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REVIEW ARTICLE

The role of 3D printing during COVID-19 pandemic: a review

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Abstract
The coronavirus disease 2019 (COVID-19) pandemic, caused by severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2), has spread through more than 180 countries, leading to diverse health systems overload around the world. Because of the high number of patients and the supply chain disruption, it generated a shortage of medical devices and personal protective equipment. In this context, initiatives from the additive manufacturing community emerged to fight the lack of devices. Diverse designs were produced and are currently being used in hospitals by patients and health workers. However, as some devices must follow strict standards, these products may not fulfill these standards. Therefore, to ensure the user's health, there is a need for understanding each device, their usage, and standards. This study reviews the use of additive manufacturing during COVID-19 pandemic. It gathers the source of several 3D printed devices such as face shields, face masks, valves, nasopharyngeal swabs, and others, discussing their use and regulatory issues. In this regard, the major drawbacks of the technology, addressed for the next pandemic scenario, are highlighted. Finally, some insights of the future of additive manufacturing during emergency are given and discussed.

Keywords Additive manufacturing · 3D printing · COVID-19 · Pandemic · PPE · Medical devices

1 Introduction

The coronavirus disease 2019 (COVID-19) had its first documented patient in December 2019, Wuhan, China [1]. Since then, the virus has spread through the world, and the World Health Organization (WHO) defined the disease as pandemic in 11 March 2020 [2]. Just 9 months after identified "patient zero", the disease has spread, on October 9th, in 188 countries and regions with more than 36.6 million confirmed cases and more than 1,063,000 global deaths according to the official data of the countries in the COVID-19 Dashboard by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University (JHU) [3].

The severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) can be transmitted though droplets [4], aerosol, and direct and indirect physical contact through contaminated surfaces, in which the virus may remain up to 72 h [4, 5]. Regarding the transmission modes involving droplets and aerosol, they are still under research and a consensus has not been reached [6, 7]. Some recent works point out that aerosol transmission may be more significant than previously considered [8, 9].

Infected people might be asymptomatic [10, 11], but may also present severe acute respiratory syndrome (SARS), resulting in intensive care unit (ICU) admission [11, 12].

These are all factors that contribute to the virus spread ratio, leading to health systems overload around the world. The high number of patients created a supply chain disruption, generating a shortage of personal protection equipment (PPE) and medical devices in hospitals for fighting off the virus.

To fight the lack of devices and equipment, companies, universities, independent groups, and individuals started a movement of production of diverse items to supply hospitals and people that are facing the shortage [13]. Various devices have been produced, such as face masks, face shields, test swabs, door handle attachments, valves [13–17] etc. and are being massively shared by social media [18, 19]. In this context, additive manufacturing (AM), commonly named as 3D printing, has emerged as one remarkable fabrication process because of its accessibility and flexibility to quickly produce complex and monolithic parts or even mechanical systems [20–22]. Another reason is that people involved with AM

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are open-mind, creative, with interdisciplinary relationships and applications. Therefore, AM technology allows the user to easily produce parts directly from a STL file format (designed in a CAD system), which can be easily found and shared in makers hubs or even at social media [19]. Finally, during the last decade, because of patent period expiration, desktop 3D printers have become accessible as low-end-machines for common people by open access projects that dramatically reduced their costs [22, 23] and the entrance barriers for low range AM equipment.

However, 3D printed parts may present different properties and finishes because of differences of materials used, technology, and individual machine software and calibration, even for a same STL project [24]. As PPE and medical devices must follow strict standards, these do it yourself (DIY) products may not fulfill the requirements of these standards, representing a risk to the users' health. Therefore, there is a need for understanding each device, usage, and standards to ensure that these products can in fact be helpful for the purpose intended with the lowest risk for patients and healthcare personal.

This study aims at reviewing the use of additive manufacturing during COVID-19 pandemic. It focuses on various PPE, medical devices, and other applications, providing their source and discussing their use and regulatory topics. Finally, a perspective for the future of AM during emergency situations is given.

2 Additive manufacturing

As defined by ISO/ASTM 52900 standard [25], additive manufacturing is a "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies". The 3D printing terminology is commonly associated with machines that are low end in price and/or overall capability [25].

The first commercial system of AM dates from the year 1987 and consists of the stereolithography (SLA) technique, which uses photo-curable polymers [20, 21]. Nowadays, a wide range of techniques and materials are available in AM technologies. The International Standard ISO/ASTM 52900 [25] divides AM processes in seven different categories: vat photopolymerization, material extrusion, material jetting, binder jetting, powder bed fusion, sheets addition, and direct energy deposition. These processes use polymers, ceramics, metals, and composites as feedstocks to build a part [20, 21, 25, 26]. Some techniques available on market are SLA, fused deposition modeling (FDM), fused filament fabrication (FFF), PolyJet, direct light projection (DLP), multi jet fusion (MJF), selective laser sintering (SLS), selective laser melting (SLM), and electron beam melting (EBM).

Because of its wide range of materials and techniques, AM can be used in a myriad of areas and applications, from rapid prototyping to medicine and aerospace end-use parts [20, 27]. The direct-from-CAD production, freedom of design, ease of customization, low number of steps, and rapid production of unique or small batches of parts are some of the main advantages of AM [20, 22, 27, 28]. However, there are a few common drawbacks for AM techniques that are still present, like parts anisotropy [20], high cost of industrial equipment, high cost of feedstocks (when compared to traditional techniques) [21], and high cost for big batches [22, 28]. Another serious concern still present in AM is the repeatability among machines of the same brand and models and even between consecutives processes [20].

3 Pandemic and additive manufacturing

At the same time that the COVID-19 pandemic increased the demand for medical devices and created a new market of products for general public, it provoked various supply chain disruptions, rapidly generating a shortage of many critical items, such as PPE [14, 16, 29–31]. Following this issue, companies, groups and individuals started to cooperate to supply people and hospitals that are facing items shortage [14, 24, 28, 32, 33]. In this regard, AM has emerged as a potential flexible solution for locally supplying various types of these items, demonstrating the potential of AM for a local and flexible production of strategic items, reducing supply chain dependency [13, 27, 34].

One of the main reasons that made AM an important tool during the pandemic is the great number of users around the world [19], many of them very specialized, innovative and creative. During the last decade, the decrease in the cost of processors and the expiration of patents made desktop 3D printers as low-end-machines [22, 23]. Furthermore, the feedstock price, mainly filament polymers, for these printers are in constant lowering [22]. Thus, the ability to produce parts for supplying the pandemic shortage is not exclusive for industry: makers, people who own or have access to rapid manufacturing machines such as 3D printers, have been proven to significantly contribute during the disease [23].

A second reason is that people who have a 3D printer do not require CAD-design knowledge to produce parts. 3D printable files can be easily found in internet via 3D printing open-design repositories, makers hubs or even at social media [19], only requiring a desktop printer to start production.

A third reason is that complex parts that would require a long period of time of manufacturing planning via traditional processes can be quickly put into production by AM. It has a minimal lead time to deliver small batches of parts, producing an almost immediate response to the crisis [22, 28, 35]. Consequently, when media started to share information on shortage of items, people could start helping as soon as they had STL files. The technique ability for rapid prototyping also allowed the fast production of the first designs and machine prototypes. Furthermore, an AM facility for low-end machines does not require complex planning or infrastructure. As example, François et al. [36] presented a technical note on the production of devices related to the COVID-19 pandemic for Greater Paris University Hospitals and various state institutions. They reported that 60 FFF machines were ordered, delivered, and settled in a period of 4 days. Therefore, if there is an urgent demand of emergency items, a 3D printer facility can be quickly installed and put into work. Using a single desktop 3D printer, Thomas et al. [37] took 21 days from conception to delivery of 50 reusable personalized face masks based on the Stopgap surgical face mask design [38].

