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Review Article

The Future of 3D Printing in Medicine

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Abstract

Three-dimensional (3D) printing has provided individuals in various industries with a tool to bring their creations to life. The medical field is no stranger to 3D printing, which has been utilized in various applications since its inception. The various additive technologies currently available to elucidate the differences between them will be discussed briefly. The current applications of 3D printing in medicine could be divided into applications in medical education, patient care, equipment modification or fabrication, and research. The various applications in these categories are described with examples of upcoming research and technology that may be available in the near future. Despite the benefits of 3D printing, challenges remain, and technology improvements are required before there will be more adoption in the medical field. The technology is growing rapidly and evolving, and more 3D printing applications will be seen in the future.

Introduction

There has always been a desire to manifest ideas into physical objects, and three-dimensional (3D) printing has brought us closer than ever to that goal. Although 3D printing was conceptualized in the 1970s and has been available since the 1980s, it has not truly had as large an impact as it had in the last few years. This has been due to the price decrease in 3D printers and printers that are now produced commercially, which enables them to be used by an increasing number of people.

Early adopters of this technology were enthusiasts and finding people with technological experience in setting up and running 3D printers was challenging. As the printers became more user friendly, the amount of software developed to improve user experience adoption increased. 3D printing was found in health care, from researchers to front liner staff during COVID-related printing, which included items, such as protective equipment and other applications in various specialities that are found in the literature.

Although it has proven to be a valuable tool, the current technology has limitations in applications with printing time and materials that impact its practicality. In this article, an insight into the various 3D printing technologies currently available will be provided and some of the applications in various specialities of medicine will be discussed and how they impact current practice and future directions.

Technologies currently available for 3D printing

Subtractive

Computer numerical controlled (CNC) milling uses various tools, such as drills, routers, and lasers, to remove material from a solid object until the desired shape is obtained. This technology; however, has the disadvantage of creating complex internal structures.[1]

Additive

Multiple technologies are available, including:

- Stereolithography (SLA) utilizes a laser to heat a liquid photopolymer substrate into a solid layer of the desired shape.[2]
- Selective laser sintering (SLS) uses a laser to heat a solid powder, fusing it into a solid structure.[3]
- Fused deposition modeling (FDM) or fused filament fabrication (FFF) that utilizes spools of thermoplastic material extruded

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Abbreviations: 3D, three-dimensional; COVID-19, coronavirus disease 2019; CNC, Computer numerical controlled; SLA, Stereolithography; SLS, Selective laser sintering; FDM, Fused deposition modeling; FFF, fused filament fabrication; UV, ultraviolet; DLP, Digital light processing; CLIP, Continuous liquid interface; DICOM, Digital Imaging and Communications in Medicine; CAD, computer-assisted design; CHD, Coronary Heart Disease; FDA, Food and Drug Administration.

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through a heated nozzle in layers along the *z*-axis into a 3D structure.[4]

- Material jetting printers that place a thin layer of resin in the desired design, which is then immediately cured by powerful ultraviolet light before the next layer of material is added.[5]
- Binder jet printing is an additive manufacturing process in which an industrial printhead selectively deposits a liquid binding agent onto a thin layer of powder particles, such as metal, sand, ceramics, or composites.[6]
- Digital light processing (DLP) is similar to SLA; the difference is that SLA machines use a laser that traces a layer, whereas a DLP machine uses a projected light source to cure the entire layer at once.[7]
- Continuous liquid interface printing (CLIP) uses photopolymerization to create smooth-sided solid objects of a wide variety of shapes using resins.[8]

Medical specialities that have attempted to utilize 3D printing, due to its versatility, convenience, and low cost, include cardiology, plastic surgery, neurosurgery, and urology.

Applications of 3D printing in medicine

Medical education

Cadaveric teaching has been the gold standard, and 3D printing has been increasingly used in medical education across various fields. In a study by Zhen Ye *et al*., students in the 3D printed group had better learning satisfaction and advantages in accuracy and answering time compared with the outcomes of students in the conventional group.[9]

In orthopedics, 3D printed models have helped trainees practice their surgical maneuvers and that were prepared and more confident in a surgical theater.[10] In addition, 3D models are being used as preoperative planning tools to try out various procedures and maneuvers for complex pathologies in spinal cases.[11] In urology, 3D models and 3D printing have been used to simulate various procedures, such as percutaneous nephrolithotomy, partial nephrectomy, renal transplantation, laparoscopic pyeloplasty, prostate brachytherapy, transurethral resection of bladder tumors, ureterovesical anastomosis simulation devices, laparoscopic trainers, and robotic surgery phantoms.[12] The ability of 3D printers to provide on-demand models means that training institutes no longer have to rely on prefabricated models from various supply chains, which makes the models an invaluable teaching tool. In addition, most models that were available were of normal anatomy, and pathological models were not very common; however, now real cases from Digital Imaging and Communications in Medicine (DICOM) files of real cases can be made into physical 3D models. This provides educators with the ability to have models of rare pathologies for demonstration in teaching. 3D printing in neurosurgical education encompasses a variety of neurosurgical subspecialties, including vascular, skull base, endoscopy, craniosynostosis, skull lesions or skull defects, intrinsic brain tumors, and others, with vascular and skull base specialities accounting for half of the 3D-printed models.[13] In cardiac surgery, 3D models have been used to elucidate coronary heart disease (CHD) anatomy after cardiac surgery.[14] The models provided were used as an adjuvant to other teaching methods and helped to make the training experience more comprehensive for the trainees.

