/>. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors of this publication are members of Abaton's Board of Directors, which could be perceived as a competing interest. However, the authors do not receive a salary or any gifts-in-kind for their service on the Board, and Abaton is a 501(c)3 non profit. The Arca device design has not, nor ever will be submitted for patent. The intention of the authors is to disseminate the design as an open source document for replication in locations where it might be of assistance. The authors further declare that they in no way financially or otherwise benefitted from the grant funding and personal donations made to Abaton. This does not alter our adherence to PLOS ONE policies on sharing data and materials.

Introduction

The SARS-CoV-2 coronavirus (COVID-19) pandemic has caused a worldwide shortage in personal protective equipment (PPE) including N95 filtering facepiece respirator (FFR) and surgical masks. Both mask types have been shown to dramatically reduce the rate of infection by airborne viruses such as influenza, but the masks are designed for single use before disposal [1]. Due to a shortage of FFRs and the critical role FFRs play in protecting health care workers at the outset of the COVID-19 pandemic, the Center for Disease Control recommended limited reuse of decontaminated FFRs to extend supplies of PPE [1,2]. The Occupational Safety and Health Administration has similarly produced guidelines for the limited reuse of FFRs [3].

Aerosolized or vaporized hydrogen peroxide (H_2O_2) is an established reactant for decontaminating surfaces inoculated with resistant bacterial and viral pathogens [4]. Recent studies demonstrate that H_2O_2 delivered in an aerosol or vapor as low as 500 ppm has been shown to achieve 1000 times reductions in viral organism activity on inoculated FFRs while maintaining adequate mask fitment through multiple decontamination cycles [5–8]. Previous work has demonstrated that scalable, proof-of-concept H_2O_2 decontamination systems could achieve adequate minimum concentrations reported in the literature to eradicate Coronavirus and other pathogens [9,10].

To mitigate infection risk with reuse of FFRs, the Food and Drug Administration granted emergency use authorizations (EUs) to several commercially available hydrogen peroxide FFR decontamination procedures [11]. However, the commercially available methods of FFR decontamination are costly and limited in availability [12–14]. The H_2O_2 decontamination methods which received an EUA include those listed in Table 1. The number of maximum decontamination cycles per FFR varies by method with a range of two to 20 cycles [15]. The price per institution for these systems can exceed \$50,000 (Table 1). Low-resource institutions are often unable to access these services and purchase adequate supplies of PPE [16]. Therefore, the development of a smaller-scale, less-costly decontamination devices is warranted.

This study seeks to evaluate the efficacy of a low-cost design engineered for use in low-resource settings to expand the supply of decontaminated PPE for safe re-use by frontline workers. Our objectives were to test the device's efficacy at different H_2O_2 concentrations and Arca device cycle durations by evaluating: 1) the concentration in parts per million (ppm) of H_2O_2 produced inside the chamber and the concentration in ppm of H_2O_2 vented from the chamber, and 2) the decontamination of Mesa Biologic Indicator filter strips (BI) inoculated with 10^6 *Geobacillus Stearothermophilus*.

Table 1. Value Comparison of H_2O_2 decontamination systems with EUs.

Decontamination System	Estimated Annual Cost to Institution	Maximum Decontamination Cycles per FFR
Bioquell Technology System	\$53,000 [17]	4
Battelle Critical Care Decontamination System	\$0 ^a	20
STERRAD Sterilization System	\$149,000 [18]	2
Steriluent HC 80TT Vaporized Hydrogen Peroxide Sterilizer	Not Reported	10
Stryker STERIZONE VP4 Sterilizer for N95 Respirator Decontamination	Not Reported	2
Stryker Sustainability Solutions VHP N95 Respirator Decontamination System	Not Reported	3
Duke Decontamination System	Not Reported	10
Technical Safety Services (TSS) 20-CS Decontamination System	Not Reported	20
Michigan State University Decontamination System	Not Reported	3
Roxby Development Zoe-Ann Decontamination System	Not Reported	4

^aBattelle was awarded a federal contract for subsidized N95 decontamination with costs upwards of \$1 million per system [19].