4 Data sharing

One of the main advantages of AM is the direct-from-CAD production. The user can easily produce parts from CAD files, which can be designed or obtained from internet specialized repositories. Currently, there are various file repositories like Thingiverse [39], NIH 3D Print Exchange [40], GrabCAD [41], Pinshape [42], Cults [43], Yeggi [44], MyMiniFactory [45] and others. These websites store 3D printable files, usually in STL file format, which are shared by users. These repositories allow the upload, download, exchange, and even edition and new upload of 3D printing files and information by anyone.

During the pandemic, data sharing has rapidly increased to spread initiatives and solutions as an attempt to fight off the virus. From this perspective, social media [19, 33], company websites [46, 47] and file repositories have played a main role in sharing data [23, 33, 35]. As social distancing was the main strategy for most governments to reduce transmission rates, people at homework increased social media use [19]. After the virus was announced by China, a wave of information sharing occurred though social media as never seen before. Unfortunately, part of these were unreliable information like conspiracy theories or misleading rumors, generating panic and depletion of stockpiles [48]. However, social media also played a role in sharing initiatives aiming at providing PPE and medical devices for people in need [18, 19, 49]. In line with social media, file repositories websites were used for sharing downloadable CAD files for 3D printing parts to be used during the pandemic [19, 49]. Furthermore, there are several websites hosting platforms like github and gitlab, dedicated to open projects related to COVID-19. These platforms facilitate quick design interaction among different professionals by allowing access to anyone interested to contribute and share their developments [50]. Global network put together volunteers and experts via dedicated hubs to provide diverse types of products to supply the community [28]. These interactions, associated with the use of desktop 3D printers, act as an iteration chain process for optimizing the project and reaching a final design in a short period of time.

In addition, various companies worked on more engineered and reliable data and designs solutions using 3D printing workforce around the world. Some examples of notable projects, just to cite a few, are ISINNOVA's valves [51, 52], Prusa's face shields [53] and Materialise's [46] solutions for non-contact tools and masks. Furthermore, there are projects like the Open Source Medical Supplies that gathered together multidisciplinary professionals, such as engineers, medical professionals, makers, researchers etc. to lead and inform people who are trying to fight the equipment shortage [54]. Finally, scientific papers [12, 50, 55, 56] were also used as a way of data and information sharing. In this case, more detailed data in fabrication methods and results are given, as well as more reliable data because of the peer-reviewing process. However, they are less accessible to common public since they can be found only in specific scientific media and some publications are not open access.

5 3D printed devices

The following sections present and discuss diverse types of solutions produced by AM during COVID-19 pandemic.

5.1 Personal protective equipment—PPE

PPE are the most printed devices during the pandemic because of their relative simplicity, low geometrical tolerance requirements and lower-risk classification within Food and Drug Administration (FDA) or other regulatory bodies, when compared more complex devices like ventilators and valves [23].

Face shields constitute majority of the projects among PPE [23, 57]. FDA considers face shields as Class I medical devices [4, 58], and WHO considers them as an alternative to medical masks during shortages [59]. They are a head-worn frame with a clear plastic sheet to protect the user's face from direct contamination via sprays and splashes [4, 13, 23, 60]. Another requirements are that they must be easy to disinfect, comfortable during long periods, durable and allow additional PPE wearing [61]. It is important to remark that in highly infectious situations the face shield must be used with additional PPE equipment [4, 61]. The frame consists of a simple geometry that can easily be 3D printed [53, 56, 61, 62]. A further approach uses SLA to produce a hollow frame to be used with an external airflow, defogging the visor and preventing ambient air from entering [63]. The plastic sheet is cut manually, using scissors and an office puncher [56], or automatically, using laser cutters [60]. Some material of choice are polycarbonate, Propionate, acetate, polyvinyl chloride, and polyethylene terephthalate glycol (PETG) [60]. An elastic band may be suitable in some models [61, 64]. The face shield design must cover the sides of the face and below the chin [59]. Printing time and price of face shields are design, machine, material, and parameters dependents [4, 56, 57]. Figure 1 shows diverse 3D printed face shields models built using different AM techniques and materials. Designs of face shields can be found in various file repositories [39, 40, 42, 43, 45].

Safety goggles act in a similar way of face shields: they work as a physical barrier for the eyes. Eye protection is indicated as a protection from infected patients' exhaled droplets [10]. Farsoon, Huaxiang and LEHVOSS companies designed, validated, and made available for download two sizes of safety googles to be made by SLS, SLA or FFF technologies. The lens are to be cut separately in acrylic material [65]. There are other available models, such as PUC-Rio's [66], FRC Team's [67] and Creality's [68] designs. However, there is no information if these models were validated.

N95 respirators (class II device by FDA [58]) and surgical masks (class I device by FDA [58]) are critical PPE. Both are recommended by the WHO for health workers during this pandemic [59], and are intended to filter particles of bacteria and virus to avoid contamination [31]. N95 respirators have a minimum efficiency reporting value (MERV) of 95% for particles larger than 0.3 µm [32, 69]. Even though COVID-19 virus particle size are under 0.16 µm [1, 70], these respirators are capable of filtering droplets that work as vehicles of virus transportation [32]. Surgical masks cannot assure the same protection as a N95 respirators [64, 69], but they can provide significant reduction, leading various countries and states to incentive or obligate people to use even homemade fabric masks to reduce contamination ratio [59].

Because of the critical function and high demand, diverse 3D printable projects and designs were proposed. 3D printed adaptor valves to be connected with full-face snorkeling masks and a high-efficiency particulate air (HEPA) filter (Fig. 2) were suggested for health workers usage [49, 71, 72]. These full-face snorkel masks have three diaphragm

