Industrial applications of 3D printing to scale-up production of COVID-19-related medical equipment

Muhammad Zaheer Abbas*
1Faculty of Business and Law, Queensland University of Technology, Brisbane, Australia

*Author for correspondence: muhammadzaheer.abbas@connect.qut.edu.au

Additive manufacturing or 3D printing allows the rapid conversion of information from digital 3D models into physical objects. The current COVID-19 crisis underscored the value of 3D-printing technology in addressing critical shortages in the medical product supply chain. This article provides a review of the significant role of additive manufacturing technologies in addressing the COVID-19 situation. This article concludes that 3D printing has an important role in global public health because of its potential to adapt to emerging situations far more easily and quickly as compared with conventional manufacturing methods. There is a need for further research to improve the technology to mass produce better quality products more economically. Currently, the 3D-printing industry is concentrated in the US and Western Europe. Policy efforts are needed to tap all markets across the globe in order to be better prepared for a future pandemic.

First draft submitted: 25 January 2021; Accepted for publication: 27 July 2021; Published online: 9 August 2021

Keywords: 3D printing • additive manufacturing • COVID-19 • health emergency • industrial application • medical equipment

The COVID-19 pandemic has ravaged the world since the end of 2019. There is a hierarchy of medical technologies in terms of their utility to combat the COVID-19 crisis. Vaccines lie at the top of the hierarchy to curb the spread of the pandemic. Understandably, the focus of international cooperation and collaboration has been on developing safe and effective vaccines as soon as possible. Diagnostics and therapeutics can be placed second in the hierarchy. Then come personal protective equipment (PPE) and other medical equipment. Although low in the hierarchy, PPEs are critically needed as the health and safety of healthcare professionals, who face heightened risks of infection, remain threatened without proper protection. Healthcare professionals comprised 21% of cases in the 2002 severe acute respiratory syndrome outbreak [1]. To prevent such an alarming trend and to limit the devastating health and socio–economic impact of the COVID-19 pandemic, it is essential to properly support and safeguard frontline healthcare workers.

The COVID-19 health crisis put global healthcare systems under critical strain. Vulnerabilities of conventional supply-chain mechanisms were exposed as there was a significant shortage of PPE and other materials for medical personnel as well as for patients and regular people [2]. Plagued with a serious lack of resources, healthcare providers had to seek alternative sources of critically needed medical equipment. The global crisis increased the visibility of the possibilities provided by 3D printing and triggered heightened attention and urgent interest in its extraordinary potential. Although 3D printing does not offer much help in the quest for COVID-19 vaccines, it has a high level of utility in diagnostic testing, PPE supplies and other medical equipment supplies. It provides the much-needed flexibility in the manufacturing and supply chains [3].

Additive manufacturing is defined as the ‘process of joining materials to make parts from 3D-model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies’ [4]. 3D printing is ‘fabrication of objects through the deposition of a material using a print head, nozzle or another printer technology’ [4]. This method of manufacturing is ‘in contrast with conventional manufacturing processes in which physical shapes emerge either by removing material, as in machining, or changing the shape of a set

References

[1] World Health Organization. (2003). Severe acute respiratory syndrome (SARS) epidemic, 2003. Retrieved from https://www.who.int/coronavirus/publications/sars-background-note/en/

[2] Centers for Disease Control and Prevention. (2020). COVID-19: Healthcare system preparedness and response. Retrieved from https://www.cdc.gov/coronavirus/2019-ncov/hcp/prepare/supply-chain.html

[3] Advanced Manufacturing Industry Council. (2020). Additive Manufacturing. Retrieved from https://www.amicouncil.org/research/additive-manufacturing/

[4] 3D Printing Industry. (2020). What is 3D Printing? Retrieved from https://3dprintingindustry.com/what-is-3d-printing/
volume of material’ [5]. Each of these successive layers of raw material ‘can be seen as a thinly sliced horizontal cross-section of the eventual object’ [6]. Unlike any other manufacturing technology, this advanced fabrication method manufactures 3D tangible products from a predesigned computer-driven 2D blueprint or digital model, called a computer-aided design (CAD) file, of the required shape [7]. This unique and versatile manufacturing method suits time-sensitive innovation and manufacturing as it does away with the time-consuming and costly tooling and machining requirements.

The current health emergency put a fresh light on the unique capabilities of 3D printing to provide innovative solutions to emerging problems and to address medical product supply chain disruptions in an emergency. As noted by M Attaran, “the strengths of 3D printing are that it can be anywhere, can print virtually anything, and adapt on the fly” [8]. These features help 3D printing to fill the critical gaps in the supply chain of critically needed medical equipment. This article provides a review of the significant role of additive manufacturing technologies in addressing the COVID-19 situation. This review, in respect of fast-moving developments, draws upon a wide range of sources including peer-reviewed publications, blogs, quotations from stakeholders, media reports and real-world examples. This review is important as it is specifically focused on the industrial applications of 3D printing in response to the COVID crisis. This article will benefit the field and patients in the future as it draws attention of policymakers to key policy concerns and makes recommendations for policy initiatives to make better use of 3D-printing technology in a future pandemic. It offers a speculative and forward-looking perspective of the role of 3D printing in a future health emergency.