<https://doi.org/10.1371/journal.pone.0273937.t001>

Materials and methods

The Arca Aerosolized Hydrogen Peroxide Decontamination System (Arca) produces H_2O_2 inside of a sealed stainless steel chamber and circulates the aerosol with four CG IP67 personal computing fans. The Arca uses a Venturi tube design to generate an aerosol: an air compressor forces high velocity air through a tube where the cross-sectional area is reduced with the result of lowering the air pressure (Fig 1). The design lowers the pressure to below 2300 Pa, the vaporization pressure of 10% H_2O_2 in water solution [20]. The H_2O_2 is fed to the low pressure opening of the tube, where the low pressure induces partially vaporization, forming small droplets of solution (i.e. an aerosol). A catch is included at the low pressure point to trap large droplets and recirculate them back to the low-pressure area. FFRs are placed on a wire mesh rack inside the chamber and exposed to the H_2O_2 for decontamination (Fig 2). Circulated H_2O_2 aerosol is removed from the chamber interior using a Speedair 4ZL07 condenser unit to avoid operator exposure when removing decontaminated FFRs (Fig 3). The device's manufacturing and component costs totaled less than \$2,000.

The Arca's decontamination efficacy was evaluated by a testing protocol exposing Mesa-Strip BI filter strips inoculated with 10^6 *G. Stearothermophilus* [22]. We performed a total of 8 trials varying the H_2O_2 concentration (3% and 12%) and decontamination cycle duration (45, 60, 90, and 120 minutes). Decontamination efficacy was evaluated by H_2O_2 concentration and biologic testing within the device chamber and venting system.

