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REVIEW

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Impact of 3D printed medical equipment on the management of the Covid19 pandemic

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Summary

Very high mortality rates of coronavirus pandemic (COVID-19) are observed around the world due to lack of medical equipment. The increased need for medical devices and personal protective equipment (PPE) has kept several healthcare professionals at risk. Fortunately, 3D printing technology allows to overcome the lack of medical supplies. This study highlights the impact of 3D printing on the combat against COVID19, and its importance in the medical product supply chain. Indeed, the existing medical equipment fabricated by 3D printing technology and its role in the management of Covid19 pandemic is presented. Moreover, the last works are examined to know whether the models of the medical equipment are free of use and whether useful informations are presented (eg, available design data and setup guidelines).

KEYWORDS

3D printing, COVID-19, medical equipment, pandemic

1 | INTRODUCTION

Pandemic diseases that propagate around a large region of the world, like the 2009 flu pandemic (H1N1) and the 1918 influenza pandemic, grow to be a difficult task to medical resources worldwide. The present 2019 coronavirus disease (COVID-19) becomes a danger to the public at the international level.[1-3] The COVID-19 is carried mainly through connection with an infected person, through droplets that are made when the individual coughs or sneezes, or through tiny droplets from the saliva or even the nasal cavity.[4] The human respiratory system is targeted by the coronavirus.[4] Simple actions such as individual hand cleaning and social distancing are important. However, based on World Health Organization guidelines,[5] a protective material is necessary for all medical services. With the number of cases confirmed each day, the available medical equipment cannot support the volume of patients.[6] Then, the medical product supply chain is disrupted. Thus, people die because of lack of some equipment such as ventilators and protective masks.[7-9]

The existing medical system is based on private equipment from suppliers. Generally, most of the medical equipment is patented by medical firms.[10,11] In the case of a sudden surge in demand, suppliers are unable to prepare the necessary quantity of equipment: innovation and new manufacturing strategies are needed. Moreover, transport and trade restrictions, quarantines, border controls, and production disruptions greatly affect the global supply chain of critical medical devices. Fortunately, 3D printing technology can be an effective solution to overcome this problem.[12,13] Using this technology, the developed open-source designs of medical equipment are shared freely.[14-16] Then, other people around the world can reproduce the medical equipment on their 3D printers.[17-19] The most commonly used 3D printers are desktop 3D printers based on fused deposition modeling (FDM) technology.[20] Generally, these types of 3D printers are not fast when creating parts. But, by using all the existing 3D printers, the production capacity increases significantly. In recent weeks, the national governments around the world have called industry, scientific, and makers to develop and produce more personal protective equipment. With a 3D printer and the necessary material, everybody can be a part of the "citizen supply chain". The designs of personal protective equipment (PPE) are shared for free by the maker community.

The goal of this study is to present the role of 3D printing to fight against the COVID-19 pandemic. Also, the impact of 3D printed medical equipment on the medical product supply chain is analyzed. The existing designs for medical equipment are summarized. It analyzes previous works to determine whether the designs are open source and whether practical details are provided, which include accessible design source files (eg, computer-aided design, CAD), production files (eg, Surface Tessellation Language, STL) and assembly instructions.

2 | MANAGEMENT OF PERSONAL PROTECTIVE EQUIPMENT (PPE)

Quarantine procedures in the particular situation of this specific pandemic have started to give stress and worry between people. A regrettable result of this is the unnecessary anxiety buying, causing those individuals who need PPE products, such as healthcare workers, within restricted supply. Then, people from the 3D printing community have developed a variety of reusable PPE products using low-cost desktop 3D printers, such as N95 masks, surgical masks, face shields, and Controlled Air Purifying Respirator (CAPR) system. In a local context, the user must employ adequate sterilization techniques for the PPE devices.