This article has a three-part structure including the introduction and the conclusion. Part II considers the COVID-19-related industrial applications of 3D printing. In particular, it explores the applications of 3D printing to fabricate PPE (like face masks, face shields), medical and testing devices (like ventilator splitters and nasal swabs), and useful accessories (like hands-free door openers). The conclusion in Part III calls for improvements in 3D-printing technology to make it the fully-fledged first-choice manufacturing technique for mass production of medical equipment in response to a future pandemic. It also calls for a geographically dispersed growth of the 3D-printing industry so that a wide range of the global population can benefit from its unique benefits.
can take days and even weeks for traditional manufacturers [11]. This is a major drawback, especially in situations when there a need to cover the time-sensitive high demand for critical products.

Moreover, the ease of achieving customizability in shape distinguishes 3D-printing technology from traditional manufacturing methods. 3D-printing’s geometrical freedom allows adaptability and flexibility in problem-solving. Mass customization and low-volume manufacturing allow the making of more relevant products without investing excessive time and resources [15]. The customization feature becomes even more profound when 3D printing is paired with 3D scanning. 3D scanners can be used to quickly turn a physical object into a digital object [13]. 3D digitizing is the ‘method of acquiring the shape and size of an object as a 3D representation by recording x, y, z coordinates on the object’s surface and through software the collection of points is converted into digital data’ [4]. The digital design file or CAD file can be simply iterated to make any alteration or adjustment. On the contrary, making customized products by deploying traditional manufacturing techniques is both costly and time-consuming as design modifications cannot be easily achieved [10]. A traditional manufacturer may need to make costly changes to the manufacturing process, requiring new tools and molds, to realize a change in design. Even with additional costs and efforts, conventional techniques are constrained in achieving optimal customizability because reaching some places of the geometry is simply beyond the capacity of traditional manufacturing methods which offer the possibility of making much less versatile objects within a limited spectrum of shapes. Computer-aided designing has, “advanced our capacity to understand and visualize mathematical forms that extend beyond the limits of traditional Euclidean geometry” [16]. 3D printing allows us to conveniently build those complex forms.

Complexity is free in 3D printing because complex designs can be made with little or no additional cost [17]. Complexity costs the same as simplicity as a 3D printer can print self-assembled complex products without involving any additional efforts or arrangements. The zero-marginal cost of manufacturing complexity, with no constraints on the geometry, is significant in enriching approaches to problem-solving, especially in an emergency, because a lot of new possibilities emerge when complexity is free and easily achievable. The opening of new possibilities is particularly important for personalized applications in the medical field since every patient’s and caregiver’s geometry is different [18]. On the contrary, making complex products by employing traditional manufacturing techniques is both costly and cumbersome [19]. Extra complexity requires a more expensive mold with more parts [20]. Multiple parts of complex products need to be designed and manufactured separately and then assembled manually, often involving human effort. The requirement of postproduction assembly also adds to labor costs.

Furthermore, combining different raw materials into a single product is difficult in traditional manufacturing methods. Customizability in the composition is much easier to achieve while 3D-printing products. There are continual advances in combining antimicrobial polymers with 3D-printing materials to improve their antimicrobial activity against viruses, fungi and bacteria [21]. Materials like copper oxide, titanium oxide, zinc oxide, magnesium oxide have shown biocidal effects for a wide range of viruses [21,22]. The possibility of fabricating products by employing antimicrobial filament creates opportunities for promising applications of 3D printing in response to the COVID-19 pandemic. For instance, the addition of copper oxide into protective face masks can result in achieving effective anti-influenza properties and reducing the viral load on the masks [22]. The high cost of antimicrobial filaments can be a concern. Low-cost options, like N-halamines, can be considered for incorporation into polymers [23].

This section discusses some of the most notable industrial applications of 3D printing during the current health crisis. It also proposes improvements in the current capabilities of 3D printing in order to be better prepared for a future health emergency.

**Personal protective equipment**

PPE is key to the safety of both the patient and the caregiver given the extreme contagiousness of the COVID-19 virus and the volume of infected patients. According to the WHO guidelines, proper PPE is necessary for all medical services in hospitals and other healthcare settings [24]. Shortages of PPE, resulting from supply chain disruptions and demand increases, put healthcare professionals in grave danger. The 3D-printing community stepped into the void to offer support to hospitals, nursing homes and even refugee camps [25]. The 3D-printing industry fabricated various PPE devices during this COVID-19 pandemic.

**Protective face masks**

Protective face masks, as shown in Figure 1, have an important role in slowing the spread of the COVID-19 virus, which can be spread through respiratory droplets. Protective face masks are critical not only for medical personnel
who treat infected patients but also for the general public professionals who test, transport or engage with virus victims in any way.

