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Review

The personal protective equipment fabricated via 3D printing technology during COVID-19



Raj Agarwal

Mechanical Engineering Department, Thapar Institute of Engineering and Technology Patiala, Punjab 147004, India

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ABSTRACT

COVID-19 has been spread in more than 220 countries and caused global health concerns. The supply chain disruptions have abruptly affected due to the second wave of COVID-19 in various countries and caused unavailability and shortage of medical devices and personal protective equipment for frontline healthcare workers. Three-dimensional (3D) printing has proven to be a boon and revolutionized technology to supply medical devices and tackle the situation caused by the COVID-19 pandemic. The diverse designs were produced and are currently used in hospitals by patients and frontline healthcare doctors. This review summarises the application of 3D printing during COVID-19. It collects the comprehensive information of recently designed and fabricated protective equipment like nasopharyngeal swabs, valves, face shields, facemasks and many more medical devices. The drawbacks and future challenges of 3D printed medical devices and protective equipment is discussed.

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1. Introduction

The novel coronavirus disease 2019 (COVID-19) was first identified in December 2019 in Wuhan, China. After a few months, this disease has been spread worldwide very fast and speedily [1]. At present, COVID-19 is a global health concern and is distributed in more than 220 countries. The worst affected countries include the United States, India, Brazil, Russia and many more. A total of 261,810,035 cases and more than 5218,374 deaths across the globe have been reported due to COVID-19 till 29th November 2021. The official name of the currently spreading virus is severe acute respiratory syndrome coronavirus-2 (SARS-COV2), and the caused disease is COVID-19 [2]. The symptoms of COVID-19 infection seem to start after 5 to 6 days [3]. This interval of time may vary depending upon the patient's immune system and age. It spreads through human droplets during sneezing or speaking, aerosol, direct or indirect physical contact through contaminated surfaces [3]. The virus may cause shortness of breath, sore throat, sense of smell, and loss of appetite and taste [2,3]. Once the virus is entered into the human body's cells, it starts producing a replica of itself and potentially invading more and more cells.

Nearly 80,000 to 180,000 health workers and doctors were died due to deadly virus and lack of protective equipment between January 2020 and May 2021 [4]. Medical devices and protective

equipment play a significant role in the safety and protection of doctors and patients. According to World Health Organization (WHO) prediction, approximately 89 million medical masks, 76 million gloves, 30 million gowns, and 1.59 million goggles are essentially required every month for the COVID-19 response [5]. Moreover, it is expected that the medical supplies market to increase by \$22 billion by 2021 in comparison to 2019 [6]. The virus-spreading ratio is leading to overload to health systems around the world. The sudden increase in the number of patients causes a supply chain disruption. It generates a shortage of personal protection equipment (PPE) and medical devices in hospitals for doctors and patients [7,8]. Several countries lack PPE due to insufficient anticipation, national lockdowns and poor manufacturing capacity [9]. At the same time, three-dimensional (3D) printing is explored as a point of interest to various medical institutions, design engineers and researchers. 3D printing is the process of constructing an object in three dimensions from a computer-aided design (CAD) model and are built-in layer-by-layer format [9,10]. 3D printers can print any complex structure, detailed 3D construction and accurate physical replicate of the model. These unique benefits have allowed for the adaptation of this technique in different domains and diverse applications of fabricating various medical devices and protective equipment [11–13]. 3D printing uses an extensive range of materials for part fabrication. Majorly used materials in different techniques are polymers, metals and ceramics. These materials have specific mechanical and material properties, chemical and thermal properties, various processing methods, cell-material interactions, and FDA approval [14].

E-mail address: agarwal.raj.gama@gmail.com

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3D printing technology advances to solve this challenge by prototyping quickly and iterating on designs for the fabrication of different medical devices and protective equipment to supply to doctors and medical staff, patients, and people facing the shortage of PPE and medical devices [16,17]. The potential of 3D printing helps for the fabrication of various protective equipment. The primary reason for using this technology is the ease of printing complex parts with less time than traditional subtractive manufacturing [18]. It has an almost negligible lead-time for distributing a small batch of parts. Therefore, 3D printing plays a vital role in fabricating emergency items during the COVID-19 pandemic in need of medical devices. The crucial demand of these medical devices is responsible for the spread of this dangerous virus. Therefore, the focus of this study is to provide a holistic review of medical devices and protective equipment fabricated using 3D printing. Additionally, the recent developments in medical devices and protective equipment with the help of 3D printing is attentively focused on future design engineers, doctors, medical practitioners and researchers.