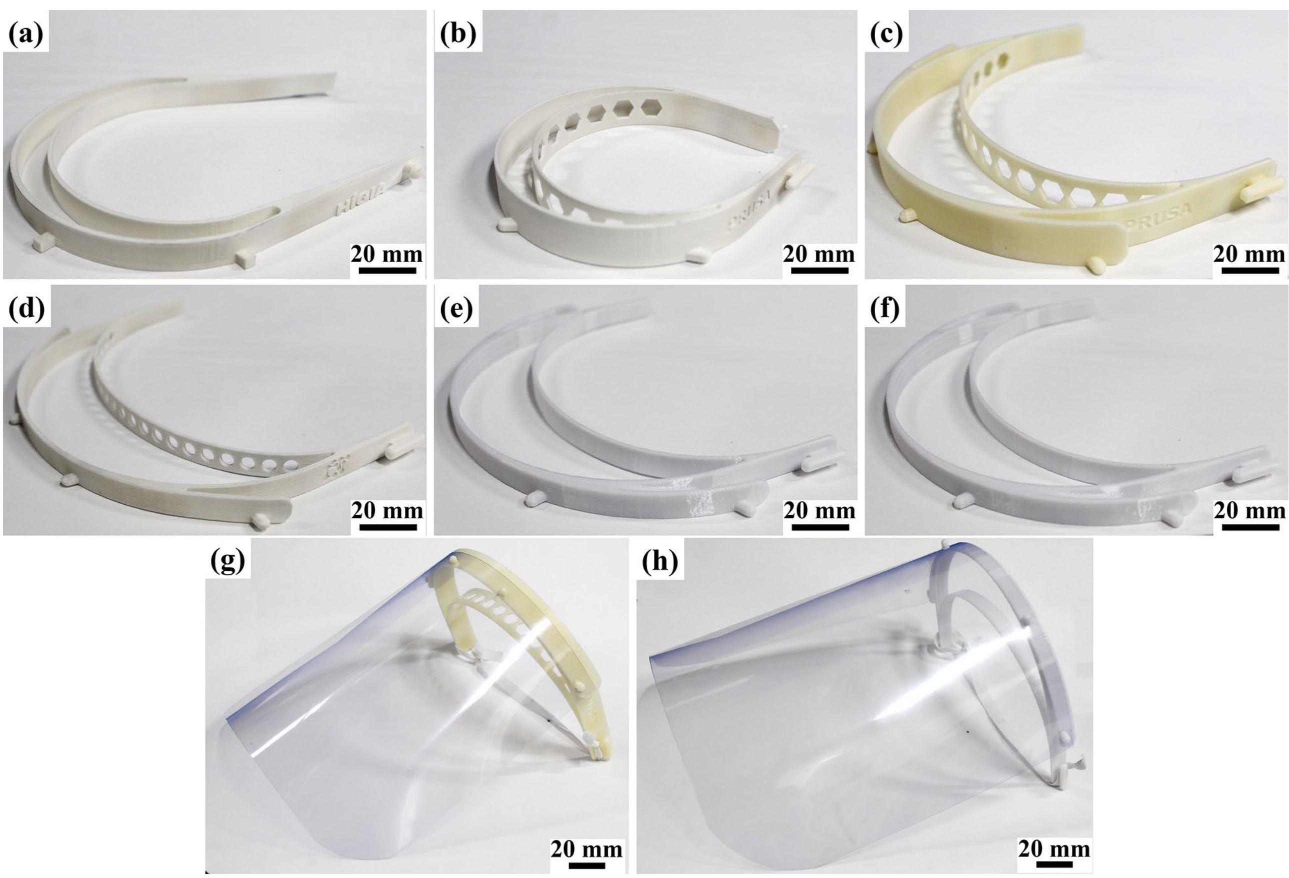

Fig. 1 Various face shields designs made by different AM techniques. **a** Hígia model [62]—SLS/PA12; **b** Prusa RC1 model [53]—SLS/PA12; **c** Prusa RC2 model [53]—FDM/ABS; **d** adapted Prusa model 1—SLS/PA12; adapted Prusa model 2—FDM/PC; adapted Prusa model 3—FDM/PC. Face shields assembly with **a** Prusa RC1 model and **b** adapted Prusa model 3

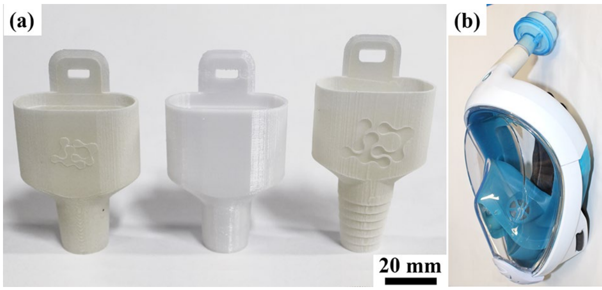

Fig. 2 **a** Different versions of valve adaptors made using SLS/PA12 and FDM/PC. **b** PPE mask assembly with snorkeling mask, adaptor and HEPA filter

valves and airways that ensure the air inlet only through the HEPA filter and prevents the visor from fogging. In a study made by Kroo et al. [71], this PPE exceeded the standards of N95 respirators. However, in a study made by Gierthmuehlen et al. [73], the full-face snorkel mask obtained only a 85% filtering efficiency for 580–660 nm particle size, which is below the N95 filters efficacy. These conflicting results raise the need for more tests to reach a definitive conclusion.

Another approach for PPE is the production of open-source powered air-purifying respirators (PAPR), classified as class II devices by FDA [58]. In this case, AM is being used for producing parts of the mask and the pump for the equipment assembly [74] or reposition parts [75]. Furthermore, Erickson et al. [76] proposed 3D printing manifolds to adapt surgical helmet systems as PPE during the pandemic since these systems are going unused because of elective surgeries delay.

A simpler approach, which acts as a substitute to surgical masks and does not require prefabricated masks is 3D prints, a half-face mask, and uses diverse materials such as filters in an air inlet/outlet. The mask efficiency will depend on the AM technique used, the print quality, the user's anatomy, and the filter material used [77]. Tino et al. [15] reviewed five different types of half-face masks made by FFF and found out some models are inviable by long printing time or inefficient sealing. Swennen, Pottel and Haers [77] presented a proof of concept of a 3D printed mask composed by two reusable components made by SLS and two disposable components (head band and filter membrane). They propose using 3D facial scanning software from smartphones to obtain a 3D model of the user's anatomy to improve the mask fit.

It is important to remark that these masks require regulatory approval [14, 15]. Nevertheless, a collaboration between the NIH 3D Print Exchange website, FDA, the Veterans Healthcare Administration, and America Makes in 3D printing solutions inform which models undergone review in a clinical setting and were found appropriate when fabricated with the specified parameters [40]. One reviewed and validated model is the Stopgap surgical face mask [38], to be fabricated via SLS or MJF, shown in Fig. 3a and b. It consists of two sterilizable 3D printed components, elastic straps, and a filter material, which must be disposed after each use. However, a preprinted work by Bezek et al. [78] tested the Stopgap [38], La Factoria 3D COVID-19 [79] and Montana face masks [80] made by powder bed fusion industrial and FFF industrial and desktop equipment. In almost all cases, masks without post-processing steps presented an overall filtering efficiency under 60% for particles between 100 and 300 nm, which is comparable to fabric masks. The only exception was the Montana design made in ULTEM material using an industrial FFF printer, which presented a 90–95% efficiency. Further, they showed that post-processing steps can improve the masks filtering efficiency. Their work indicates the need for further quantitative testing and validation of 3D printed PPE and for development and standardization of post-processing steps to improve the masks efficiency. In agreement with the previous work, Gierthmuehlen et al. [73] obtained a filtering efficacy of only 39% for La Factoria's mask model, which is a home-made vacuum cleaner bag mask model (70%). They highlight that a tight fit is essential for the masks to perform optimally.

Finally, there are parts that were designed to be used as support to PPE. N95 or surgical masks are critical and required PPE for healthcare professionals [59]. Because of the long shifts, the delicate skin behind the ears starts to breakdown by the contact with the mask bands. 3D printed ear savers, or mask extenders [35], were designed to improve the wellness of health workers and people who work for long periods with face masks. In the NIH 3D Print Exchange repository [40], there are various reviewed models such as the one submitted by tech4primary user [81], shown in Fig. 3c and d. Additionally, to improve the fit of surgical masks, Bellus3D designed a face mask fitter (Fig. 3e and f), based on a 3D printed plastic frame [82]. The design uses the company's face scan software (for smartphones) for creating an adapted geometry to the user's face.

5.2 Valves

COVID-19 patients may present SARS, with high respiratory rates and low oxygen levels [83]. Patients with these critical hypoxemic symptoms are normally submitted to invasive mechanical ventilation (IMV) procedure [84]. During this procedure, droplets and aerosols from the patient are released, creating a propitious environment for contamination of health workers [83, 85–87]. In these cases, patients remain in induced coma for long periods of time, increasing the risk of death using sedatives and the occupation of intensive care unit (ICU) beds. These are critical facts during the COVID-19 pandemic because of the shortage of ICU beds, mechanical ventilators, and high risk of contamination for