3D printing has a high potential to be used for customized and personalized applications in the medical field [27]. The flexibility of 3D printing to fabricate customized objects of any desired shape – without requiring much time, effort and monetary cost – comes handy in producing personalized face-seal designs. A generic face mask might not match with a human face due to variation in shape and size because the face and nose lengths, chin arc, jawline and nose protrusion measurements vary from person to person [28]. Small particles can possibly enter the wearer's breathing zone due to the loose fit between the wearer's face and the surface of the generic mask [22]. 3D-printing technology enables personalizing of face masks to achieve a better fit on an individual basis and improved functionality in blocking contaminated air from entering around the edges of the mask [29]. Personalized face masks significantly improve comfort by reducing and evenly distributing the contact pressure [30]. Comfort refers both to the comfort of the breathing process and the comfort of the wearer's face. As detailed in Table 1, there were significant industrial applications of 3D printing to manufacture face masks during the current health crisis.

### Protective face shields

Protective face shields, as shown in Figure 2, have threefold importance. First, face shields protect healthcare professionals from respiratory droplets resulting from sneezing or coughing or splash of any respiratory secretion from COVID-19 patients [33]. Second, face shields help preserve the longevity of face masks by preventing their contamination [34]. This capability of face shields to mitigate the soiling of face masks is particularly important in
Table 1. Notable 3D-printing companies manufacturing face masks in response to the COVID-19 crisis.

| Company          | Country   |
|------------------|-----------|
| Materialise      | Belgium   |
| AddiFabb         | Denmark   |
| Trinkle          | Germany   |
| Forecast 3D      | USA       |
| 3D Systems       | UK        |
| Essentium        | USA       |
| Nexteer          | USA       |
| MatterHackers    | USA       |
| Flowbuilt M.     | USA       |
| Evonik           | Germany   |
| Ferrovial        | Spain     |
| Fathom           | USA       |
| Fortify          | USA       |
| Voodoo           | USA       |
| Caracol-AM       | Italy     |
| Nagami Design    | Spain     |

Data taken from [31–32].

Figure 2. 3D-printed protective face shield.
Reproduced with permission from [29], licensed with CC BY 4.0.

...a pandemic situation when acute shortages in supplies of face masks are caused by disruptions and high demand. Third, face shields help slow down the spread of the COVID-19 virus as they prevent touching of face, nose and eyes [34].

The face shield is created by 3D printing the solid headband and chin piece and attaching a separately sourced transparent plastic sheet or faceguard [29]. The cost of fabricating a face shield, by using this straightforward method involving minimal assemblage requirement, ranges from $10 to $177 depending on the durability and the printing materials used [35]. Maintenance of 3D face shields is easy and cost effective as the defective parts can easily be removed and replaced in the case of damage [35]. It is essential to clean and disinfect all parts of a 3D-printed face shield before using it. As detailed in Table 2, there were significant industrial applications of 3D printing to...
Table 2. Notable 3D-printing companies manufacturing face shields in response to the COVID-19 crisis.

| Company        | Country          |
|----------------|------------------|
| Issinova       | Italy            |
| NGen           | Canada           |
| Fast Radius    | USA              |
| Prusa3D        | Czech Republic   |
| BCN3D          | Spain            |
| Titan Robotics | USA              |
| Prodways       | France           |
| Forecast 3D    | USA              |
| Carbon         | USA              |
| Blue Origin    | USA              |
| Nexteer        | USA              |
| Paragon        | UK               |
| Azul 3D        | USA              |
| Fathom         | USA              |
| SmileDirectClub| Canada           |

Data taken from [31].

Table 3. Notable 3D-printing companies manufacturing ventilator splitters in response to the COVID-19 crisis.

| Company          | Country |
|------------------|---------|
| 3D Systems       | UK      |
| Protolabs        | France  |
| Evonik           | Germany |
| EnvisionTEC      | USA     |
| Fathom           | USA     |
| CPR Technology   | Italy   |
| Roboze           | Italy   |
| Photocentric     | UK      |
| Proto21          | Dubai   |

Data taken from [31].

 manufacture face shields during the current health crisis.

Medical & testing devices

Ventilator splitters

A ventilation system is the last hope for critically ill COVID-19 patients facing respiratory failure. A ventilator, typically found in intensive care units is, "a medical device used to assist patient breathing (by mechanical or pressure control) by moving breathable air into and out of the lungs with intubation" [35]. By providing positive pressure to the lungs, it supports a critically-ill patient's respiration by maintaining an adequate level of oxygen concentration in the arterial blood [36].

The supply of available ventilators was too low to cater to all COVID-19 patients with acute respiratory distress who needed invasive mechanical ventilation [29]. Expanded use of ventilators was made possible by using 3D-printed ventilator splitters [6]. By making this quick and feasible adjustment, the capacity of a single ventilator can be increased to ventilate up to four simulated adults for a limited time [22]. These specially designed splitters divide the airway of the ventilator [37]. 3D-printing technology enables the customization of designs of these splitters to minimize dead-space volume and prevent air leakage [22]. Table 3 enlists some of the 3D companies that manufactured ventilator splitters during the current health emergency.
Diagnostic testing is crucial to identify and isolate known cases and to assess risks of further spreading of COVID-19. As noted by TA Ghebreyesus, WHO Director-General, "You cannot fight a fire blindfolded. And we cannot stop this pandemic if we don’t know who is infected. We have a simple message for all countries: test, test, test. Test every suspected case" [38]. The rapid spread of COVID-19 resulted in acute shortages of appropriate nasopharyngeal swabs [39] or nasal swabs, a medical device roughly 15 cm in length and 2 to 3 mm in diameter designed to collect secretions from the posterior nasopharynx for diagnostic sampling (Figure 3) [40]. The severe shortages were caused by both decreased supply resulting from manufacturing stoppages and unprecedented demand [39].