These are a few examples of the applications and specialities, and from the review of the literature, 3D printing was used in multiple specialities and has been used at undergraduate and postgraduate levels.

Patient care

From the literature, 3D printing is utilized at various points in patient care. In critical care, 3D printing is used in wound care, personalized splints, and patient monitoring.[15]

In dentistry, various technologies of printing and materials are utilized to create restorations (*e.g.*, crowns, bridges, veneers, and partial denture frameworks or denture bases), physical models, surgical guides or implants, and orthodontic aligners or retainers.[16] Dentistry is no stranger to 3D modeling and fabrication, and as early as the 1990s, people in the field were using wax to make models; therefore, making 3D printing a natural evolution in the field. Implant modeling and fabrication have been used for various reconstructive specialities, including maxillofacial surgery,[17] neurosurgery for cranial implants,[18,19] and plastic surgery to produce anatomic models, surgical cutting guides in reconstruction, and patient-specific implants.[20] Orthopedic surgeons have found 3D printing useful in their practice for tasks from forming scaffolds to aid in bone repair,[21] to forming patient-specific lightweight splints, implants, and biomodels.[22] In addition, a wide range of prostheses have been 3D printed, which, although not necessarily low cost versus injection molding, provides a promising possibility for individualization and custom fitting.[23]

There are various applications for 3D printing in a variety of settings, including surgical and nonsterile patient care. The commercial availability of the technology has allowed individuals with knowledge of 3D computer-assisted design (CAD) and experience with 3D printing to utilize this important tool in their practice to enhance individualized patient care. These factors influence patient satisfaction directly and indirectly.[18,19,24]

Equipment modification or fabrication

3D printing is being utilized in various manufacturing industries, including the automotive industry. As the technology improves and printed parts are of better quality, with a wider range of printable materials, 3D printing has been incorporated into an increasing number of manufacturing processes. In a study carried out by the Metal Powder Industries Federation, the researchers compared the outcomes of 17 steps of subtractive manufacturing that were required to produce a truck gear versus 6 steps to achieve the same goal using additive manufacturing.[25] Their research demonstrated that changes in the design of the materials used in subtractive manufacturing could improve reproducibility by additive manufacturing when maintaining the same function. These reductions could translate into more efficient and sustainable manufacturing in the medical industry.

The medical equipment industry is no stranger to 3D printing. The recent COVID-19 pandemic helped to overcome supply shortages in airway consumables, personal protective equipment,[26] and nasopharyngeal swabs.[27] A total of 22,135 items were manufactured were manufactured by 59 companies in 18 sectors to overcome problems in the global supply chain (*e.g.*, airway consumables and personal protective equipment).[26] In addition, the modification of medical equipment was possible due to the adoption of 3D printing,[28] and these were modifications made by medical professionals rather than large corporations, which allowed more people to be innovative; therefore, driving medical innovations forward by allowing more personalized and cost-efficient solutions that helped to overcome previous obstacles, such as long procedure times, difficult modeling, and high cost.[19]

Making 3D printing mainstream allowed individuals to innovate various fields of medical practice and produce prototypes that they could physically hold and study; this was seen in the advent of 3D printing for neurosurgical implants.[18,19] The production of customized wound dressings and even tissue printing for grafts[29] could provide better solutions for patients. 3D printing could benefit medical equipment companies, because the price of 3D printing decreased and its efficiency and versatility increased. Manufacturers could open multiple manufacturing locations on hospital grounds, which required a smaller footprint than regular factories and required fewer employees. Moreover, ordering a custom implant could be as easy as having it designed in the headquarters and then printed remotely in the hospital that ordered it. The cost to set up one regular factory could fund hundreds of these in-hospital printing stations. The printing process, because it requires no molds or custom manufacturing equipment, would make it cost-effective to customize individual medical implants and prosthetics and produce custom-fitted products without major changes to the production line.

