Applications of 3D Printing in Austere Environments

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Medical applications of 3D printing are growing rapidly and are predicted to transform the delivery of healthcare. In austere environments, 3D printing offers the potential to provide on-site, on-demand, personalized, and low-cost production capabilities of medical resources. Despite recent notable medical advances in 3D printing, significant technological and regulatory challenges remain to be addressed.

What is 3D Printing?

3D printing is a technology pioneered during the early 1980s that manufactures three-dimensional objects of various shapes, layer by layer, out of different materials.[27] Synonyms for 3D printing include: digital fabrication, additive manufacturing, rapid prototyping, fused filament fabrication, and solid free-form fabrication. Printing an object requires a 3D digital file, which may be edited with design software, to be uploaded to the 3D printer and then is digitally fabricated with printer material (**Fig. 1**).

Fused Deposition Modeling 3D Printing

Fused deposition modeling (FDM) 3D printers operate by feeding a thermoplastic filament into a print head, which melts and extrudes the molten plastic in a digitally controlled fashion layer by layer on a platform.[26] Desktop FDM printers are being evaluated for field use because of their portability, usability, affordability, and commercial availability, but they are currently limited to printing thermoplastic materials.[10]

Benefits of FDM 3D Printing

In austere environments, 3D printing technology offers many advantages for healthcare delivery.[26] 3D printing enables the localized production of customized medical resources on demand. The creation of digital libraries of 3D printable files could potentially lower costs by minimizing redundant medical inventory. Certain desktop FDM 3D printers are capable of printing their own components and, thus, have the capability for auto-repair if more than one printer is available. FDM 3D printing also offers possible sterilization and recycling capabilities. These features of 3D printing could lead to significant cost savings, improved clinical outcomes, and enhanced self-sufficiency of remote medical care facilities.

3D printing technology is affordable. Computer-assisted design software programs are free. Consumer desktop FDM 3D printers range from approximately \$300 to \$3000.[22] Many 3D designs are crowd-sourced, open source, and freely available for sharing and download in online repositories with user reviews.[12,13]

FDM 3D Printer Filaments

Most desktop FDM printers print acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA) rigid thermoplastics.[10] A 2015 SBIR grant solicitation from the National Institutes of Health stated that there are no companies supplying 3D printing materials to create flexible, implantable medical devices.[14] However, novel desktop FDM printer filaments are emerging with improved material properties.[10] These include: 1) flexible thermoplastic elastomers; 2) stronger, biodegradeable biopolyester blends; and 3) tougher, minimally off-gassing, food-safe copolyesters.[4,7,18] Several thermoplastic filaments containing recycled ABS or polyethylene terepthlate (PET) are now available for desktop FDM printers.[2,19]

Sterilization Methods for 3D Printed Surgical Resources

The ability to sterilize 3D printed surgical resources would be of great clinical benefit. Early research has demonstrated that the

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Fig. 1. Left panel: Dorsal view of 3D digital file of a custom mallet splint worn for 8 wk by an adult male patient to successfully treat an acute closed mallet injury. Right panel: Dorsal view of identical custom mallet splints 3D printed using glow-in-the-dark blue ABS thermoplastic on a 3D Systems Corp. Cube® 2nd generation FDM printer (left) and red PET thermoplastic containing 25% recycled drink bottles on a 3D Systems Corp. Ekocycle™ FDM printer (right).

high extrusion temperatures of the FDM printing process itself can sterilize thermoplastic material.[11,15,16] With proper handling, desktop FDM printers appear to be capable of printing sterile objects from nonsterile thermoplastic feedstock without additional treatment after printing.[15]

Several studies have explored low-temperature sterilization methods for FDM printed thermoplastics since these heat-sensitive materials cannot tolerate the autoclaving process.[5] ABS-M30i is an ISO 10,993 USP Class VI biocompatible thermoplastic that can be sterilized using gamma radiation or ethylene oxide gas. Preliminary studies indicate that nuclear decontaminant gel or hydrogen peroxide gas plasma could sterilize FDM printed ABS thermoplastic.[5,17]

A 2014 study showed that a FDA-approved glutaraldehyde protocol was capable of sterilizing an Army/Navy retractor printed using PLA on a desktop FDM printer.[16] Glutaraldehyde appears to be the preferred room-temperature sterilization process for PLA because it is affordable, simple to use, quick, and reusable without adversely impacting the biochemical or physical properties of PLA. Additional research is needed to ensure that the sterilization protocols for 3D printed materials meet regulatory standards.