2.1 | Protective masks

The protective mask is a medical device aimed to filter bacteria and to avoid contracting a virus. These masks must be worn by the general public to protect themselves from microorganisms in the pandemic context. Since the beginning of COVID 19, the problem of supplying a protective mask has become one of the main challenges to overcome.[21] Several initiatives are taking place to remedy these deficiencies around the world. In all situations, the end customers must plainly recognize that only prototypes are obtainable at this stage and local test techniques are important to evaluate the quality of the protective mask.

Swennen et al[22] have presented a procedure to produce 3D printed personalized masks using available methods and materials. The authors have shared the design of this mask for free of charge. A 3D printed reusable N95 comparable respirator was developed by Provenzano et al[23] at the George Washington University. These masks can be used with multiple filtration units, easy to produce and easy to clean. The 3D model is available upon request. Chagas et al[24] summarize several open source projects to fabricate personal protective equipment and the developed approaches in COVID-19 diagnostics. Students at Cedarville University have printed 3D masks for healthcare workers.[25]

FIGURE 1 Copper3D NanoHack mask model. Left: flat part. Right: final 3D configuration [Colour figure can be viewed at wileyonlinelibrary.com]

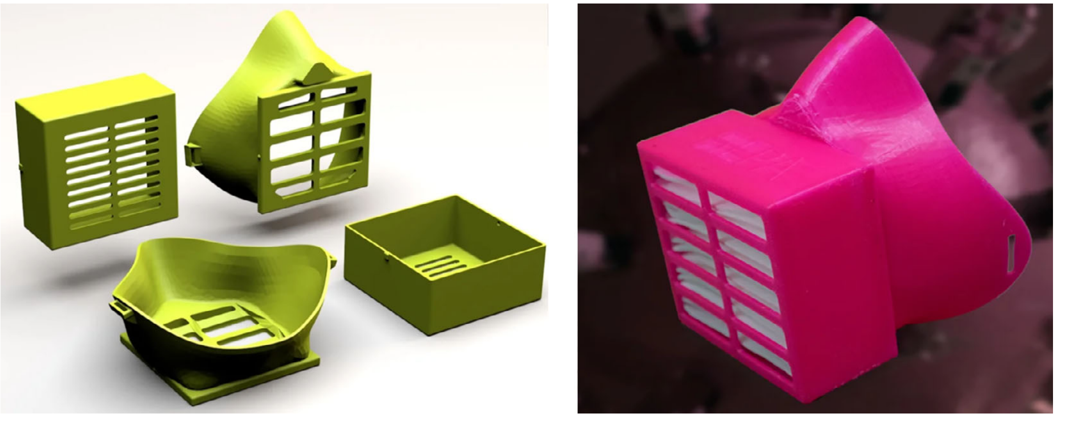

FIGURE 2 HEPA mask model, left. A 3D printed model of this mask, right [Colour figure can be viewed at wileyonlinelibrary.com]

The project NANOHACK was launched by the manufacturer, Copper 3D, to produce the model N95 of protective mask using 3D printing technology.[26] A new version of the project NANOHACK 2.0 was published. It is an improved version that protects against the COVID-19 infection. The production files (STL) are provided for free of charge. Polylactic Acid (PLA) filament can be used to fabricate this mask as a flat part. Therefore, it is designed to be manually assembled into the final 3D configuration after heating to a temperature of 55°C to 60°C (Figure 1).

Another design of the protective mask was developed by the Thingiverse user Kvatthro.[27] Moreover, this mask can be produced using a desktop 3D printer and PLA filament. It is designed with a box for HEPA filter insertion (Figure 2). The Chinese company, Creality, suggested a similar style of the HEPA mask with different arrangements of the filter container,[28] that allows to insert folded fabric or filters (Figure 3).

2.2 | Face shields

During the Covid19 pandemic, a face shield was designed and fabricated using 3D printing. It contains a 3D printable headpiece and an attachable transparent sheet of plastic. This device protects the user's eyes and mouth (Figure 4).