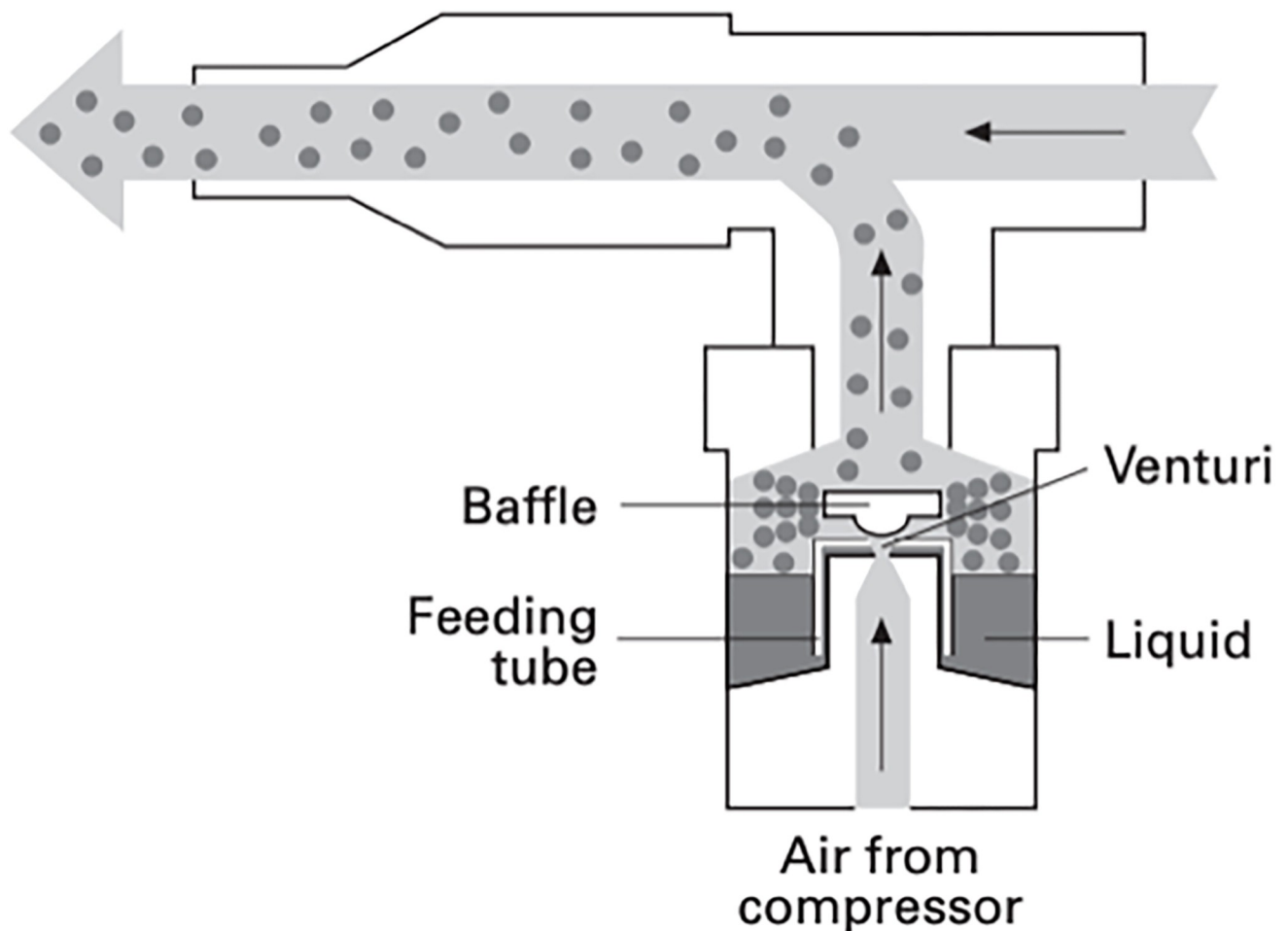


Fig 1. Nebulizer Venturi tube design [21].

<https://doi.org/10.1371/journal.pone.0273937.g001>



Fig 2. Arca interior demonstrating mesh rack, circulating fans, and Venturi tube nozzle.

<https://doi.org/10.1371/journal.pone.0273937.g002>

Concentration testing was performed using Bartovartion Very High Level Peroxide Test Strips, which change color to indicate exposure to H_2O_2 at concentrations from 0 to 5000 ppm [23]. For each trial, one BI was secured with Scotch Magic™ Tape to an FFR located centrally inside the chamber. An additional concentration strip was placed on the exterior of the door and evaluated for vented H_2O_2 from the chamber after each cycle was completed and the door to the chamber opened. All cycles were performed in a well-ventilated area.

Additionally, one BI was submerged in 3 mL of 3% and one in 3 mL of 12% H_2O_2 for 120 minutes each to serve as negative controls. One BI was not exposed to H_2O_2 to serve as a positive control.

The BIs were handled using sterile technique and after testing were shipped in sealed plastic bags to STERIS Laboratories. Sterility testing was performed according to STERIS Laboratories protocol ST/01, in which the BIs were incubated in 10 mL of Tryptic Soy Broth at 55–60 degrees Celsius for seven days. The cultures were evaluated daily and interpreted as “No growth” only if the medium remained clear without color change or turbidity after seven days [24].

Results

Concentration testing

The concentration strips for all decontamination cycles showed internal concentrations of H_2O_2 exceeding 5000 ppm. The exterior concentration strips monitoring for vented H_2O_2 all showed undetectable levels of H_2O_2 (Tables 2 and 3).



Fig 3. Arca exterior showing nebulizer (top), condenser unit (bottom), and electronics housing (left).

<https://doi.org/10.1371/journal.pone.0273937.g003>

Table 2. Concentration strip results for 3% H_2O_2 solution testing.

	45 Minutes Cycle	60 Minutes Cycle	90 Minutes Cycle	120 Minutes Cycle
Internal Strip	>5000 ppm	>5000 ppm	>5000 ppm	>5000 ppm
Exterior Strip	No color change	No color change	No color change	No color change

<https://doi.org/10.1371/journal.pone.0273937.t002>

Table 3. Concentration strip results for 12% H_2O_2 solution testing.

	45 Minutes Cycle	60 Minutes Cycle	90 Minutes Cycle	120 Minutes Cycle
Internal Strip	>5000 ppm	>5000 ppm	>5000 ppm	>5000 ppm
Exterior Strip	No color change	No color change	No color change	No color change

<https://doi.org/10.1371/journal.pone.0273937.t003>

Table 4. BI growth at 7 days following exposure to 3% H_2O_2 solution.

Trial	120 Minutes Submersion	45 Minutes Cycle	60 Minutes Cycle	90 Minutes Cycle	120 Minutes Cycle
Growth Result	No growth	No growth	No growth	No growth	No growth

<https://doi.org/10.1371/journal.pone.0273937.t004>

Table 5. BI growth at 7 days following exposure to 12% H_2O_2 solution.