3D Printer Filament Recycling

Reclamation devices to recycle FDM 3D printed ABS or PLA thermoplastic objects back into printer filament are available for hobbyists.[8,9] Several open-source and proprietary devices to manufacture desktop FDM printer filament from plastic waste are being prototyped.[3,6] However, further development is required to refine these small-scale recycling processes to ensure the reliable production of high-quality printer filament from waste plastic and printed objects.

Drawbacks of FDM 3D Printing

FDM 3D printers generally take minutes to hours to print an object.[26] Therefore, the speed of FDM 3D printing must be increased dramatically to apply this technology for manufacturing resources on demand for medical emergencies. Desktop FDM 3D printers can require troubleshooting and repair and, therefore, some training and knowledge is required to use and maintain 3D printers and their related software.[10]

A 2013 study showed that desktop FDM printers had off-gassing rates of 190 billion and 20 billion ultrafine particles per minute for ABS and PLA thermoplastic, respectively.[20] FDM thermoplastic printer materials are also being developed with potentially much lower rates of off-gassing.[4] At present, 3D printer manufacturers recommend that their desktop FDM printers be operated in well-ventilated areas.[1]

Research on FDM printers has shown that the layer-to-layer interface reduces yield strength and stiffness compared to conventionally manufactured ABS thermoplastic.[26] Several design strategies can be employed to address this drawback: 1) thicken structures to at least 5.75 mm to optimize mechanical performance; 2) select a printing orientation such that the printed layers of critical structures are not transverse to functional loads; and 3) use novel thermoplastic materials with highly bonded layers to minimize delamination.[21,26]

3D Printing Customized Medical Products

The flexibility of 3D printing permits a range of complexity of printed objects, ranging from small, simple items to larger, sophisticated devices.[10] However, the major challenges to the widespread adoption of 3D printed medical products are securing FDA regulatory approval and complying with relevant patent, copyright, and trademark laws.

3D printing technology is being investigated across a range of medical applications, including the production of personalized casts, splints, and prosthetics.[25] FDM printing may be useful in remote medical care facilities in which rehabilitation therapists and their specialized fabrication equipment are unavailable for the management of musculoskeletal injuries (Fig. 1).

Mobile Fabrication Units for Austere Environments

The U.S. Marine Corps slogan “gung ho” originates from gong he, an abbreviation for the Chinese Industrial Cooperative, an organization that launched thousands of mobile, flexible, lightweight factories that employed rural workers to manufacture a variety of low-cost goods across China during World War II.[23] This historical concept of mobile factories is undergoing a modern renaissance with the advent of affordable and portable 3D printing technology.

Today's civilian and military mobile fabrication units ("fab labs") combine digital and traditional manufacturing tools, including 3D printers, computer-assisted design software, 3D scanning, laser cutters, computer-assisted milling machines, rapid tooling, injection molding, and wood and metal working equipment to make and repair items in the field.[10] The primary advantages of a localized manufacturing approach are reduced reliance on complex supply chains, shorter transport time and lower procurement and storage costs for goods, and improved flexibility in the provision of products tailored to local needs and preferences. The ideal 3D printer for austere environments would: 1) be affordable, portable, robust, reliable, low-maintenance, and user-friendly for minimally trained personnel; 2) be capable of using locally available recycled materials, sterilizing prints, manufacturing printer replacement parts, and being powered through renewable, off-grid energy sources; 3) exhibit minimal off-gassing; and 4) be used for both medical and nonmedical applications.

The latest innovations in 3D printing support its application in austere environments. Unused printed ABS and PLA thermoplastic objects can be converted back into FDM printer filament.[8,9] Desktop FDM printers can use filaments containing recycled plastic waste.[2,19] Commercially available solar panels can address the modest power requirements of desktop FDM printers.[24] A solar-powered, ultraportable 3D printing system that fits inside a carry-on suitcase has been developed for potential use in manufacturing medical supplies locally in off-grid regions. Thus, it may be possible someday to use affordable, portable FDM 3D printers to print low-cost, functional medical resources on site from recycled plastic using off-grid renewable energy sources to deliver the highest standard of medical care in remote, low-resource environments.

Conclusions

3D printing appears to be a promising technology for supporting healthcare delivery in austere environments. On-site 3D printing of medical resources could save costs, avoid redundancy, enhance self-sufficiency, and optimize health outcomes in remote medical care facilities. Medical applications of 3D printing will continue to expand as printer performance improves and more printer materials become available. Regulatory and legal concerns will need to be addressed for 3D printing medical products. More development is needed to validate sterilization protocols and recycling processes for 3D printing medical resources in austere environments.

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