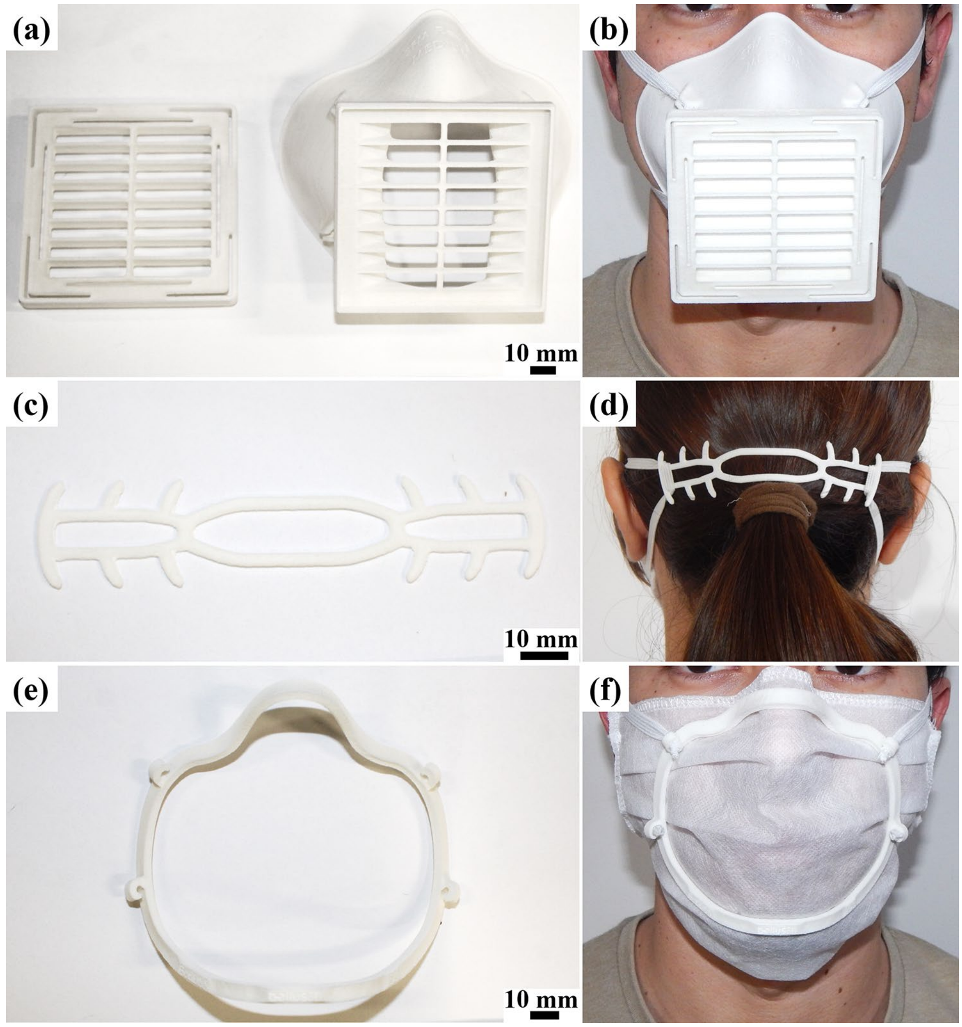

Fig. 3 Face mask and support parts made by SLS/PA12. **a** Stopgap surgical face mask [38] **b** Ear saver designed by tech4primary user from NIH 3D Print Exchange [81]. **c** Face fitter designed by Bellus3D [82]

health workers. A possible way for reducing intubation is using non-invasive ventilation (NIV) procedures, such as continuous positive airways pressure (CPAP). The WHO recommends the use of NIV as a first approach before intubation of patients [10]. Wang et al. [88] made a study in which 27 COVID-19 patients presenting SARS were submitted to NIV. From these patients, only 4 had to be intubated. However, because COVID-19 can be transmitted through aerosols and droplets [4, 14], NIV with inappropriate seals should not be used [87, 89]. Hence, exhaled air from the patients submitted to NIV cannot be returned to the environment or must be filtered with a HEPA filter.

Italian ISINNOVA company created a solution using 3D printing connector valves to be used with Decathlon's *Surface Snorkeling Mask Easybreath*® as full-face masks for CPAP procedure (Fig. 4c). The valves, named as *Charlotte* (Fig. 4a) and *Dave* (Fig. 4d), can be downloaded at ISINNOVA's website. FFF/polylactic acid (PLA) are the recommended fabrication method/material [51]. This assembly can be used with an oxygen flow or mechanical ventilator, may minimize environment contamination [12], and can be sterilized and reused [32].

Another approach related to the shortage of available mechanical ventilators are 3D printed splitters (class II devices by FDA [58]), which allow the use of a single mechanical ventilator by two different patients [15, 90]. Furthermore, there are also open-source NIV helmets projects like the Bubble Helmet from COSMIC Medical [91] that may use 3D printed valves as ports for the assembly.

Venturi valves (Fig. 4b) operate by Bernoulli's principle of jet gas mixing [11] and can deliver a fixed fraction of inspired oxygen (FiO2) [69, 87], depending on the valve geometry [87]. They are used with a mechanical ventilator and a Venturi mask during NIV procedures [11, 87]. They are also described as part of the CPAP system when connected to a mechanical ventilator [12]. Therefore, these valves are essential during COVID-19 pandemic because of the high demand for respiratory devices. In Brescia, Italy, a supply chain disruption made these valves scarce. Again, ISINNOVA 3D printed by FFF Venturi valves in a short

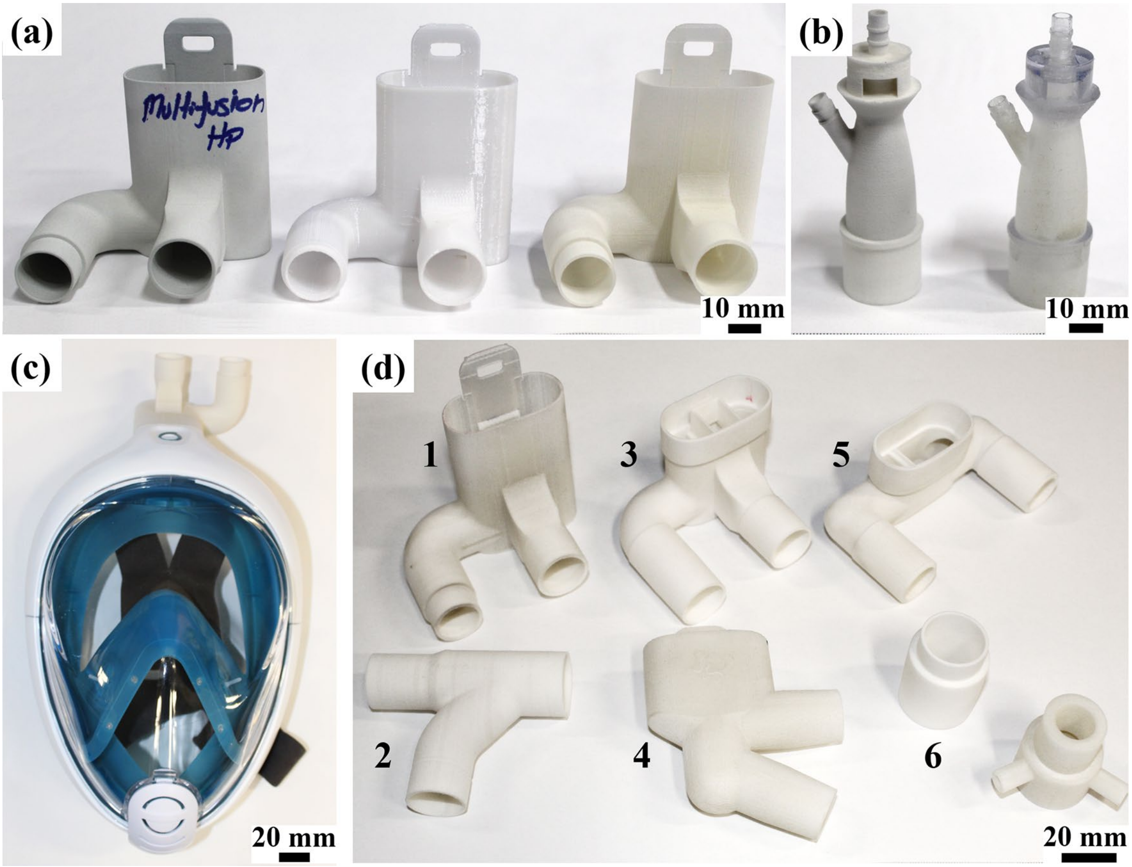

Fig. 4 **a** ISINNOVA's *Charlotte* valve [51] made by different processes and materials—from left to right: MJF/PA12, FDM/PC and SLS/PA12. **b** Venturi valve models by SLS/PA12 and PolyJet/VeroClear®. **c** Snorkeling mask connected to an ISINNOVA's valve for being used during CPAP procedure. **d** Diverse types of valves: 1—*Charlotte* [51]; 2—*Dave* [51]; 3,4,5—Modified *Charlottes*; 6–adaptors made by SLS/PA12

period of time, based on reverse engineering, and have saved lives [52]. These valves were also further produced in SLS and SLA [52]. Filip Kober further created 3D models to be printed in SLA, downloadable at GrabCAD [92]. SLA is the technique of choice because part porosity may alter the functionality of the valves, changing delivered FiO2 [15]. The models were simulated using computational fluid dynamics (CFD) to ensure the correct values of FiO2 [52].