2. 3D- printed models for training and education

The 3D printing technology can fabricate any complex geometry with ease of comfort and provides freedom of imagination. One of the essential applications of 3D printing is that the COVID-19 model can be manufactured for training and education purposes. Therefore, the capability of 3D printing is utilized to fabricate the COVID-19 replica model. Fig. 1 represents the solid visual model manufactured via 3D printing technology. The model explores the protein and spikes of the virus. Fig. 1(a) shows the fabricated part and the support structure fabricated via fused deposition modeling based on 3D printing technology. In contrast, the post-processed model replicating the virus is presented in Fig. 1(b). These models are advantageous and helpful for future researchers, doctors and medical professionals to understand the complex replica to improve surgical planning, diagnosis, treatment and patient education.

3. Protective equipment fabricated via 3D printing

During the COVID-19 pandemic, the potential of 3D printing technology for fabricating specific medical devices and PPE has been observed and reviewed, as presented in Table 1. This section discusses the diversified solutions manufactured with the help of 3D

Table 1

Medical devices and PPE fabricated using 3D printing techniques.

S. No.	Item	3D printing techniques	Refs.
1.	Facemasks	FDM, SLS	[15,24,25]
2.	Face-shield	FDM	[26–28]
3.	Respiratory valves	FDM, SLA	[19,29]
4.	Antimicrobial mask	FDM	[30,31]
5.	N95 respirators similar	FDM	[29,32]
6.	Nasopharyngeal swabs	FDM, SLA, SLS	[33–35]
7.	Surgery mask	FDM	[29]
8.	Hands-free devices	FDM, SLA	[36,37]
9.	Safety goggles	FDM, SLS	[29]
10.	Isolation wards	Not specified	[38]
11.	Mask fitter	FDM	[27]
12.	Ear saver	FDM	[39,40]
13.	Isolation chambers	Not specified	[38]
14.	Field Respirators	Not specified	[41]
15.	Educational model	FDM	[29]
16.	Snorkel mask	FDM	[24,42]
17.	Ventilation devices	FDM	[43]
18.	Air-purifying respirators	Not specified	[44]

*FDM- fused deposition modeling, SLA- Stereolithography, SLS- Selective laser sintering.

printing to fight the lack and shortage of PPE and medical devices. PPE are furthermost manufactured devices during the COVID-19 pandemic due to their simplicity and low geometrical tolerance requirements. PPE include face shields, medical protective facemasks, goggles, gloves, surgical hood, outer apron and powered air-purifying respirator [19–23]. Out of these PPEs, facemask and face shield are considered mandatory for medical frontiers for protecting themselves from the COVID-19 virus. 3D printing is explored for the fabrication of unique and innovative facemasks and face shields.

3.1. Nasopharyngeal (NP) swabs

Nasal swabs and NP swabs are the precise and safest procedure used for collecting a sample of patients for diagnosis of COVID-19. Cox and Koepsell [33] used 3D printing to fabricate custom-made Nasal swabs to supply the shortage of NP swabs. The 3D printed NP swabs and their photomicrograph of air-dried stained cells was collected through the corresponding swab, as depicted in Fig. 2(a) and (b). Callahan et al. [34] validated the use of multiple 3D printed NP swabs to collect high-sensitivity virological testing samples for the

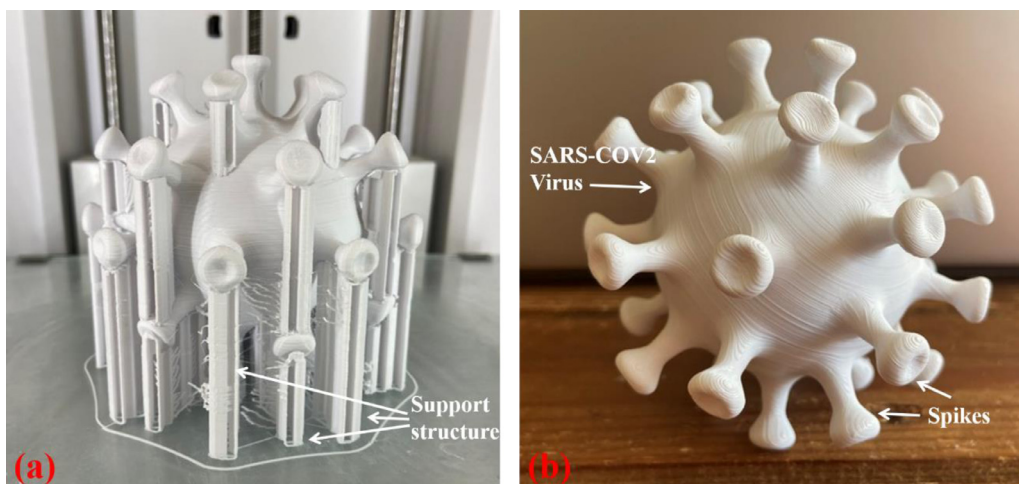


Fig. 1. (a) 3D-printed COVID-19 model with support structure, (b) appropriate spikes and geometry of the model.