The large-scale testing desperately required an adequate supply of nasal swabs, which provide the highest sensitivity for diagnosing COVID-19 infection [39]. There were severe challenges in ramping up testing across the globe because the conventional manufacturing of nasal swabs was centralized in Italy [3]. Moreover, the conventional method of manufacturing diagnostic swabs is tedious and limited. Industrial use of 3D-printing technology helped to promptly address shortages for COVID-19 testing [42]. With a total print time of around 3 h and 40 min, 300 nasal swabs can be 3D printed at once [43]. The cost of 3D printing the swabs is around US$ 0.25 per swab [29]. Table 4 enlists some of the 3D companies that manufactured nasal swabs during the current health emergency.

Door handle accessories
Faced with the risk of highly-transmittable viral infection, hospitals are bound to take meticulous precautionary measures to limit the spread of the COVID-19 virus via direct contact. Door handles in hospitals are one of the most common mediums for infection as they “may act as vectors for the transmission of viruses and multidrug-resistant...
Table 4. Notable 3D-printing companies manufacturing nasal swabs in response to the COVID-19 crisis.

| Company      | Country |
|--------------|---------|
| Markforged   | USA     |
| Forecast 3D | USA     |
| Carbon       | USA     |
| Paragon      | UK      |
| EnvisionTEC  | USA     |
| Formlabs     | USA     |
| Origin       | USA     |
| Structo      | Singapore |

Data taken from [31].

Figure 4. 3D-printable model of door handle accessory. Reproduced with permission from [29].

organizations responsible for nosocomial infections” [44]. For the sake of ward control and patient privacy, hospitals normally have a large number of doors. Regular surface cleaning does not completely address the risk of transmission from door handles which are routinely subjected to a lot of physical contact [29]. The use of automatic doors may be considered to avoid the risk of spreading infection from door handles, but most hospitals may lack financial resources to materialize this option. The same goal of avoiding direct skin-to-surface contact can be achieved in a much more economical way by using 3D-printing technology to design and manufacture hands-free door openers. This novel accessory creates an extension to existing door handles to enable opening doors by using forearms instead of hands (Figure 4). Operating doors with forearms substantially reduces the risk of transmitting the COVID-19 virus because this body part is rarely used to touch the mouth, nose and eyes [45].

Even the simplest interventions to limit transmission can play a significant role in slowing down the spread of the COVID-19 virus. Ready-to-print designs of door handle accessories are available for free download and fabrication.
by using a variety of 3D-printing approaches and materials [46]. 3D-printed door handle accessories are easy to install and do not require drilling holes. To assist hospitals in setting it up, Materialise provided video instructions on "How it works" [47]. Table 5 enlists some of the 3D companies that manufactured door handle accessories during the current health emergency.

There were also some unanticipated contributions from the industry that deserve a mention in this section (Table 6). Many automobiles manufacturers volunteered their 3D-printing facilities for the fabrication of COVID-19-related medical products [8]. 3D printing allows companies the flexibility to adapt quickly and convert their production in the light of changing needs of industry or society. This unique capability of 3D printing empowers companies to practically contribute physical objects in response to an emergency. Several unanticipated contributions from the industry were possible only because of the enabling role of 3D printing. No other manufacturing method allows such a quick adaptation to deliver in an entirely new and irrelevant field. As noted by a spokesperson for Volkswagen, "Medical equipment is a new field for us. But as soon as we understand the requirements, and receive a blueprint, we can get started" [48]. Likewise, a spokesperson for BMW said, "the production of components using 3D-printing technology is a possibility" [48].

3D printing creates possibilities that no other manufacturing method can potentially create. Without the power of 3D printing, one could hardly imagine that technology companies, manufacturers of automobiles, aerospace corporations, and tire manufacturing companies would ever be able to deliver medical equipment in a health emergency.

Despite its unique capabilities and remarkable contributions during the COVID-19 crisis, at present, 3D printing is aptly suitable only for low-volume and specialized products. When it comes to large-scale production, 3D printing does not compete with traditional production processes, like injection molding. Desktop 3D printers, based on stereolithography or fused deposition modeling technology, have been most commonly used for 3D printing medical devices [50]. These printers are not fast as they "rely on stepwise, layer-by-layer approach to fabrication of objects, which inevitably takes time and is the main factor limiting manufacturing throughput" [51]. The fabricating...
time increases even more if there is a demand for a higher-quality product [25]. For the widespread adoption of 3D printing as a mainstream manufacturing technique, it is important to tackle the problem of slow printing speed.

