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Review Article

Three-dimensional (3D) printing: A potentially versatile tool in the field of medicine

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ABSTRACT

Three-dimensional (3D) printing or additive manufacturing, is a relatively recent and rapidly evolving technology that has a far-reaching impact in the current context of medical education. Since its introduction in the 1980s, additive manufacturing has made tremendous progress. In essence, this technology render a computer-assisted design template based on a set of processed data acquired from various imaging sources such as 3D scanning, computed tomography (CT) and Magnetic resonance imaging (MRI), into a physical object which is an accurate representation of the original. The printing is constructed in layers using a diverse array of printing materials. The process is fast, easy, cost-effective, and repeatable. The scopes of application of 3D-printing are increasing by the day with limitless potential in future. Proper implementation of 3D printing with respect to its availability and accessibility will establish it as a perfect complementary modality to the traditional teaching and learning approaches. In this review paper, the concept of 3D printing, its use in medical education, surgical training, patient interaction, potential benefits and shortcomings, and future scope are highlighted.

1. Introduction

Three-dimensional (3D) printing is a fast-developing technology that offers a wealth of teaching-learning resources and applications in the modern medical field. It is also known by the name additive manufacturing. In this process, a three-dimensional virtual digital model is printed into a real physical object which perfectly matches the computer blueprint. During the printing process, the 3D printers gradually add layers of material in a controlled manner to create the final product without any subtraction. The final products demonstrate structural fidelity consistent with the real specimen. Charles Hull is credited with the patenting of 3D printing during the early 1980s.[1] Initially, the process was developed for use in the engineering and industrial sector. Later, with the advancement of printing materials the technology evolved and made its foray into the field of medicine.Three dimensional virtual models are also in use in medical education for several years. But they are deficient in their tactile experience which is offered by a 3 D printed model. Three-dimensional printing lends itself to multidisciplinary teaching which is the backbone of integrated medical curriculum. In this review we will seek to elucidate the wide range of utility of this teaching tool in the context of current medical education and research.[2–4]

2. Basic Principle of Additive Manufacturing (Figure 1)

Stages in 3D printing.[4–6]

1. Producing the computer aided design (CAD). A digital 3D model of the target object is created either directly by 3D surface scanning or indirectly by assembling together the serial slice images

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obtained by CT scan or MRI scan with the help of a range of free and professional CAD programmes. Other image acquisition modalities include Positron Emission Tomography (PET), Cone Beam Computed Tomography (CBCT), Single Photon Emission Computed Tomography (SPECT) and Ultrasonogphy. These images are saved in DICOM format (Digital Imaging and Communications in Medicine) and after post processing by CAD programs the digital 3D model is produced.

2. Conversion to Stereolithography (STL) file. A critical stage in the additive manufacturing process is the requirement to convert a CAD model into an Stereolithography (STL) file. The Stereolithography (STL) file format uses a series of linked triangles to recreate the surface geometry of a solid model. With the increase in resolution, more triangles are generated, approximating the surfaces of the 3D model more closely along with increasing the size of the STL file.
3. STL file modification and transfer. The converted STL file may require further processing before being uploaded on AM device.
   (a) Repairing any errors within STL file such as gaps, missing triangles or double triangles.
   (b) Orientation of 3D model with respect to build platform.
   (c) Modification of dimensions if required.
   The prepared STL file is then transferred to AM machine for build preparation and to start the build process.
4. Machine Set up. 3 D printing machines often comprise of many small and intricate parts. So adequate maintenance and proper calibration is essential for producing accurate prints. When the print material is loaded into the printer, the machine should be set at an optimum level. Machine set up also includes cleaning of build chamber, establishing build -parameters, flow rate, energy source etc.
5. Building the part. Once all the required parameters are established, the building process begins. Most additive manufacturing machines require no further monitoring once the printing process has begun. The machine will follow an automated process and issues generally only arises when the machine runs out of the material or there is error in the software. Inert gases like nitrogen or Argon are typically used in AM system to control build character environment.
6. Build removal. The removal of a build is a highly technical process involving precise extraction of the build. In some additive manufacturing technologies removal of the build is as simple as separating the printed part from the build platform. Some methods require complicated removal procedures and highly skilled machine operators along with safety equipment and controlled environments.
7. Post Processing. Post processing refers to stages of finishing the parts for application purpose. This may involve polishing and coating. Some components may require surface coating to strengthen the final part and painting to give an acceptable surface finish.
8. Application. After post processing parts are ready to use for specific application. Some AM process created components may contain small voids or bubbles trapped inside the components and in few cases bonding may not be proper.[4–6]