In addition, 3D printing is revolutionizing the pharmacological industry toward the production of customized medicines; however, there is still a need to explore the aspects of cost, flexibility, and bioequivalence.[30] These aspects could open the door to customized drug delivery systems, on-demand manufacturing, and dose flexibility.[31] Aprecia (Aprecia Pharmaceuticals - Corporate HQ, 10901 Kenwood Rd, Blue Ash, OH 45242) recognized the commercial potential of 3D printed pharmaceuticals early on and received US Food and Drug Administration (FDA) approval for its Spritam epilepsy medication in 2015. Since then, the company has collaborated with the non-profit R&D firm Battelle to increase manufacturing output and move its ZipDose 3D printing system from clinical supply to commercial sale.[32] However, the printing time is long compared with the time required for methods such as injection molding, which require printing farms of multiple 3D printers to operate simultaneously. Printing failures are detrimental to the production line due to the long printing time, and the multiple 3D printers that are required for mass production increase the initial costs and cost per unit, which makes them useful for low-volume production (10-100 parts) but impractical in large-scale manufacturing.[33]

3D printing and research

3D printing has been a topic of research and a tool to help research. Research into implants of various materials for maxillofacial,[34] neurosurgical,[18,19] and orthopedic[35,36] studies are found in the literature. The availability of consumer-grade low cost 3D printers offsets an otherwise large cost, which is another obstacle to this type of research, and allows more people to attempt similar studies as individuals rather than requiring studies to be conducted in large institutes and without substantial company funding; therefore, preventing bias.

Regarding tissue bioprinting, techniques such as inkjet printing, laser-assisted printing, extrusion, and cell electrospinning[37] have been used to try to produce tissues from individual cells in an attempt to produce complex tissues or even organs. Significant research is ongoing into the 3D printing of tissues and organs. This might have multiple implications when positive results are reached. In pharmaceuticals, these printed models might help to study the organ effects of pharmaceuticals, which could overcome the high cost and ongoing controversy that surrounds animal testing.[38] These organs could be used for tissue or organ regenerative engineering to help with the shortage and incompatibility of organ donors.[39] In laboratories, 3D printing could be used in bioanalytical and diagnostic testing research,[40] to help create extremely complex architectures that are similar to those of biosensor arrays, which were not readily available to the average laboratory in the pre-3D printing era. Printing of customized equipment and equipment modifications in laboratories could help to reduce costs and time compared with other fabrication methods.[41]

Models of diseased organs could be used for research into new surgical techniques or equipment to determine their efficacy and possible side effects.[42] 3D-printed mannequins and radiological models have been used as phantom simulations for CT-guided procedures.[43] As these models improve, and with the possible advent of tissue printing, these models might replace current methods for research. The availability of these models might drive research faster and further, because they might provide an alternative to human participants in the future.

Future directions

The use of 3D printing in medical applications has great promise for the future; however, significant barriers exist to successful implementation, regardless of scientific knowledge. The goal of research is to successfully 3D print organs for transplant, and soon there might be breakthroughs that allow autologous 3D printed organs that use a patient's cells. However, 3D printing the complex cytoarchitecture of organs remains difficult. Furthermore, 3D printing could be used more as a teaching tool. For pharmacology, research into 3D printed patient-specific medicine is expected to expand, and companies, such as Curifylabs have developed an automated digital technology (Curify MiniLab) to 3D print medicines; however, the potential of multiple formulations in one tablet is unknown. For medical companies, research into modifying existing products to facilitate 3D printing, and expanding the range of materials that can be 3D printed, would be a logical direction for research, in addition to improvements in the efficiency and speed of 3D printing.

Conclusions

3D printing is an amazing and exciting tool and has had a significant impact on various industries over the last decade. Improvements in traditional techniques and research by incorporating newer and more efficient additive manufacturing methods could increase the utilization of this valuable tool.

Although 3D printing of fine details was initially challenging compared with other manufacturing techniques, technology, such as SLS has in-market printers that can layer heights as low as 0.05 mm and can produce details from 0.15 mm, and they are improving. The commercialization of 3D printers has helped increase the rate of improvements and has improved the user experience and ease of use. In addition, it requires less troubleshooting, which makes it more accessible to individuals.

Numerous medical specialities have utilized 3D printing in their practice, and applications are appearing continuously in the literature. The practicality of having physical 3D models on-demand has helped in training, surgery planning, and research and has led to improvements in medical equipment. It is not difficult to imagine medical equipment companies using 3D printing centers in large hospitals as in-house tools to provide their customized products, outsource designs, and develop new customized manufacturing chains. Perhaps requesting a custom implant in the future would be as easy as sending a 3D file to the printer for printing.

The technology is not perfect, it requires experience with troubleshooting the software and equipment. In addition, prolonged printing times mean that printing failures are detrimental and time-consuming. Despite the wide range of printable materials, many other types of material cannot be utilized in 3D printing; moreover, special preparations are required before the materials can be used, and 3D printing of very large items (*i.e.*, hospital beds) is still not currently a practical means of manufacturing. It is exciting to see the future of 3D printing and the innovations in technology and applications in medicine, and as some experts predict, the industry is only getting started.[44]

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Conflict of interest

The authors have no conflicts of interest related to this publication.

Author contributions

Study concept and design (MM), acquisition of data (MM, AMS), analysis and interpretation of data (MM, AMS), drafting of the manuscript (MM, AMS), critical revision of the manuscript for important intellectual content (MM, AMS), administrative, technical, or material support (MM, AMS), and study supervision (MM). All authors have made a significant contribution to this study and have approved the final manuscript.

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