3D printing, in its current form, is not a viable alternative to factory production also because of the cost of mass production. Although manufacturing of parts in metal is possible using 3D printers, the process would be far more expensive as compared with traditional factory production [52]. The cost per item is high if identical copies are 3D manufactured at scale because the base material is costly [10]. To provide a more robust production alternative, the next goal of 3D-printing technology should be to provide mass-production capabilities with a key focus on reducing cost, improving accuracy, and enhancing the speed and reliability of 3D printers. In order to make 3D printing the fully-fledged first-choice manufacturing technique for mass production of medical equipment in response to the next pandemic, significant research and concerted policy efforts are needed in all the different additive manufacturing processes – like binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion and others.

Moreover, quality control and compliance with health standards can be a concern. To ensure safety and efficacy, a certain level of quality control is needed before a 3D-printed medical device reaches the general market. As compared with advanced level equipment, like biomedical devices and tissue-engineered scaffolds, 3D-printed medical products manufactured in response to COVID-19 are less complicated and may require less stringent regulatory and dimensional accuracy standards [10]. A lower degree of risk in the intended use of a device is expected to require lower level of regulatory control. Some level of testing and validation is, however, required in normal circumstances to make sure that 3D-printed medical devices do not cause any unintentional and avoidable harm to the patients.

In the COVID-19 emergency, leading to life-or-death choices due to supply shortages, it was not possible for many governments to carry out formal regulatory testing by using standardized methods and enforce strict regulatory controls on 3D printing, which provides a sustainable backup solution to address supply chain failures. For safety of patients and healthcare workers, it is important to follow a certain level of safety standards and quality measures even in an emergency situation. Learning from the COVID-19 experience, governments may develop safety protocols related to the use of 3D printing in a future health emergency. To maintain the acceptable quality of health-related 3D-printed objects, these protocols should provide guidelines about CAD modeling of medical devices, the suitable 3D-printing technology and appropriate materials to be used to fabricate such devices [53].

It is important to provide a framework for additive manufacturing of medical devices because printing parameters, fabrication materials, fiber thickness and printing raster orientation have an impact on the quality and mechanical properties of 3D-printed parts [54]. To address the dangers of using 3D printing in a health emergency, concerning regulatory authorities of governments should develop mechanisms for expedited evaluation and approval/certification of prototypes of urgently-needed medical equipment. Approvals and certifications are very complicated in the absence of clearly defined standards [55]. Government authorities should also issue guidance documents to make designers and manufacturers of 3D-printed medical parts aware of their potential legal liability. Concerted policy and regulatory efforts are needed to realize the goal of using 3D-printing technology to swiftly fabricate safe and certified medical products on a scale in a future pandemic.

**Conclusion**

3D printing is not yet another manufacturing technique, it is a completely different technique. Because of its unique capabilities, 3D printing has a major role in health emergencies like COVID-19. It offers the much-needed flexibility, agility and diversity of solutions in response to an emergency. 3D printing is a resilient technology as it delivered the much-needed medical supplies in a timely fashion under extraordinary time pressure, despite all odds that negatively impacted conventional supply chains during the pandemic. It provides sustainable possibilities in ways that cannot be even imagined by traditional manufacturers. The flexibility of this technology to design and fabricate customized objects – without requiring much time, effort and monetary cost – comes handy in an emergency like the COVID-19 pandemic.

It can be noted from the above analysis that industrial 3D printing had a significant impact in addressing COVID-19 related shortages of materials. Despite its unique capabilities and remarkable contributions, industrial 3D printing does not compete with traditional production processes in speed, cost and quality when it comes to mass production. Significant research and concerted policy efforts are needed in all the different 3D-printing processes in order to make it the fully-fledged first-choice manufacturing technique for mass production of medical equipment in response to a future pandemic.
More importantly, it can be noted that the 3D-printing industry mostly concentrated in the USA and Western Europe manufactured COVID-19-related medical materials. There are no examples of 3D manufacturing in response to COVID-19 from markets in low- and middle-income countries. It is a cause of serious concern if a vast majority of markets in the developing world remain untapped. Affordability and availability of medical technologies are major concerns in low- and middle-income countries. The 3D-printing industry can improve the quality of healthcare in these countries by addressing these concerns in an inexpensive way. Policy efforts need to be made on a priority basis to tap all markets across the globe in order to be better prepared for a future pandemic.

**Future perspective**

The combination of human creativity and 3D-printing technology can solve critical problems in an emergency situation. Shared objectives can be accomplished more quickly if creative people from a wide range of professional backgrounds are familiar with the capabilities of 3D printing. To open up new possibilities in health-related applications of 3D printing, it would be desirable to create an environment where medical professionals and engineers can work together to solve emerging problems. In the foreseeable future, governments may be expected to support education and training in respect of 3D printing. As well as including 3D printing in the curriculum at the primary school level, the disciplines may be taught in the engineering and medical curriculum right from the undergraduate level.

Learning from the COVID-19 experience, governments may be expected to support decentralization of manufacturing capabilities and diversification of supply chains. It will improve responsiveness and product availability while reducing transportation costs and risks associated with cross-country transportation. Most of the hospitals and medical centers, at least in economically-advanced countries, may be equipped with their own in-house 3D-printing capabilities to produce patient-specific medical parts and to break their dependence on global supply chains. Moreover, governments may be expected to remove regulatory uncertainties regarding the use of 3D printing in the medical sector. A clear regulatory framework and a specialized mechanism for fast-track safety review and quality validation of CAD designs may be provided to use the full potential of 3D printing as a life-saving technology in a future pandemic.