Trial	120 Minutes Submersion	45 Minutes Cycle	60 Minutes Cycle	90 Minutes Cycle	120 Minutes Cycle
Growth Result	No growth	No growth	No growth	No growth	No growth

<https://doi.org/10.1371/journal.pone.0273937.t005>

Decontamination testing

All BIs exposed to H_2O_2 had no growth at seven days of incubation (Tables 4 and 5). The positive control that was not exposed to H_2O_2 demonstrated bacterial growth.

Discussion

The limited supply of FFRs during the SARS-Cov-2 pandemic endangers health care and other frontline workers. While the FDA and CDC have encouraged the decontamination of FFRs for reuse, existing decontamination systems are inaccessible in low-resource settings. Development of systems designed for deployment in low-resource settings will increase the supply of PPE for at-risk personnel.

This study attempted to evaluate a novel device's ability to eradicate bacterial pathogens from the surface of an FFR without exposing users to unsafe levels of H_2O_2 . Our testing demonstrates that the novel Arca device can decontaminate bacterial pathogens without exposing users to high concentrations of H_2O_2 . These results are consistent with the literature on existing gaseous H_2O_2 technologies. The eradication of bacteria achieved at every trial suggests that the Arca could achieve adequate decontamination with a lower concentration H_2O_2 solution, a shorter cycle duration, or a smaller volume of H_2O_2 . Based on previously reported H_2O_2 testing, the bactericidal properties of the device suggest virucidal efficacy as well [9,25].

The Arca has a throughput of 16 FFRs per cycle, with a daily output of up to 512 FFRs. The marginal cost to clean each additional FFR is significantly less than \$1, as operating expenses include small volumes of widely available concentrations of H_2O_2 and the variable cost of electricity to power the device. The Arca's production cost at less than \$2,000 per unit is significantly lower than the price of existing commercially available solutions. At scale, this manufacturing cost should decrease. These devices are intended to be donated at no cost to

recipient institutions, therefore the operating expenses are the only costs passed on to end users. Future iterations of the device could reduce costs further by using more off-the-shelf components in its manufacturing process. The decreased cost of the Arca improves its accessibility in low-resource settings compared with existing FFR decontamination systems.

Limitations

The sterility testing performed on the BI strips resulted in a binary “No growth” or “Growth” outcome, and did not demonstrate log kill rates. Therefore, it is possible that small populations of bacteria survived decontamination cycles but did not change the TSB medium’s turbidity. However, the same testing methodology is used as part of quality assurance testing to assess sterility achieved by FDA-approved devices, with an industry standard sterility assurance level (SAL) of 10^{-6} . The FDA requires only an SAL of 10^{-3} for products that contact intact skin [26].

Testing was performed under optimal conditions using a single FFR. Real world use may lead to decreased efficacy due to variations in power supply to the Arca, increased pathogen burden, or greater surface area of multiple FFRs. Additionally, while bacteria are considered more resistant to H_2O_2 than viruses, the eradication of this study’s BIs may not be generalizable to all mutations of SARS-CoV-2.

Future directions

Experimental derivation of the absolute minimum cycle duration, volume of H_2O_2 , and percent H_2O_2 solution to achieve decontamination will allow for greater throughput of the Arca device. Testing in a BSL-3 lab will evaluate the Arca’s efficacy at decontamination of SARS-CoV-2 and other pathogens directly inoculated on PPE.

Fitment testing of FFRs after decontamination will allow for experimental derivation of the maximum decontamination cycles per FFR. Additional testing of other PPE and various equipment may expand the use cases for the Arca.

Additionally, “real world” field testing will help to determine any potential causes of diminished aerosol concentration, inadequate decontamination, or non-optimal user experience.

Conclusion

The Arca Aerosolized Hydrogen Peroxide Decontamination System can safely decontaminate FFRs inoculated with bacteria using a minimum cycle time of 45 minutes with 6 mL of H_2O_2 solution.

Acknowledgments

We would like to acknowledge the tireless work of our systems engineers, Garry Osborne and Keith Crowder, as well as our head of business development, Michael Mazza. Without their constant support, the Arca would have been neither built nor tested. Our acknowledgements would not be complete without thanking Dr. Sarah Huepenbecker and Natalie Punchak for their sage advice and emotional support.

Author Contributions

Conceptualization: Loren Benjamin Mead, Tanner Mathison.