5.3 Isolation chambers and wards

A measure to prevent the SARS-CoV-2 dissemination is the isolation of suspected or confirmed patients. As explored before, patients in hospitals may spread the virus through aerosols and droplets [4, 14]. Therefore, some devices can reduce environment contamination. Cubillos et al. [93] developed a negative air flow isolation chamber for COVID-19 patients. Their device consists in a rigid cubic frame chamber draped with a clear plastic bag in which a continuous negative air flow prevents air from inside the chamber from contaminating the external environment. It uses 3D printed ports that allows suction, oxygen delivery and nebulization. The instructions and plans are available under a Creative Commons License, Attribution-NonCommercial-ShareAlike 4.0 International. A collaboration of Sector 67 with University of Wisconsin-Madison Department of Surgery, Dr. Hau Le, and UW-Madison College of Engineering [94] developed a negative pressure isolation head box, named as "badger box", which uses AM to produce glove grommets. Another example of isolation chambers, although more simplistic, were produced in Texas A&M University [95]. The chambers work as a physical barrier for contaminated patients and consist in CNC cut vinyl and 3D printed parts.

In large-scale projects, the creation of 3D printed isolation wards by the Chinese company WinSun can be highlighted [96, 97]. The wards are used as a professional and comfortable environment for patient isolation and treatment. They can also serve as a properly sanitized and protected resting place for healthcare professionals working directly to combat the pandemic. The standard model is 10 m^2 and 2.8 m tall. The 3D printed wards construction process is automated, resulting in low labor cost and rapid construction. The buildings can be moved to different locations and can be easily connected to a power supply network [13, 34]. Finally, build process uses as feedstock material industrial or solid construction waste and, after demolition, can be reused in new 3D printed buildings [96].

5.4 Field respirators

An alliance between the Consorci de la Zona Franca de Barcelona, HP, CatSalut and Leitat Technological Center developed a field respirator, named as LEITAT 1, using AM for prototyping and parts production. The device, a mechanical bag valve mask, is to be used for short term emergency ventilation. The emergency ventilator, tested in ICU patients and approved by the Spanish Medicines Agency, has parts produced by MJF and is industrially scalable [98, 99]. Moreover, Petsiuk et al. [100] designed an automated fully open source bag valve mask-based ventilator, which also serve as a temporary emergency ventilator. In their work, they give a detailed protocol and links to the downloadable files, which include 3D printable parts of the ventilator assembly. The reported results exceed human capabilities in bag valve mask-based manual ventilation.

5.5 Nasopharyngeal swabs

Massive testing is an important measure for fighting the COVID-19 pandemic. For this, specimens from the upper respiratory tract must be collected and tested by reverse transcription polymerase chain reaction (RT-PCR) [10]. In this sense, nasopharyngeal swabs provide the highest sensitivity for the virus detection [50]. These are FDA Class I medical devices [58] with a rod-shape and a head coated with short synthetic filaments or spun fiber, used to collect secretions from the upper respiratory tract from the patient. The swab usually has a breakpoint on the shaft for enabling the head storage in a vial with viral transport media. Then, the sealed vial is sent for testing. To ensure a safe and reliable test, the swab must be flexible and sterilizable [15, 101]. Cotton head swabs are not indicated for COVID-19 [10, 50].

Cox and Koepsell [29] created a FFF printable and sterilizable PETG nasopharyngeal swab. They made clinical tests using commercial swabs as control and found the 3D printed model has the same efficiency of the control group. Callahan et al. [50] made a multi-step preclinical evaluation on 160 designs and 48 materials of test swabs and validated 4 prototypes. From this study, a consortium including Carbon, FormLabs, Envisiontec, Origin and Abiogenix companies was created and can produce up to 4 million FDA registered test swabs per-week via vat photopolymerization with medical grade resin [102]. In the same work, swabs designed for MJF medical grade nylon were also validated [103]. Arnold et al. [101] developed a swab with an open lattice design to be produced by DLP process. The model was tested and obtained a 90% match of results taking commercial swabs as golden standard, showing the design is adequate for test. Ford et al. [104] designed and developed over 20 nasopharyngeal tips. Their final design showed a 94% concurrence with the current synthetic version in an initial study and multisite clinical trials are currently underway. The STL models from the previous works are only available by request to the companies.

Finally, some nasopharyngeal swabs designs can be found at file repositories, such as the model from Fig. 5, designed by MarianneE (Johns Hopkins University Applied Physics Laboratory) user in the NIH 3D Print Exchange repository [105]. This design is for production using SLS/PA12. However, it is important to remark that there is no evidence these items have undergone any clinical test or validation, and the manufacturers should be certified by ISO 13485 (Medical Devices Quality Management System) for ensuring safe and reliable tests.

5.6 Hands-free tools

The COVID-19 virus may remain on different surfaces for periods up to 72 h [5]. Thus, avoiding direct contact with surfaces is an important way to reduce contamination during the pandemic, especially in public and medical centers [15]. Some objects such as buttons, door handlers, switches etc. are potentially virus spreaders because of the high number of interactions with different people [36].

As a solution for reducing direct hand contact, various hands-free tools were designed. François et al. [36] designed and produced by FFF a high volume of various hands-free tools to be used in Greater Paris University Hospitals and other sites.

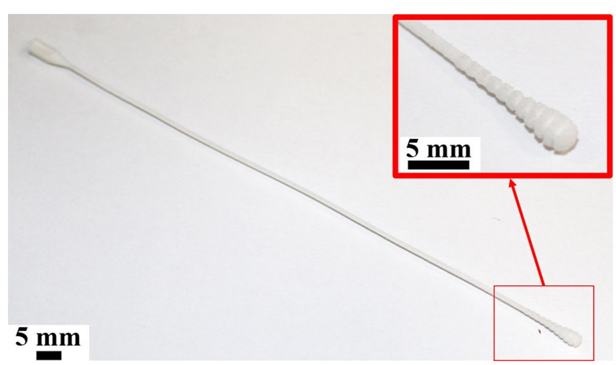

Fig. 5 Nasopharyngeal swab from MarianneE user from NIH 3D Print Exchange repository [105] made by SLS/PA12. This design has not undergone any validation process and is exhibited only as example

Hands-free door openers are devices that are fixed to door handles and allow door opening and closing with elbows or forearms [36]. Materialise company designed different types of hands-free door openers for cylindrical, rectangular, circular, and spherical handlers that can be 3D printed by MJF, SLS or FFF technologies [46]. Figure 6a and b show Materialise's rectangular and circular hands-free door openers, and the rectangular model usage. Furthermore, hands-free tools for opening doors, pushing buttons, hooking handles, opening water taps, and other daily tasks were created by various designers for personal use. These hands-free designs can be found in various repositories websites such as Thingiverse [39], NIH 3D Print Exchange [40] and others. Figure 6c and d shows hands-free tools by SimonSolar2C [106] and bgiovanny [107] users from Thingiverse repository and an example of use.

5.7 Antimicrobial devices

One major drawback of using AM polymers in some applications, such as masks, valves, and no-contact tools, is that SARS-CoV-2 presents a high stability (up to 72 h) on these surfaces. On the other hand, the virus stability on copper surfaces are reduced to 4 h, as found by van Doremalen et al. [5]. The previous work is in accordance with literature related to the use of some metallic coatings or nanoparticles into polymers. Some metals such as copper and silver have antimicrobial characteristics and can be used in the development of bioactive polymers [108]. Borkow et al. [109] showed that a face mask doped with copper and copper oxide particles reduce the risk of influenza (H1N1 and H9N2) contamination.