More importantly, the overall cost of 3D printing is expected to decline further in the future. Development of more versatile 3D printers can be foreseen that can fabricate better quality parts more quickly and cost effectively. Greater resolution and manufacturing precision will be achieved at lower costs and faster rates. The breadth of 3D-printing applications will continue to grow. New technologies related to 3D printing will emerge and the scope of printing materials will expand with the passage of time. 3D-printing technology will become more accessible in economically advanced countries. It will shape the future of many industries and new players will enter the market. However, concerted efforts would be required at global and national levels to promote 3D printers to low- and middle-income countries.

**Acknowledgments**

MZ Abbas, member of the Australian Centre for Health Law Research (ACHLR), is a postdoctoral research fellow at the Queensland University of Technology (QUT), Brisbane, Australia. In this role, the author is working with M Rimmer on his Australian Research Council Discovery Project ‘Inventing the Future: Intellectual Property and 3D Printing’ (Project ID: DP170100758). The author would like to acknowledge with great appreciation his wife S Riaz for her unconditional support and valued cooperation. The views presented in this paper and any mistakes are, however, the sole responsibility of the author.

**Financial & competing interests disclosure**

The author has received funding from the Australian Research Council Discovery Project (project ID: DP170100758). The author has no other relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript apart from those disclosed.

No writing assistance was utilized in the production of this manuscript.
Executive summary

Introduction
- The importance of personal protective equipment (PPE) for the health and safety of healthcare professionals is highlighted.
- The concept of additive manufacturing is explained in the context of COVID-19 and supply-chain disruptions.

Industrial applications of 3D printing in response to COVID-19
- The unique capabilities of 3D-printing technology are emphasized.
- 3D-printing technology rose to the challenge by enabling an agile manufacturing environment to scale production speedily.
- 3D-printing technology's unique ability to do multiple iterations, with low lead times, is important in an emergency situation to fabricate time-critical medical products.
- Making customized products by deploying traditional manufacturing techniques is both costly and time-consuming.

Protective face masks
- 3D-printing technology enables personalizing of face masks to achieve a better fit on an individual basis.
- Personalized face masks significantly improve comfort by reducing and evenly distributing the contact pressure.

Protective face shields
- Protective face shields are important in protecting healthcare professionals from respiratory droplets, preserving the longevity of face masks, and preventing contact with face, nose, and eyes.
- The cost of 3D printing face shields is low and maintenance of such shields is easy in the case of damage.

Ventilator splitters
- A ventilator helps in maintaining an adequate level of oxygen concentration in the arterial blood by providing positive pressure to the lungs.
- The available supplies of ventilators were too low to cater to unprecedented demand for respiratory support apparatus during the current COVID-19 crisis.
- Expanded use of ventilators was made possible by using 3D-printed ventilator splitters.

Nasal swabs
- The rapid spread of COVID-19 resulted in acute shortages of appropriate nasopharyngeal swabs.
- Industrial use of 3D-printing technology helped to promptly address shortages for COVID-19 testing.

Door handle accessories
- Door handles in public places are routinely subjected to a lot of physical contact.
- The goal of avoiding direct skin-to-surface contact was achieved in an economical way by using 3D-printing technology to design and manufacture hands-free door openers.

Regulatory compliance
- In the current health emergency, it was not possible for many governments to carry out formal regulatory testing and enforce strict regulatory controls on 3D printing.
- Learning from the COVID-19 experience, governments may develop protocols related to the use of 3D printing in a future health emergency.
- Concerning regulatory authorities of governments should develop mechanisms for expedited evaluation and approval/certification of prototypes of urgently-needed medical equipment.

References
Papers of special note have been highlighted as: ● of interest; ●● of considerable interest

1. Maracaja L, Blitz D, Maracaja DLV, Walker CA. How 3D printing can prevent spread of COVID-19 among healthcare professionals during times of critical shortage of protective personal equipment. J. Cardiothorac. Vasc. Anesth. 34(10), 2847–2849 (2020).
2. Amin D, Nguyen N, Roser SM, Abramowicz S. 3D printing of face shields during COVID-19 pandemic: a technical note. J. Oral Maxillofac. Surg. 78(8), 1275–1278 (2020).
3. Verboeket V, Khajavi SH, Krikke H, Salmi M, Holmstrom J. Additive manufacturing for localized medical parts production: a case study. IEEE Access 9, 25818–25834 (2021).
4. ISO/ASTM International. Additive manufacturing – general principles – terminology (ISO/ASTM 52900:2015). 1–19 (2017).
5. Schwab K, Davis N. World Economic Forum. Reforming the physical world. In: Shaping the Fourth Industrial Revolution. Switzerland (2018).
6. CIOL. From face shields to ventilators and nasal swabs, 3D printing is changing the medical scenario (2020). http://www.ciol.com/face-shields-ventilators-nasal-swab-3d-printing-changing-medical-scenario/
7. Bhatia SK, Ramadurai KW. 3-dimensional printing and rapid device prototyping. In: 3D Printing and Bio-Based Materials in Global Health. Springer, Cham, Switzerland, 21–38 (2017).
Industrial applications of 3D printing to scale-up production of COVID-19-related medical equipment

8. Attaran M. 3D printing role in filling the critical gap in the medical supply chain during COVID-19 pandemic. Am. J. Ind. Bus. Manag. 10(05), 988–1001 (2020).