Data curation: Tanner Mathison, Garry Osborne, Anne Marie Richards.

Funding acquisition: Tanner Mathison.

Investigation: Loren Benjamin Mead, Tanner Mathison.

Methodology: Loren Benjamin Mead, Tanner Mathison, Garry Osborne, Anne Marie Richards.

Project administration: Loren Benjamin Mead, Tanner Mathison.

Supervision: Loren Benjamin Mead, Tanner Mathison.

Validation: Loren Benjamin Mead.

Writing – original draft: Loren Benjamin Mead.

Writing – review & editing: Tanner Mathison, Anne Marie Richards.

References

1. Apr 03 RR], 2012. Lab study supports use of N95 respirators for flu protection [Internet]. CIDRAP. [cited 2020 Jun 14]. Available from: <https://www.cidrap.umn.edu/news-perspective/2012/04/lab-study-supports-use-n95-respirators-flu-protection>.
2. Recommended Guidance for Extended Use and Limited Reuse of N95 Filtering Facepiece Respirators in Healthcare Settings | NIOSH | CDC [Internet]. 2020 [cited 2020 Jun 28]. Available from: <https://www.cdc.gov/niosh/topics/hcwcontrols/recommendedguidanceextuse.html>.
3. Enforcement Guidance for Respiratory Protection and the N95 Shortage Due to the Coronavirus Disease 2019 (COVID-19) Pandemic | Occupational Safety and Health Administration [Internet]. [cited 2021 Jan 11]. Available from: <https://www.osha.gov/memos/2020-04-03/enforcement-guidance-respiratory-protection-and-n95-shortage-due-coronavirus>.
4. Chemical Disinfectants | Disinfection & Sterilization Guidelines | Guidelines Library | Infection Control | CDC [Internet]. 2019 [cited 2021 Jan 11]. Available from: <https://www.cdc.gov/infectioncontrol/guidelines/disinfection/disinfection-methods/chemical.html>.
5. Technical Report for Hydrogen Peroxide Methods for Decontaminating N95 Respirators [Internet]. [cited 2020 Jun 28]. Available from: https://static1.squarespace.com/static/5e8126f89327941b9453eeef/t/5ed525e43bb86f3745a1ded6/1591027172069/2020-05-29_N95DECON_HydrogenPeroxide_V2-1_TechnicalReport_FINAL.pdf.
6. Viscusi DJ, Bergman MS, Eimer BC, Shaffer RE. Evaluation of Five Decontamination Methods for Filtering Facepiece Respirators. *Ann Occup Hyg*. 2009 Nov; 53(8):815–27. <https://doi.org/10.1093/annhyg/mep070> PMID: 19805391
7. Polkinghorne A, Branley J. Evidence for decontamination of single-use filtering facepiece respirators. *J Hosp Infect* [Internet]. 2020 May 27 [cited 2020 Jun 30]; Available from: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7251398/>. <https://doi.org/10.1016/j.jhin.2020.05.032> PMID: 32473179
8. Schwartz A, Stiegel M, Greeson N, Vogel A, Thomann W, Brown M, et al. Decontamination and Reuse of N95 Respirators with Hydrogen Peroxide Equipment to Address Worldwide Personal Protective Equipment Shortages During the SARS-CoV-2 (COVID-19) Pandemic. *Appl Biosaf*. 2020 Jun; 25(2):67–70. <https://doi.org/10.1177/1535676020919932> PMID: 36035079
9. Cheng VCC, Wong SC, Kwan GSW, Hui WT, Yuen KY. Disinfection of N95 respirators by ionized hydrogen peroxide during pandemic coronavirus disease 2019 (COVID-19) due to SARS-CoV-2. *J Hosp Infect*. 2020 Jun 1; 105(2):358–9. <https://doi.org/10.1016/j.jhin.2020.04.003> PMID: 32277965
10. Grossman J, Pierce A, Mody J, Gagne J, Sykora C, Sayood S, et al. Institution of a Novel Process for N95 Respirator Disinfection with Vaporized Hydrogen Peroxide in the Setting of the COVID-19 Pandemic at a Large Academic Medical Center. *J Am Coll Surg*. 2020 Aug 1; 231(2):275–80. <https://doi.org/10.1016/j.jamcollsurg.2020.04.029> PMID: 32353399
11. Health C for D and R. Emergency Use Authorizations. FDA [Internet]. 2020 Jun 7 [cited 2020 Jun 7]; Available from: <https://www.fda.gov/medical-devices/emergency-situations-medical-devices/emergency-use-authorizations>.
12. Battelle CCDS for COVID19—Satellite Locations [Internet]. Battelle. [cited 2020 Jun 28]. Available from: <https://www.battelle.org/inb/battelle-ccds-for-covid19-satellite-locations>.
13. SteraMist [Internet]. Engineering For Change. [cited 2020 Jun 28]. Available from: <https://www.engineeringforchange.org/solutions/product/steramist/>.
14. DOD Contract for 60 N95 Critical Care Decontamination Units: \$415M Contract, Each Unit Can [Internet]. U.S. DEPARTMENT OF DEFENSE. [cited 2020 Jun 30]. Available from: <https://www.defense>.