In this context, Copper 3D company uses the antiviral properties of copper to produce a face mask (named as NanoHack) using the company's bioactive materials PLACTIVE® and MDflex®. The filtering system still require non-printed material (non-woven polypropylene embedded in copper nanoparticles) [110].

Another approach for antimicrobial devices is using antimicrobial coatings on surfaces to reduce biofilm formation. Muro-Fraguas et al. [111] used plasma-polymerization to create an acrylic acid (AcAc) coating on 3D printed PLA Petri dishes and obtained antibacterial properties using different *Pseudomonas aeruginosa* and *Staphylococcus aureus* strains.

5.8 Training and education

One of the various applications for AM is the education area. It can be used from printing simple forms to help children to develop abilities and skills [112, 113] to adults and professionals, where complex replicas to improve diagnosis, surgical planning and patient education can be printed [113, 114]. In this regard, AuMed [115] designed a manikin to help training of inexperienced healthcare workers in COVID-19 diagnosis by nasopharyngeal swab testing. In the education context, according to Hervás-Gómez et al. [113], the use of AM in education is growing, following the development of the Industry 4.0. Moreno Martínez and Morales Cevallos [116] point out the opportunity to use the AM notoriety during the COVID-19 pandemic to use this technology to improve students interest, participation and proactivity in experimentation and manipulation. The use of 3D printed tactile models can also be a tool for communication with individuals who are visually impaired [112].

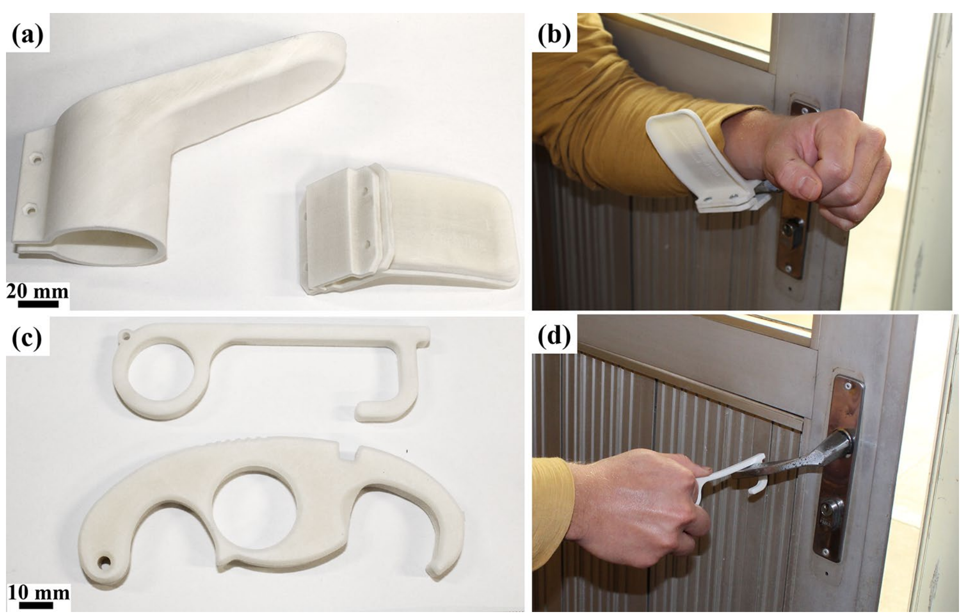

Fig. 6 Hands-free models made using SLS/PA12. **a** Materialise's hands-free circular and rectangular door openers [46]. **b** Rectangular model usage. **c** Hands-free tools from SimonSolar2C [106] and bgiovanny [107] users from Thingiverse repository. **d** Tool being used for opening door

Figure 7 presents two visual-tactile models of the SARS-CoV-2 morphology. Both models explore the proteins, lipid membrane and RNA from the virus. The models shown in Fig. 7a and b also contain support bases with Braille transcription for people who are visually impaired. Finally, because of the rapid shift to online education that occurred in various countries, simple solutions, such as 3D printed mounts to point webcams downwards, may help instructors to present a board-based pedagogical method [117].

5.9 Mask manufacturing tools

In a document with advice on the uses of masks during the pandemic [59], the WHO guided governments to encourage the general public to wear face masks. Because of the shortage of surgical and N95 masks, homemade fabric masks emerged as an interim solution. Consequently, some people started to sew their own fabric masks and, in some cases, to sell or donate these items. As a way for helping people to increase the production of these wearables, 3D printable mask pleaters and bias tape makers were designed and made available for download at diverse repositories, such as Thingiverse [39]. Bias tape makers are folders that assist the fabrication of cloth bias tape, as shown in Fig. 8, used in finishing edges of fabric masks. Mask pleaters help the production of pleated face masks. Both are time-consuming tasks, and these simple designs act as tools for increasing production.

5.10 Endoscopic procedure mask

The risks to health workers associated with aerosols and droplets during IMV procedures were discussed in Sect. 5.2. However, there are other medical procedures, like endoscopic skull base surgery, that also create high risks of pathogens transmission. In this context, Helman et al. [55]

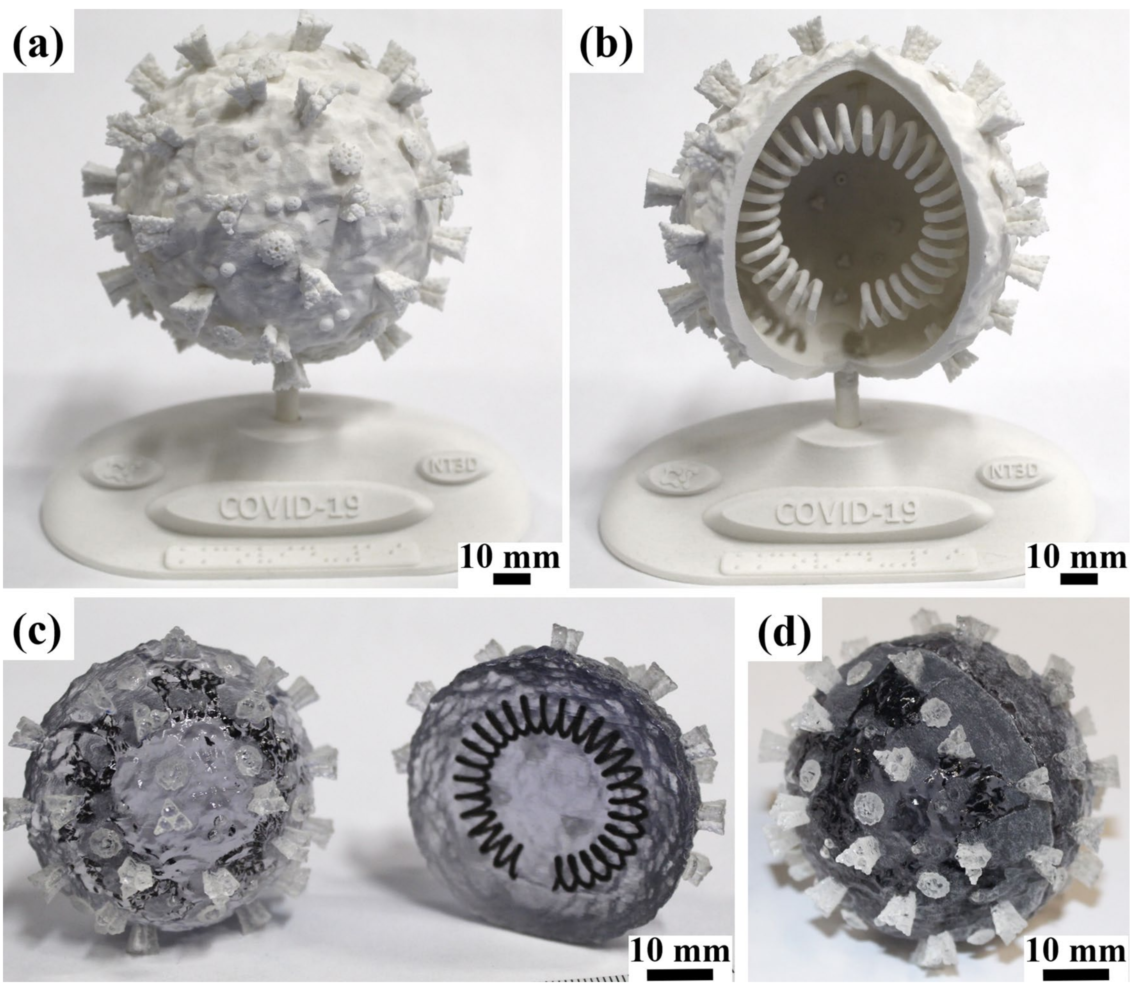

Fig. 7 Visual and tactile educative models of SARS-CoV-2, showing RNA, proteins, and lipid membrane. **a** SLS/PA12 model with base containing braille writing and **b** PolyJet/VeroClear® + TangoBlack-Plus® two-halves model. Models from own authorship and available by request to the main author