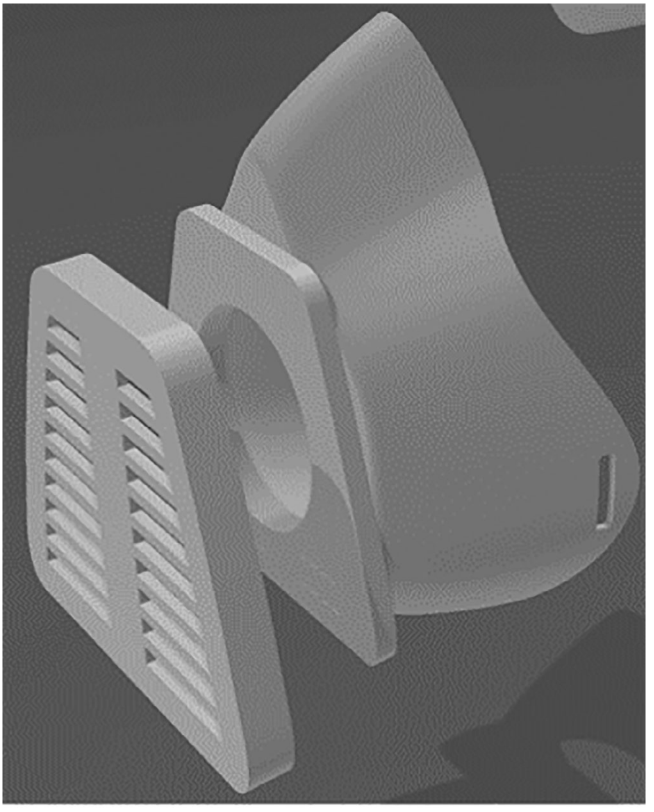

FIGURE 3 Creality mask

Table 1 summarizes the different PPE that has been fabricated using 3D printing technology during the COVID19 pandemic. It is noticed that the 3D printed PPE must be approved by a regulatory body.[30] Most PPE is difficult to sterilize. However, several studies were conducted to investigate the insertion of drug molecules in the PPE during fabrication to offer an antimicrobial and antiviral protection.[31-34] A non-exhaustive list of open-source medical devices for COVID-19 is given in Table 2. The link to download the STL files is also given.

3 | VENTILATOR SYSTEMS AND ITS COMPONENTS

The ventilation system helps patients to maintain an adequate level of oxygen (>88%) in the arterial blood.[36] Ventilation system is the last hope for the majority of patients most affected by the new coronavirus "Covid-19." Most of the national health systems do not have the needed ventilation systems that the Covid-19 pandemic is believed to require. This situation forced the doctors to make a difficult decision regarding the patients: who should be connected to these devices and who will be disconnected from them.

Since the appearance of COVID-19 pandemic, local and international communities have been working together to develop an open-source ventilator. Their documentation and information are freely available on their Slack team. For example, a 3D printed ventilator system was designed and tested. The design files and STLs are freely available. Also, some makers are working on the development of pandemic ventilators.[37] Despite the many promising approaches, it is found that there is not enough information on the performance of ventilator designs to recommend them for medical use. Also, it is noticed that a basic test was carried on the designed ventilators and some ventilators were not tested at all. It is reported that the makers can use the free inactive patent that contains useful information

FIGURE 4 Face shields [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 3D printing technology used to fabricate medical device to fight against COVID19[29]

3D printing technology	Device to support healthcare professionals
Fused deposition modeling (FDM)	Adaptors for a variety of medical devices Oxygen valves Ventilators 3D printed quarantine booths Face masks (eg, surgical and N95 Respirator) Visors/Face shields Screwless hands-free door handle openers Door handle attachments Hand sanitizer holders
Selective laser sintering (SLS)	Oxygen valves
Stereolithography (SLA)	Venturi type valves for respirators COVID-19 test swabs 3D printed lung models for use in surgical planning & understand COVID-19

to improve the open-source ventilator design.[38] These designed ventilators must be validated by a medical team. The untested ventilators can harm the lungs of the patients.[39-42]