9. Braddock S, Bowyer A, Haufe P. The intellectual property implications of low-cost 3D printing. ScriptEd 7(1), 5–31 (2020).

10. Tarfaoui M, Nachtane M, Goda I, Qureshi Y, Benyahia H. 3D printing to support the shortage in personal protective equipment caused by COVID-19 pandemic. Materials 13(5), 3339 (2020).

11. Capital Market laboratories. 3D printing industry steps up to remedy coronavirus equipment shortages. (2020). http://www.cmiviz.com/stocks/DDD/news/e/ibdlink-2020-5-1-3d-printing-industry-steps-up-to-remedy-coronavirus-equipment-shortages

12. Dougherty D. The maker mindset. In: Free to Make: How the Maker Movement is Changing Our Schools, Our Jobs, and Our Minds. North Atlantic Books, CA, USA (2016).

13. Osborn LS. 3D printing and trademarks: the dissociation between design and manufacturing. 3D Print. Intellect. Prop. 63, 121–142 (2019).

14. Oladapo BI, Ismail SO, Afolalu TD, Olawade DB. Review on 3D printing: fight against COVID-19. Mater. Chem. Phys. 258, 123943 (2021).

15. Dickinson H. The next industrial revolution! The role of public administration in supporting government to oversee 3D printing technologies. Public Adm. Rev. 78(6), 922–925 (2018).

16. Connell M, Labaco RT, Birtchnell T. Out of hand: materialising the digital. Maas Media 115 (2016).

17. Osborn LS. Patents – indirect infringement and intermediaries. In: 3D Printing and Intellectual Property. Cambridge University Press, Cambridge, UK, 104–120 (2019).

18. Chandler DC, Salmi M. Law and technology of 3D printing and medical devices. In: 3D Printing, Intellectual Property and Innovation: Insights from Law and Technology. Ballardini R, Norgård M Partanen J (Eds). Kluwer Law International BV, The Netherlands (2016).

19. Lipson H, Kurman M. The ten principles of 3D printing. Big Think (2013). https://bigthink.com/experts-corner/the-ten-principles-of-3d-printing

20. Wärnér C, Verbruggen D, Ehmann S, Klanten R. The aesthetics of complexity. Printing Things. Visions and Essentials for 3D Printing. Gestalten, Berlin, Germany (2014).

21. Coet JJ, Haggstrom J, Vivekanandan R et al. COVID-19 and a novel initiative to improve safety by 3D printing personal protective equipment parts from computed tomography. 3D Print. Med. 6(20), 1–12 (2020).

22. Zuniga JM, Cortes A. The role of additive manufacturing and antimicrobial polymers in the COVID-19 pandemic. Expert Rev. Med. Devices 17(6), 477–481 (2020).

23. Mokhena TC, John MJ, Mochane MJ et al. Antibiotic 3D-Printed Materials for Healthcare Applications Antibiotic Materials in Healthcare. Kokkarachedu V, Kanikireddy V, Sadiku R (Eds). Academic Press, MA, USA (2020).

24. World Health Organization. ‘When and How to Use Masks’. World Health Organization (2020). http://www.who.int/emergencies/diseases/novel-coronavirus-2019/advice-for-public/when-and-how-to-use-masks

25. Mueller T, Elkaseer A, Charles A et al. Eight weeks later – the unprecedented rise of 3D printing during the COVID-19 pandemic – a case study, lessons learned, and implications on the future of global decentralized manufacturing. Appl. Sci. 12(10), 1–14 (2020).

26. Swennen Gwen RJ, Pottel L, Haers PE. Custom-made 3D-printed face masks in case of pandemic crisis situations with a lack of commercially available FFP2/3 masks. Int. J. Oral Maxillofac. Surg. 49(5), 673–677 (2020).

27. Salmi M. Additive manufacturing processes in medical applications. Materials (Basel) 14(1), 1–16 (2021).

• Provides a good review of additive manufacturing processes and materials utilized in medical applications.

28. Ishack S, Lipner SR. Applications of 3D-printing technology to address COVID-19-related supply shortages. Am. J. Med. 133(7), 771–773 (2020).

29. Tino R, Moore R, Antoline S et al. COVID-19 and the role of 3D printing in medicine. 3D Print. Med. 6(11), 1–8 (2020).

30. Cai M, Li H, Shen S, Wang Y, Yang Q. Customized design and 3D printing of face seal for an N95 filtering facepiece respirator. J. Occup. Environ. Hyg. 15(3), 226–234 (2018).

31. Tarfaoui M, Nachtane M, Goda I, Qureshi Y, Benyahia H. Additive manufacturing in fighting against novel coronavirus COVID-19. Int. J. Adv. Manuf. Technol. 17, 1–15 (2020).