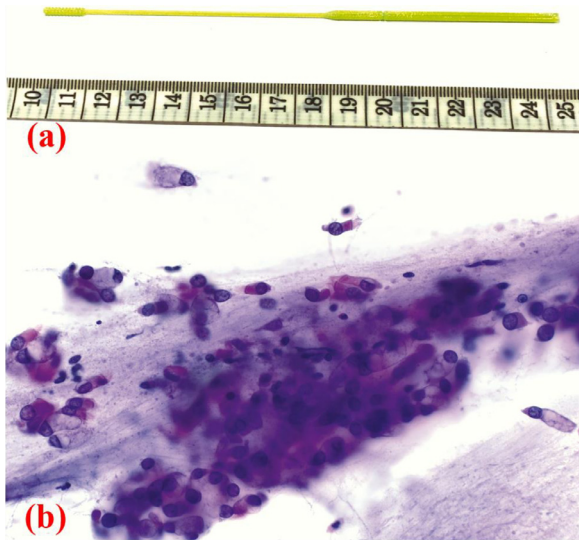


Fig. 2. (a) 3D printed Nasopharyngeal swabs, (b) photomicrograph of air-dried stained cells collected using 3D printed swab [Reprinted with permission [33]].

COVID-19 virus clinically. The innovative, cooperative, rapid-response NP swabs were produced with the help of 3D printing.

3.2. Facemasks

In the critical situation of the COVID-19 pandemic, a crucial lack of facemasks is provided with the help of 3D printing technology. Wearing facemasks is as essential in public as breathing in the public area, as it corresponds to the supreme effective way to prevent inter-human transmission [15]. 3D printing provides the freedom of customized 3D protective facemask. The custom 3D protective facemask consists of 3D-printed reusable components and filter membrane support, as presented in Fig. 3(a) and (b), respectively. These components can be assembled with a changeable non-woven particle filter

as depicted in Fig. 3(c) and (d), respectively. The surgeon who wears disposables surgical masks can be reduced with the help of this customized 3D protective facemask, as shown in Fig. 3(e) and (h). Moreover, the reusable cartridge filled between the facemask can be 3D printed, as illustrated in Fig. 4(a) and (b).

3.3. Face-shields

Face shields are mainly used in medical, dental and veterinary domains to provide the coverage of the entire face for protection [39,46]. The face shield is a head-worn frame that covers an individual's eyes, nose, and mouth to prevent and protect against respiratory droplets, inhalation of saliva, dust, and pollen [47]. The frame in a face shield is simple geometry that can easily be fabricated with the help of 3D printing [39]. Delbarre et al. [48] used 3D printing to fabricate shields for slit lamps during the COVID-19 pandemic. Fused deposition modeling (FDM) based 3D printing is used to fabricate face-shield as depicted in Fig. 5(a) [49]. 3D printed face shields contain a 3D-printed headband, a shield and an elastic strap, as presented in Fig. 5(b) [49]. The face shield frame was fabricated using 3D printing technology utilizing PLA material, as depicted in Fig. 6(a) [26]. The transparent film is assembled in the face-shield frame, and the completed face-shield prototype and protection usage by the surgeon is depicted in Fig. 6(b) and (c) [26].

3.4. Respiratory valves

Respiratory valves are the essentials needed part of ventilator breathing machines. Inappropriately, due to the high demand of scale and supply chain disruptions caused due to COVID-19, innovates the fabrication of respiratory valves via 3D printing technology [50]. Moreover, the connector connected to the breathing devices can be 3D printed [51]. The application of the original respiratory valve and the 3D-printed respiratory valve is exactly similar [52]. Based on the success of the 3D-printed respiratory valve, the number of 3D-printed respiratory valves were fabricated in Italy, as shown in Fig. 7



Fig. 3. (a) reusable 3D-printed facemask, (b) filter support; (c) polypropylene particle filter and (d) facemask prototype 3D image, (e) surgical facemask, (f) FFP2 facemask, (g) 3D facial, (h) 3D-printed facemask [Permission not required as per journal policy [15]].