For those who design open-source ventilators, there is abundant literature. For example, the essentials of mechanical ventilation can be found in *"The Ventilator Book"* by Owens[43] and *"Principles and practice of mechanical ventilation"* by Tobin.[44] Pham et al[45] provide a state-of-the-art of mechanical ventilation. Moreover, the main classes of commercialized ventilators were presented. Kerechanin et al[46] have designed field-portable ventilator systems for military and domestic emergency medical response. This paper may be beneficial for open-source designers because it contains design considerations. Jürß et al[47] presented the design, construction, and the concept of a new compact

TABLE 2 Examples of open-source critical medical devices[35]

Device	Description	Link
NanoHack Protective mask	Provides basic protection for from airborne particles	Files: https://copper3d.com/hackthepandemic/ https://3dprint.nih.gov/discover/3dpx-013667
H connector for ventilators	Expanded use of a single ventilator to ventilate four simulated adults	Files: https://copper3d.com/hconnector/
Prusa protective face shield:	Provides protection from large splashes	Files: https://www.prusaprinters.org/prints/25857-prusa-protective-face-shield-rc1
Reanimation valve	Connects to a Venturi Oxygen mask to regulate the percentage of oxygen delivery	Files: https://grabcad.com/library/respirator-free-reanimation-venturi-s-valve-1
Hands-free door opener	Attaches to the door handle to prevent microbial contamination	Files: https://www.materialise.com/en/hands-free-door-opener

FIGURE 5 The original valve (on the left) and its 3D printed twin [Colour figure can be viewed at wileyonlinelibrary.com]

and low-cost lung ventilator. Many of the components for this lung ventilator were fabricated by 3D printing technology. Shahid[48] developed a prototype of the artificial respiration machine using AMBU (Artificial Manual Breathing Unit) bag compression. Electric schematic, pictures, and some results can be found in this paper. A low-cost portable mechanical ventilator ($420 prototype) was designed and prototyped by Al Husseini et al.[49] This paper can be used as a guide to build a similar device. A minimal oxygen consumption pneumatic ventilator during a respiratory malfunction pandemic was developed by Williams et al.[50] For different lung compliances, three designs were tested. The main schematics are given, but insufficient for a complete open hardware design. It is noticed that most of the low-cost ventilators use the bag approach; however, the contemporary professional ventilators, commonly, are not produced with bags.

The current effect of COVID-19 in Italy has caused local crisis due to the lack of medical equipment such as masks and Venturi valves. During this crisis, Venturi valves (Figure 5), important elements of respiratory support equipment, demonstrated a hard problem to reproduce. The design of Venturi valve is protected under patent law. But particular disasters leading to life-or-death choices may explain the total usage of intellectual property. This specific need led the 3D printing community to develop a solution for producing these valves to reinforce regional supply.[51] Another method of reinforcement is the use of a single ventilator for multiple patients with a 3D printed ventilator splitter.

4 | CONCLUSION AND RECOMMENDATION

In the above, a subset of projects that are aiming to produce protective equipment against COVID-19 using 3D printing are summarized. For a disaster situation, open-source systems allow rapid development based on the contributions of many people who work remotely. The "citizen supply chain" based on 3D printing has confirmed to be a powerful solution during COVID19. This solution can be used in many industrial sectors. In fact, many of the 3D printed PPE products need several hours to print it on conventional desktop 3D printers.

During COVID 19 pandemic, organized communication between 3D printing community and local hospital supply chain is recommended. Despite the urgency of the growing COVID-19 crisis, healthcare devices must be very controlled for safety. Indeed, the 3D printed medical equipment must follow the standard safety and quality measures. Moreover, the development of antimicrobial polymers for 3D printing provides the possibility to fabricate several critical medical products. In the future, a 3D printed PPE manufacturing protocol may be developed. This protocol contains the following information: CAO model, 3D printing technology to use, material, and assembly instructions.

Sometimes, it is important to develop an open-source program for disasters before the disaster strikes, because some regions of the world suffer from supply disruptions and shipping challenges. Moreover, it is necessary to develop policies and funding mechanisms for such projects. An additional challenge is keeping a suitable level of sterility of the equipment manufactured.

CONFLICT OF INTEREST

The authors have no competing interests.

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