32. Davies S, O’Connor D, Griffiths L. The latest 3D printing efforts against COVID-19. TCT Magazine http://www.tctmagazine.com/additive-manufacturing-3d-printing-news/live-blog-how-the-3d-printing-industry-fighting-covid-19/

33. Morgan Frey. 3D printing companies ramp up efforts to tackle healthcare equipment shortage. S&P Global Market Intelligence (2020). http://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/3d-printing-companies-ramp-up-efforts-to-tackle-healthcare-equipment-shortage-57944522

34. Castellucci M. Hospitals, systems leverage 3D printing capabilities during pandemic. Modern Health Care 50(15), 1–3 (2020).
35. Advincula R, Ryan Dixon JC, Niu I, Chung J, Kilpatrick L, Newman R. Additive manufacturing for COVID-19: devices, materials, prospects, and challenges. In: MS Communications. Cambridge University Press, Cambridge, UK 10(3), 413–427 (2020).
36. Sapoval M, Gaultier AL, Giudice C Del, Pellerin O, Kassis-chikhani N. 3D-printed face protective shield in interventional radiology: evaluation of an immediate solution in the era of COVID-19 pandemic. *Diag. Interv. Imaging* 101(6), 413–415 (2020).
37. Ayyıldız S, Dursun AM, Yıldırım V, Ince ME, Güçelik MA, Erdöl C. 3D-printed splitter for use of a single ventilator on multiple patients during COVID-19. *3D Print. Addit. Manuf.* 7(4), 181–185 (2020).
38. Jiang L. Fighting the COVID-19 fire with molecular diagnostics innovations. *Cambridge Network* (2020).
39. Callahan CJ, Lee R, Zulauf KE et al. Open development and clinical validation of multiple 3D-printed nasopharyngeal collection swabs: rapid resolution of a critical COVID-19 testing bottleneck. *J. Clin. Microbiol.* 58(8), 1–10 (2020).
40. Haleem A, Javaid M. 3D-printed medical parts with different materials using additive manufacturing. *Clin. Epidemiol. Glob. Health* 8(1), 215–223 (2020).
41. USF Health Radiology. 3D-printed nasopharyngeal swabs for COVID-19 testing. (2020).
42. EnvisionTEC. EnvisionTEC to 3D-print mass quantities of nasopharyngeal swabs for COVID-19 testing based on successful clinical trial. (2020). https://envisitiontec.com/envisiontec-to-3d-print-mass-quantities-of-nasopharyngeal-swabs-for-covid-19-testing-based-on-successful-clinical-trial/
43. Cox JL, Koepsell SA. 3D-printing to address COVID-19 testing supply shortages. *Lab. Medicine* 51(4), 45–46 (2020).
44. Chen KL, Wang SJ, Chuang C et al. Novel design for door handle – a potential technology to reduce hand contamination in the COVID-19 pandemic. *Am. J. Med.* 133(11), 1245–1246 (2020).
45. Larran E. Additive manufacturing can assist in the fight against COVID-19 and other pandemics and impact on the global supply chain. *3D Print. Addit. Manuf.* 7(3), 100–103 (2020).
46. Materialise. Hands-free door opener to prevent the spread of coronavirus. Materialise. http://www.materialise.com/en/hands-free-door-opener
47. Materialise. Hands-free 3D-printed door opener to help against the spread of coronavirus. http://www.youtube.com/watch?v=02n7Pd360JU&feature=emb_logo
48. Reuters. Volkswagen tests ventilator output as carmakers join coronavirus fight. *Reuters* (2020).
49. Caulfield J. 3D printing finds its groove fabricating face shields during COVID-19 crisis. *Building Design+Construction* (2020).
50. Martin-Noguerol T, Paulano-Godino F, Menías CO, Luna A. Lessons learned from COVID-19 and 3D printing. *Am. J. Emerg. Med.* doi: 10.1016/j.ajem.2020.08.010 (2020) (Epub ahead of print).
51. Trivedi M, Lee J, Silva S et al. Additive manufacturing of pharmaceuticals for precision medicine applications: a review of the promises and perils in implementation. *Addit. Manuf.* 23, 319–328 (2018).
52. Birchnell T, Urry J. Thinking additively. *A New Industrial Future? 3D Printing and the Reconfiguring of Production, Distribution, and Consumption*. Routledge, Abingdon, UK and New York, USA (2016).
53. Belhouideg S. Impact of 3D-printed medical equipment on the management of the COVID-19 pandemic. *Int. J. Health Plann. Manage.* 35(5), 1014–1022 (2020).
54. Manero A, Smith P, Koontz A et al. Leveraging 3D printing capacity in times of crisis: recommendations for COVID-19 distributed manufacturing for medical equipment rapid response. *Int. J. Environ. Res. Public Health* 17(13), 4634 (2020).
55. Petro S, Shao H. On standardization efforts for additive manufacturing. *5th International Conference on the Industry 4.0 Model for Advanced Manufacturing*. Lecture Notes in Mechanical Engineering. Wang L, Majstorovic V, Mourtzis D, Carpanzano E, Galantucci L. (Eds). Springer, Cham, Switzerland (2020).

* Provides a detailed discussion on the standardization efforts with regard to additive manufacturing.