Fig. 8 **a** Bias tape maker made by SLS/PA12 used for **b** folding cloth. Model designed by ongaroo user from Thingiverse repository [118]

developed a 3D printed mask for endoscopic skull base surgery. They redesigned the mask edge circumference from open-source mask models and added an inlet and outlet to the sides of the masks for tubing. Then, they used a surgical glove to provide a flexible physical barrier that allows usage of medical instrumentation. They performed various tests in two cadaveric models and found the device offers the surgeon appropriate surgical degrees of freedom, maneuverability and reduces risks of contamination. The mask model is available by request to the main author of the work.

5.11 Metallic devices

As explored in Sect. 5.7, the COVID-19 virus stability on copper surface is up to only 4 h [5]. Following these findings, ExOne company and the University of Pittsburgh worked in collaboration to develop sterilizable copper filters made by binder jetting technology. They use the process intrinsic porosity after sintering to produce filters with specific porosity levels to meet N95 filtration standard. One major advantage of the filter is that it is reusable, reducing waste disposal [119].

To summarize the data from all the 3D printed devices presented in the previous sections to fight against COVID-19 pandemic, Table 1 gathers information about used AM technologies and their respective references.

6 Drawbacks

As AM has assumed an important role during COVID-19 pandemic, there are some major drawbacks that must be discussed.

Different parts produced from a same STL file may present significant variations in geometry and mechanical properties because there are differences in material type and quality, software, calibration and equipment [24, 28]. In a work by Mueller et al. [28], the authors raise several questions about the material selection and quality control of 3D printed parts for COVID-19 pandemic. Most of medical devices must comply with strict standards to ensure a safe and reliable use, avoiding any preventable harm for patients and professionals. As an example, FFF filament may retain moisture, which could act as a virus transmitter during use or reuse [24]. In addition, 3D printed parts have different characteristics from parts produced by conventional methods: the layer upon layer process may generate poor interfaces, delamination, and unintentional porosity [122]. Thus, as pointed by Larrañeta, Dominguez-Robles and Lamprou [14], these parts may not provide the same security levels. In a preprinted work from Bezek et al. [78], face masks produced by FFF presented defects that decreased their efficiency in filtering particles. Novak and Loy [57] indicate the need for design for additive manufacturing (DfAM), which considers the AM process characteristics and particularities during project. Therefore, makers must be aware of optimized printing parameters for the application and the required quality of each printed part [123].

In addition, since there is no review process for any STL file uploaded in file repositories, there is no assurance that the final models will be functional. Another issue is the high number of different types of projects that can be found for a same device, such as face-shields and face masks. As an example, Novak and Loy [57] studied the manufacturability of 37 and 31 different face-shield and face mask models, respectively, from companies, groups, and individuals. They found large differences in terms of cost and manufacturing time between the models. This may be a concern when choosing which model to produce. Another issue is choosing valid models that were previously tested and reviewed by medical workers, since there are various designs that lack this information. In this regard, companies and scientific papers are a better source of projects that were generally developed by multidisciplinary teams and went through a validation process.

With regards to issues, the regulatory agencies and intellectual property are two relevant topics. Beyond medical review and validation, medical devices must be approved by the country's regulatory agency, such as FDA for USA, the Medicines and Healthcare products Regulatory Agency (MHRA) for the United Kingdom and the Brazilian Health Regulatory Agency (Anvisa) for Brazil. Hence, it is worth to say that every single person involved in the production of medical devices must be aware of his/her legal responsibility even as a philanthropic action. Usually, the process for approval by a regulatory agency is

Table 1 3D printed parts produced during COVID-19 pandemic

Item	AM technologies	References/Sources
Face shields	FFF, SLA, SLS	[53, 62, 63]
Safety goggles	FFF, SLA, SLS	[65–68]
N95 respirators similar	FFF	[49, 71, 72]
Half-face masks	FFF, MJF, SLS	[38, 77, 79, 80]
Antimicrobial mask	FFF	[110]
PAPR parts	FFF	[74–76]
Ear Savers	FFF	[81]
Mask fitters	FFF	[82]
Isolation chambers	FFF	[93–95]
Isolation wards	Not specified	[97]
Valves for CPAP	FFF	[51]
Splitter valves	Not specified	[90, 120]
Valves for NIV helmets	Not specified	[91]
Venturi valves	FFF, SLA, SLS	[92]
Field Respirators parts	Not specified	[98, 100]
Nasopharyngeal swabs	DLP, FFF, MJF, SLS, SLA	[29, 101–105]
Hands-free door openers	MJF, FFF, SLS	[46]
Hands-free tools	FFF	[106, 107]
Manikin for swab testing training	Not specified	[115]
Educational models	SLS, PolyJet	Own authorship
Mounts to point webcams downward	FFF	[117]
Bias tape makers	FFF	[118]
Mask pleaters	FFF	[121]
Copper filters	Binder jetting	[119]
Surgery mask	FFF	[55]

expensive and requires considerable time [23]. Regarding this, during the pandemic, some agencies had published official declarations on the use of unapproved medical products during the emergency [124, 125]. Previous to the pandemic, in December 2017, FDA had published a guidance with technical considerations for additive manufactured medical devices [126]. However, Pecchia et al. [18] point that emergency situations demand universal regulations, mainly for low- and mid-income countries. Further, the authors also argue about the importance of regulations and standards for guiding the manufacturers for ensuring high safety levels, since even small defects may harm the user. For the intellectual property theme, most of the medical equipment from the existing medical system is based on patented equipment from medical suppliers [31]. Regarding this, Tino et al. [15] alert for the reverse-engineering process and its possible legal issues. They point that goodwill from regulators, legal experts, and governments are essential for saving lives during an emergency such as the COVID-19 pandemic. As an example, ISINNOVA company rapidly patented their *Charlotte* valve to prevent any price speculation and left it free to use [51]. Furthermore, Mahr and Dickel [127] discuss how the COVID-19 pandemic rapidly changed our thinking on intellectual property and highlight the need for regulators, ethicists, lawyers, and members of the industry community to discuss and create guidelines for the maker community during global crisis scenarios.

Finally, as shown by the current study and summarized in Table 1, majority of parts and projects are developed in polymer AM. Larrañeta, Dominguez-Robles and Lamprou [14] pointed FFF, SLS and SLA as the main AM techniques used for producing COVID-19-related parts. Besides, Novak and Loy [23] studied the AM projects availability and also found that FFF, SLA, MJF, SLS and other polymer-based techniques are the flagship AM processes during the pandemic. Beyond polymers, AM can work with metals, ceramics, and composites. In 2017, the unit sales for metal AM systems grew by 79.9%, well above the 12.6% growth of unit sales of overall AM industrial system [21]. However, even with an exponential growth, metallic AM solutions during COVID-19 pandemic are almost zero. This statement could be related to the high costs of metal AM machines and feedstocks, leading to a low number of disponible workforce. Thus, metal AM fully potential was not explored during the pandemic.