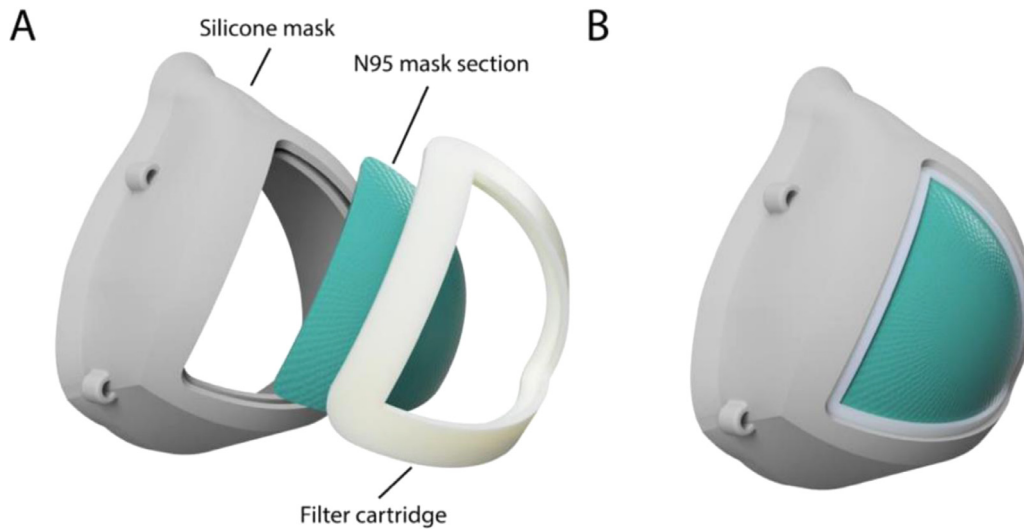


Fig. 4. (a) 3D printed cartridge filter, (b) front view of mask [Permission not required as per journal policy [45]].

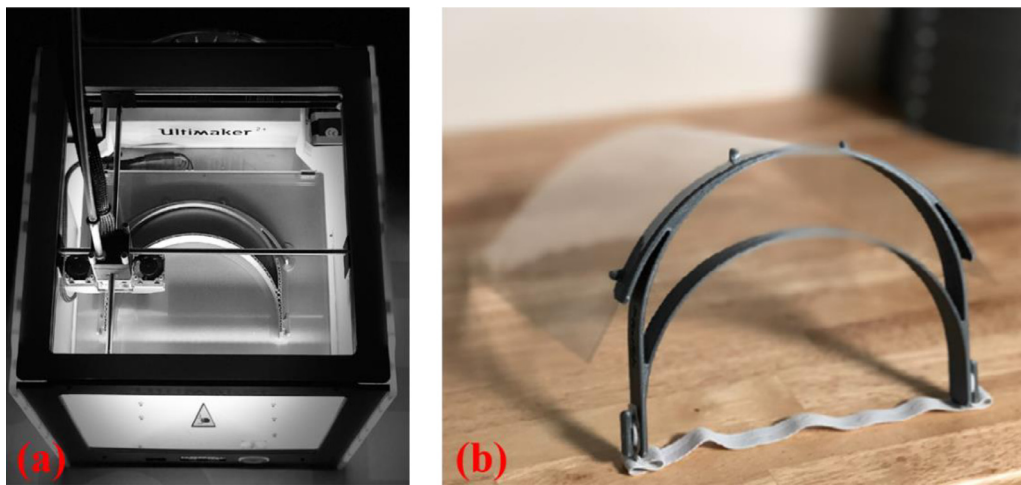


Fig. 5. (a) 3D-printing of the headband by FDM, (b) 2-arches 3D-printed headband face-shield [Reprinted with permission[49].

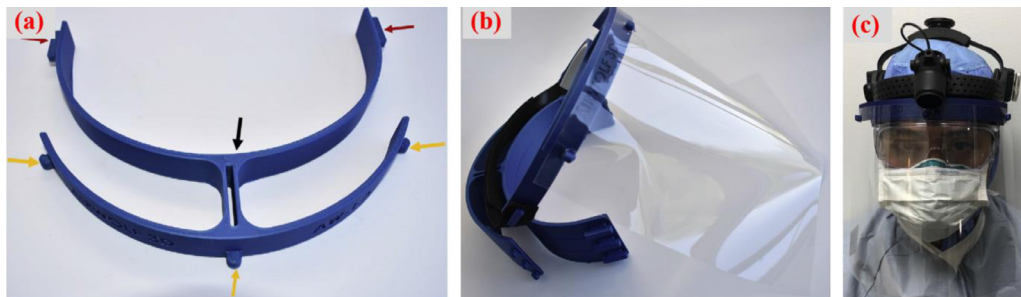


Fig. 6. (a) 3D printed fame of face-shield, (b) assembled face-shield prototype, (c) surgeon wearing 3D printed face-shield [Reprinted with permission [26].