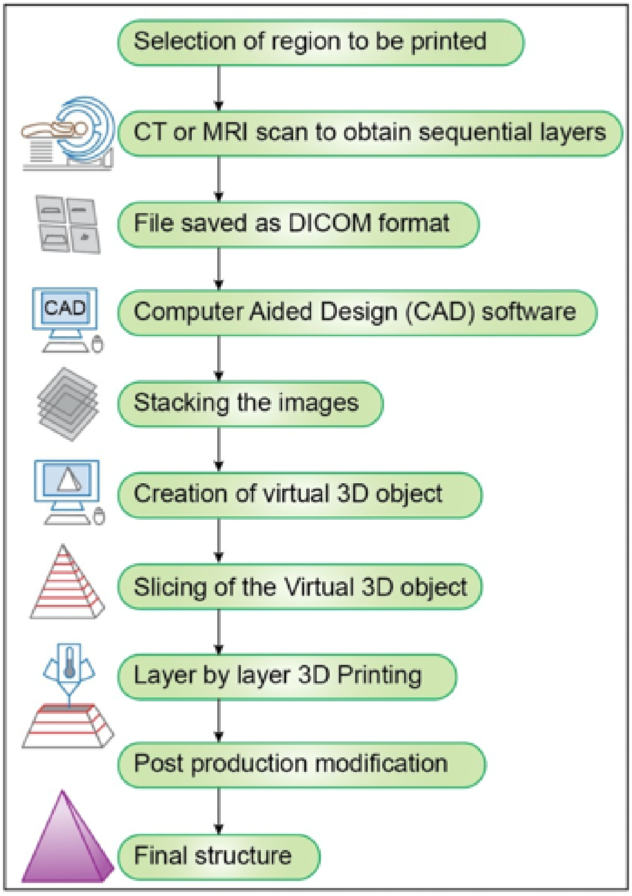

Fig. 1: Schematic representation of workflow of 3D Printing

3. Processes of 3D Printing

The International organization for standardization (ISO)/American society for testing and materials (ASTM) classifies 3D printing processes into seven categories:

1. Binder jetting (BJ). Liquid binders are selectively deposited on a thin layer of powdered particle, allowing them to bind together.
2. Material jetting (MJ) Droplets of photosensitive resin are selectively deposited and cured thereafter by

ultraviolet light.

3. Material extrusion (ME) Material is selectively dispensed in a molten or semisolid form through a nozzle or orifice.
4. Vat photopolymerization (VP). Liquid photopolymer resin kept in a vat is cured by targeted ultraviolet light.
5. Powder bed fusion (PBF). A laser or electric beam is employed to melt and fuse powdered material together.
6. Sheet lamination (SL) Thin sheets of material are fed by roller and bonded together and cut into shape.
7. Directed energy deposition (DED) Focused thermal energy generated by laser beam/ electron beam melts powdered material or material wire.[7,8]

At present, the utilization of 3D printing in medicine can be categorized into 3 major groups.

1. Producing models for teaching anatomy and planning and practice of surgical procedures.
2. Creating prosthetics for implantation.
3. Bio typing or biological tissue engineering.

4. Use of 3D Models in Teaching Anatomy

Cadaveric dissection and prosection has been the cornerstone of traditional gross Anatomy teaching for ages. But cadaver acquisition and storage are restricted by several legal, ethical, religious, logistical, financial, and infrastructural issues which varies from region to region.[9]

For example, there are conflicting views regarding the ownership of cadavers or whether it is acceptable to utilize unclaimed bodies without informed consent.[10]

One of the major controversies in current Anatomy education is the relevance of dissection-based teaching in the context of modern medical undergraduate curriculum. There are views that supports cadaveric dissection as an integral part of teaching anatomy and some institutions in UK and Europe has made it redundant Many institutions are now seeking a hybrid modality including Plastination, 2D and 3D imaging and 3D printing to conduct anatomy teaching.[11–18]

As a teaching-learning tool, 3D printed models offer advantages above traditional cadaveric dissection and plastinated specimens.