[gov/Newsroom/Releases/Release/Article/2148352/dod-contract-for-60-n95-critical-care-decontamination-units-415m-contract-each/](https://www.fda.gov/Newsroom/Releases/Release/Article/2148352/dod-contract-for-60-n95-critical-care-decontamination-units-415m-contract-each/).

15. Guide to decontamination methods for filtering facepiece respirators [Internet]. [cited 2021 Jan 11]. Available from: <https://www.vizientinc.com/covid-19/covid-19-ffr-decontamination-methods#summary>.
16. McMahon DE, Peters GA, Ivers LC, Freeman EE. Global resource shortages during COVID-19: Bad news for low-income countries. *PLoS Negl Trop Dis*. 2020 Jul 6; 14(7):e0008412. <https://doi.org/10.1371/journal.pntd.0008412> PMID: 32628664
17. Portable Ambulance Decontamination Systems Market Survey Report. 24.
18. McCreanor V, Graves N. An economic analysis of the benefits of sterilizing medical instruments in low-temperature systems instead of steam. *Am J Infect Control*. 2017 Jul 1; 45(7):756–60. <https://doi.org/10.1016/j.ajic.2017.02.026> PMID: 28365144
19. Battelle under fire for decontamination system performance [Internet]. MassDevice. 2020 [cited 2021 Jan 11]. Available from: <https://www.massdevice.com/battelle-under-fire-for-decontamination-system-performance/>.
20. Vapor Pressures | USP Technologies [Internet]. [cited 2022 Mar 26]. Available from: <https://www.h2o2.com/technical-library/physical-chemical-properties/physical-properties/default.aspx?pid=25&name=Vapor-Pressures>.
21. O'Callaghan C, Barry PW. The science of nebulised drug delivery. *Thorax*. 1997 Apr 1; 52(Supplement 2):S31–44. <https://doi.org/10.1136/thx.52.2008.s31> PMID: 9155849
22. Spore Strip Steam—Technical Report.pdf [Internet]. [cited 2021 Jan 11]. Available from: <https://info.mesalabs.com/hubfs/1.%20Sterilization%20and%20Disinfection%20Control/Website/Technical%20Reports/Spore%20Strip%20Steam%20-%20Technical%20Report.pdf>.
23. Very High Level Peroxide Test Strips, 0–5000 ppm [Vial of 50 Strips] | Bartovation Test Strips [Internet]. [cited 2020 Jun 30]. Available from: <https://bartovation.com/product/disinfectants-sanitizers/peroxide/high-level-peroxide-500-5000ppm-for-concentrated-h2o2-solutions-50-strips/>.
24. Form-14-Guide-to-Testing-Services.pdf [Internet]. [cited 2022 Jul 30]. Available from: <https://www.steris-ast.com/wp-content/uploads/2020/02/Form-14-Guide-to-Testing-Services.pdf>.
25. Tuladhar E, Terpstra P, Koopmans M, Duizer E. Virucidal efficacy of hydrogen peroxide vapour disinfection. *J Hosp Infect*. 2012 Feb 1; 80(2):110–5. <https://doi.org/10.1016/j.jhin.2011.10.012> PMID: 22153909
26. Sterility Review of 510(k) Submissions: Common Microbiology Issues Found in 510(k) Submissions [Internet]. [cited 2022 Jul 30]. Available from: <https://www.fda.gov/media/141277/download>.