Fig. 7. Respiratory valves developed for Italian hospitals [Reprinted with permission [19].

[19]. Patients and doctors at hospitals currently use these 3D-printed respiratory valves.

3.5. Field respirators

Full-face respiratory protective devices are required in the specific work zones where a patient has respiratory symptoms and when handling the bodies of deceased suspected patients (death due to COVID-19). A field respirator is a device that is used for short-term emergency ventilation. These respirators are designed to guard patients against inhaling hazardous airborne microorganisms. The field respirators help the wearer breathe easily by letting air out and preventing the humidity inside. Petsiuk et al. [41] developed a fully open portable bag-valve mask-based ventilator compression system via 3D printing technology. This automated ventilator can be provided as a temporary emergency ventilator.

4. Potential application and drawbacks of 3D printed devices

The foremost disadvantage of polymer usage in 3D printing during several applications like masks and valves is that the COVID-19 virus might present in the fabricated part as the SARS-CoV-2 virus can stay at surfaces at high stability (up to 72 h) [53]. The solution to this problem lies in using several metallic coatings or doping nanoparticles into polymers [29]. The bioactive polymers can be developed by doping and coating several metals like copper and silver, with antimicrobial characteristics [31]. The manufacturing process with antimicrobial polymers for antimicrobial medical devices can be achieved by using copper nanocomposite additives to mix recycled material in a pallet that might provide antimicrobial PLA filament. Copper and copper oxide additives are proven to offer antimicrobial

characteristics to the polymer. Borkow et al. [30] presented that doping of a face mask with copper and copper oxide nanoparticles decrease the hazard of virus contamination. The 3D printing technology can fabricate facemasks with anti-viral agents coating that can attack the virus once the virus particles are exposed.

The country lockdowns, quarantine of patients and doctors may tremendously affect the conventional production chain and distribution systems. For this, 3D printing is the most innovative, adaptive and versatile production technology to support the supply chain distribution with strong collaboration among countries. Currently, 3D printing is used for fabricating various medical devices and equipment, as presented in Fig. 8. As it is a relatively new technology, 3D printing did not reach its full potential. New materials in polymers, metals, ceramics, and composites classes are being developed and are opening new applications. Bioprinting, a variant technology of 3D printing, promises to produce organs and tissues in the future and can currently create 3D in vitro models that help researchers understand disease spread in tissues and speed up the development of specific drugs. Finally, the 3D printing technology fabricates the part in a layer-by-layer format that summed to manufacture complex parts with ease, along with its freedom of design, correlate with innovative designs.

5. Conclusion

The COVID-19 pandemic is spreading very rapidly as it is caused due to breathing in an airborne virus. COVID-19 has affected the human lives, gross domestic product of countries, economic growth and suddenly amplified the demand for medical devices and protective equipment. It triggered the supply chain disruptions and created a shortage of PPE and medical devices for doctors, medical practitioners and patients.

The 3D printing technology has emerged as a preferable solution for fabricating medical devices and protective equipment to provide supply chain disruption caused due to COVID-19 pandemic. 3D printing is an innovative technique known to construct any complex parts with ease and comfort. This technique is currently used to provide the demand for necessary medical devices and protective equipment. This technique gives the freedom of imagination to fabricate any complex geometry with accuracy. 3D printing is recognized as the solution for supplying the shortage of medical devices and protective equipment during the COVID-19 pandemic. The witnessed and established medical devices and PPE with the help of 3D printing are face-masks, face-shield, respiratory valves, antimicrobial masks, nasopharyngeal swabs, surgery masks, hands-free devices, safety goggles, isolation wards, ear saver, isolation chambers, field Respirators and COVID-19 models for educational purposes. Therefore, 3D printed protective equipment and medical devices might be helpful



Fig. 8. Application of 3D printing technology for fabrication of PPE.

for doctors, medical practitioners and patients to save their lives from this deadly dangerous virus.

Declaration of Competing Interest

The author declares no conflict of interest.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.stlm.2021.100042](https://doi.org/10.1016/j.stlm.2021.100042).

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