1. In the face of declining cadaveric dissection, 3 D printing can produce an endless variety of learning resources by data acquired from a large range of specimens. The models can be created in a multitude of materials with scope for customization as per the requirement. Moreover, compared to virtual 3D images, these 3D printed models will provide the scope for tactile learning experience. In Australia's Macquarie University 3D printing project was undertaken to make high quality copies of already existing but limited bone bank which included rare anatomical and pathological variants and fragile specimens. It enabled the production of multiple exact replicas of osteology resources that the students can easily handle. Currently used atlases and commercially available plastic models are idealized and don't incorporate the anatomical variations. But advent of additive manufacturing will reinclude all those variations; In one study, students generated 3 D replicas of left coronary trifurcation and preserved for the future generation.[19–23]
2. 3D printing is a cost effective and hassle-free alternative to plastination and cadaver dissection, in terms of production and procurement. No ethical or legal issue involved. A rough estimate of setup expenses of a Plastination facility vis a vis 3D printing shows that the later comes much cheaper. Moreover, the production of every single plastinate will involve the recurring dissection cost of the specimen whereas in case of 3D printing these production costs are one off as any number of copies can be produced readily. Models are durable, and devoid of health and safety issues as opposed to traditional wet and fixed cadaver specimens.
   Topics like embryology can be immensely benefitted by capturing the dynamic development in Utero, both normal and abnormal, with the help of 3D ultrasound and MRI scan to create accurate 3 D digital image. This database will be utilized for creating physical 3 D fetal models depicting the spectrum of normal development along with developmental anomalies like cleft lip, dwarfism etc.[24,25]
3. 3 D printing can be used to overcome the limitation of visualization of body images on a flat screen or surface. As an example, the complex and obscure structural orientation and relationships of nerves and vessels in the scull base can be fully appreciated by using 3D printing technology to produce anatomically tailored models. Recently a team working at Monash university engineered a hyper realistic facsimile of a human body part using 3 D printing, color software and CT scans for teaching and training purpose.[7]
4. Can be constructed on a larger or smaller scale as per the requirement. Larger models can be kept in the laboratory on a permanent basis whereas smaller ones can be transported outside the classroom for SDL and into the clinical environment for multidisciplinary integration. Some of the models are fit for layer-by-layer dissection. Some models are customized to depict blood flow circuits using active flow loops as in case of a heart model. Different components of a specimen such as vessels and nerves can be printed out in multicolor using poly materials.[26]
5. Student response is significantly better in terms of conceptualization and confidence over 2D images and

3D virtual models. In a study performed by Garas et al. Students preferred 3D models over plastinated and cadaver specimens. Studies conducted by different researchers Revealed better post test score when taught with 3 Do specimens. In comparison to cadaveric prosecutions, results using 3D models consistently highlight that they are equally or more beneficial in teaching practical anatomy.[27–31]

5. Use of 3D Models in the Surgical Training

3D printed models serve as preoperative training tools for residents in a variety of surgical fields such as anesthesia, orthopedics, otorhinolaryngology, general surgery, ophthalmology, and so on. The simulation sessions are conducted either on general or patient-specific models. Compared to other simulation modalities like virtual reality or 3D digital imaging they provide more satisfactory and accurate depiction.[32–34]

1. It provides invaluable surgical practice opportunities and exposure to resident trainees. Realistic models which closely resemble specific types of tissue like skeletal, vascular, cardiac etc., can be manufactured by using different alternative materials.[35–39]. It allows the creation of a simulated environment which help gain life like visuospatial and tactile orientation. Performing mock procedures on advanced 3D models, prior to operating on a patient, especially in complex and challenging cases, for example, endovascular stent implantation, simulating in vivo environment. translates in better expertise and improved surgical skill. They facilitate learning with scope for making errors but without involving any risk to patients.[40–46]

   The Accreditation council for medical education in US has mandated simulation-based training for surgical residents for better cognitive, affective, and psychomotor skills.[47]
2. Provide an opportunity to plan the optimal surgical approach to cut short the operation time and predict potential complications. Studies revealed that 3D print-assisted surgery resulted in better pre-surgical instrument adaptation, lesser blood loss, and faster healing.[48,49]
3. 3D printed models can be utilized for better post operative care. An instance of better post operative interdisciplinary handover involves the transfer of congenial cardiac surgery patients from OT to PCICU. The operating team with the help of patient specific 3D printed models can effectively communicate the relevant anatomical abnormality and the surgical interventions to the non-operating health care professionals. An improved understanding by the care giver favors a better post operative care.[50]