7 Potential uses of AM in future pandemics

In the history of mankind there are records of several pandemics such as smallpox, cholera, Black Death (plague), AIDS, influenza, SARS, West Nile disease and tuberculosis [128]. The "Spanish flu" influenza pandemic, the most lethal pandemic in recent history, killed more than 20 million people worldwide [128, 129]. Influenza A (H1N1), a more recent pandemic, occurred in 2009 and contaminated over 1.6 million people and had 18,449 confirmed deaths [130]. In a more localized spread, Ebola outbreak in West Africa in 2014–2015 resulted in 28,600 cases, resulting in 11,350 deaths, though it is estimated that up to 70% of cases may not have been accounted [131]. Even though infectious diseases have always plagued humanity, during the last decade, there has been a significant increase in the number of emerging and reemerging infections, reaching more than 20 infectious agents [132]. In fact, since 1980 the number of infectious diseases has increased by nearly fourfold because of the population growth, increased number of domesticated species, and globalized economy—with an increased people mobility [133]. Therefore, there is no reason in expecting COVID-19 pandemic will be the last, or it will take a long time for a new outbreak.

In this regard, beyond the already developed applications for AM during emergency situations, there might be new uses that will come from the technology advancements. As explored previously, AM is a relatively recent technology, having its first commercial system dated from 1987. The technology has currently attracted attention from research and industry, with new technologies and materials coming up daily. The next sections show and discuss some specific AM fields that may affect possible future applications for AM during future pandemics.

7.1 New materials

New material development will make AM more competitive toward conventional production technologies as it will create opportunities to new design freedoms and applications [26]. As a previously discussed example, bioactive materials, such as bioactive plastics, which present antimicrobial properties [108–110], are still being developed and will reach common public, opening a window for mass fabrication of bioactive devices, such as valves, hands-free tool and masks. Regarding this, Zuniga e Cortes [134] highlight the importance of developing these materials as they may be an important tool for fighting off the COVID-19 and future pandemics.

7.2 Metal and ceramic additive manufacturing

As reported, metal and ceramic AM did not show significant engagement during the COVID-19 pandemic. Even though metal AM has grown exponentially in the last years [21], it is still an expensive technology with less facilities around the world. However, this growth will create new opportunities for the technology expansion, development, and accessibility, making it an important tool for possible next pandemics.

7.3 Design for additive manufacturing

The advantages of AM, such as freedom of design, allow using lattice structures, organic shapes, stacking, cooling channels, topology-optimized geometries and more. These features are related to AM-engineering design, named as design for additive manufacturing. The DfAM also relates to process particularities, such as layer-by-layer manufacturing, thermal history, and residual stress [135]. This area is quickly evolving, aided by software development, and will strongly impact AM industry and development. In a review work, Thompson et al. [135] study the importance of DfAM and highlight that the future will bring educational materials for institutions, industry and hobby community. Consequently, DfAM will evolve and leverage AM productivity, suitability of design, lower production costs, and open new opportunities of applications.

7.4 Rapid tooling

AM is a powerful tool for prototyping and small batch production. However, when dealing with big batches, conventional techniques, such as injection molding, are economic favorable [136–138]. As an example, a preprinted work by Kunkel et al. [139] presented a qualitative comparison between AM and injection molding capabilities for large-scale production of face shields. For a single AM machine, the production capability was of about 10 per day, while for an injection molding machine it reached a capability of 2000. Nevertheless, AM can be used for rapid tooling, an accelerated production of tools for injection molding. Furthermore, conformal cooling channels can be added in the design. Conformal cooling channels, which cannot be produced by conventional production technologies, are cooling channels in tooling that follow the shape of the designed parts. These channels provide enhanced thermal control with improved heat exchange, implying in faster production cycles, better products, and increased injection tool life [69, 135, 136, 140]. This area is related to the DfAM field and is developing as research is done [135]. Therefore, AM will be able to accelerate the production of tooling devices for optimized mass production. As an example made reality during the pandemic, to achieve mass production, Catalysis Additive Tooling company took 2 weeks to design and produce a 3D printed metallic injection mold for manufacturing headbands for face shields [141].

7.5 Bioprinting

A technology with great potential to help fight pandemic diseases is bioprinting. This is a technology, emerged from 3D printing in 2003 [142], that uses bioink as deposition material [143]. Groll et al. [144] define bioink as "a formulation of cells suitable for processing by an automated biofabrication technology that may also contain biologically active components and biomaterials". Still in its infancy, the technology can be used in regenerative medicine to support the manufacture of tissues and organs for transplantation [145, 146]. It could also be used for producing lung models—or any other organ model -, which could be used to study a disease dynamic and analyze an infected organ response to drug targets, detecting the disease progression in vitro [147, 148]. In this regard, Berg et al. [148] have shown the model ability to mimic the distribution of an influenza A virus strain in a real lung, something impossible for traditional cell culture.

7.6 3D printed medicines

As the pandemic diseases can easily overpass frontiers, it is important to develop strategies for producing and distributing drugs to all parts of the world during supply chain disruptions. Regarding this, there is the possibility to 3D print oral solid dosage forms (OSDF) with different drugs in a customized way [140, 149]. These medicines can be produced with controlled dosages, according to patients' characteristics, with controlled release and, most importantly in a pandemic scenario, in a decentralized way [140]. Therefore, AM can be used for producing drugs at hot spots where conventional drugs cannot reach [140]. However, quality control, costs lowering, and the selection of the AM technology according to the formulation requirements are some key challenges that must be addressed for this application to be viable possible future pandemic scenarios [140].

7.7 Industry 4.0

The AM technology is described as part of Industry 4.0 [28, 113]. Regarding this, Choong et al. [34] highlights that AM machines will continue to be key parts in the cyber-physical post-pandemic scenario. In a review by Khan and Javaid [150], the authors point AM machines as part of an automated emergency system composed by innovative technologies, such as drones, machine learning, and artificial intelligence, to quickly deliver PPE at required places without human contact. Therefore, AM will benefit from Industry 4.0 development.

8 Final considerations

Additive manufacturing has emerged as an essential technology during COVID-19 pandemic. Because of the supply chain disruption, various devices, such as face shields, face masks, valves, nasopharyngeal swabs, and other devices were in shortage. Quick and innovative design associated with AM were successfully used for production of these items, saving lives from health workers, patients, and general population. These devices could be almost instantaneously produced in diverse parts of the world, as soon a project file was projected or shared through global network, pointing out for a future reduction in logistics with local production. Other major features that leveraged AM role during pandemic were the great number of 3D printers spread around the world, even in developing countries, the ease of sharing and downloading printable parts, and its ability for rapid prototyping first designs and equipment parts. Accompanied from diverse initiatives of companies, groups, and individuals in helping people in need, a mass production of devices was reached.

As this massive production gained the notoriety of people and media, it also brought up some issues to be overcome before the next emergency. The lack of centralized standards and guidelines from regulatory agencies caused different people, groups, and companies to take the initiative for producing non-validated parts from their own experience. This issue called the need for producing pre-approved guidelines for these situations that will allow people to help in a short period of time, without being threatened by legal issues and harming final users. Furthermore, intellectual property emergency laws must be developed to ensure people lives, as during the pandemic the supply chain disruption created a shortage of diverse essential devices from medical suppliers. In this line, public domain open-source equipment and devices can be developed and act as an emergency option during these situations. Within that, scientists must work in testing and publishing results. These works will remain in literature as a reliable peer-reviewed data, beyond media and social media volatile information, and will help the development of guidelines and projects that may be centralized and stay as resource during future pandemics.

Finally, AM is still a relatively recent technology. Materials, techniques, software, and applications are being developed daily. This will ensure that additive manufacturing will continue to be fundamental to help humanity fight the next coming pandemics.

Author contributions GAL: main idea; literature search; data analysis; draft; critical review. GBN: literature search; draft; critical review. GC: critical review. JVLS: literature search; draft; critical review.

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Availability of data and materials Not applicable.

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

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