6. Use of 3D Printing for Creating Implants and Prostheses

Additive manufacturing is playing a vital role in the creation of customized and patient-specific medical appliances and pieces of equipment such as prosthetics, orthotics, and implants. Commercially available standard size implants serve the requirement for most of the cases but may not be adequate for all. Customized implants/ prostheses are for those patients falling outside the normal range or for whom there is a disease specific requirement.[4] Individual fitting and exact match with customized pieces leads to improved surgical outcome. Tailored nasal implants have been successfully introduced to close nasal perforations with better retention.[51] Repair of distal tibial fractures is done by using generic locking plates which are designed on average human. Occasional mismatch may occur in patients with larger or smaller tibia or persons with tibial deformities. In these patients a model of the mirror image of intact opposite distal tibia would provide the design of best fit plate.[52–55] Printing a life size 3Dp model will reduce the chance of generating wasted implant. Such an improvement in terms of both cost and operative time has been reported in orthopedic hip replacement surgery.[56] Customized prostheses are being successfully employed for mandible, hip reconstruction, knee reconstruction, dental restoration.[57–62] Biocompatible material like bio ceramics or biodegradable polymers are being used for construction of bone, repair of bone and construction of cartilage and bones. In children with tracheobronchomegalies, bronchial splints printed from polycaprolactone has been surgically attached to maintain airway patency. Morrison et al., 2015). 3D printing technique can also produce soft tissue replacement like auricular prostheses by using specific compliant materials.[63–66]

7. 3D Printing of Living Tissue

Tissue engineering for regenerative medicine combining biomaterials and stem cells is being explored. Studies using bio polymer-based scaffold demonstrated that it is interacting with the stem cells that are seeded onto it. Such 3 D p scaffolds are long lasting in nature, rendering them suitable to replace diseased, malfunctioning, and non-functioning organs such as the heart, retina, kidney, skin, vascular network.[67,68] Organs as a whole or in part may be recreated to perform the exact biological function. There is also the potential of producing organs in a convenient shape to fit the internal topography. It will revolutionize the treatment outcome and reduce the shortage of organ transplants. If organs or tissue grafts can be printed from tissues collected from the patient, it will solve the hazard of host rejection and alleviate the necessity to obtain a tissue match before the procedure or take immunosuppressants thereafter. In the future it will be possible to print out a strip of living tissue from the cultured cells retrieved from the patient's body and then utilize it as a test site for administering medications and vaccines.[69–71]

8. Medical Research

3 D printing will enable the production of conceptual and point of care devices both therapeutic and diagnostic, across a multitude of specialty and superspecialist fields including pharmacology, bio engineering, genetics, forensic science etc.[72,73]

3D printed microfluidic device fitted with biosensors has been put to test to monitor blood glucose and lactate level.

Drug pharmacokinetics have been profiled in Vitro dynamic 3D printed device in pharmaceutical research.[74,75]

Complex physiological and pathological processes can be better understood by researching on phantoms manufactured by 3 D printing.[76,77]

Investigation on hemodynamics or aerodynamics can be performed by using velocity encoded MRI or by employing optical flow measurement on transparent models.[78,79]

9. Limitations of 3D Printing

1. The quality of the output depends upon the nature of the input and the equipment used. High-quality prosected specimens illustrating all the salient features without being clumsy are essential for image acquisition, and data processing. Not all dissected specimens are reproducible by scanning and 3 d printing. The quality of the printer and the printing material playa very important part.
2. Additive manufacturing can only be applied for the structures within a certain dimension range. It cannot produce extremely large structures like a whole body. Models manufactured on a convenient size scale may be misleading regarding the actual dimension of those anatomical components and their relations.
3. 3D models fail to accurately replicate the texture and biomechanics of certain human tissue. Neither they can depict the differential textures when closely related tissue types are opposed.
4. Poly material printing is to undergo a lot of improvement before it attains perfection.[3,80–84]

10. Conclusion

Numerous researchers have identified and emphasized the immense potential of 3D printing as a teaching learning tool. But effective implementation and integration of this technology requires careful consideration of the economic and practical realities at the ground level. The general consensus is overwhelmingly positive with majority of the subjects reporting a higher level of learning experience and better academic performance. It will be one of the most significant technological tools to advance and augment our understanding and approach to healthcare. Active exploration of 3D printing will surely bring in a paradigm shift in the field of medicine.

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None.

12. Conflict of Interest

None.

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