PHYSICS REVIEW

# Medical Imaging Technology, 3D Printing, and Medical Applications

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## Abstract

3-dimensional (3D) printing denotes the various approaches that aid the manufacture of 3D anatomical structures from the patient data that is acquired. These models are rapidly gaining popularity in the medical community. Medical imaging modalities such as Magnetic resonance imaging (MRI), Computed Tomography (CT), and even ultrasonography have been used to manufacture the 3D models. Currently, 3D printing has various medical applications, which include pre-surgical planning, intra-operative planning, simulation models, manufacture of prostheses and surgical tools. The PubMed database was searched for articles on 3D printing and applications of 3D printing. Relevant articles with basic physics, applications, advantages, and limitations were included in the study. The studies considered were dated from 2012 to 2024. 3D printing is rapidly achieving prominence in the medical field due to its numerous applications. 3D printed equipment has various advantages, such as better fit due to customized implants, and better patient comfort, with lesser manufacturing cost. Simulation models, preoperative and intra-operative models help in guiding the surgeons during the surgery as well as deciding appropriate approaches for a better surgical outcome and success.

KEY WORDS
Printing, Three Dimensional, Magnetic resonance imaging, Patient specific modelling / trends, Tomography, X-Ray Computed

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## *Background*

3-dimensional (3D) printing is the course through which 3D objects are fabricated via sequential layer-by-layer deposition of matter followed by its fusion. In the medical field, it may also be mentioned as "rapid prototyping" and/or "additive manufacturing."[1] Modalities in medical imaging such as Magnetic Resonance Imaging (MRI), Computed tomography (CT), and Ultrasonography (USG) have been used to manufacture 3D models. It has an expansive scale of applications, which range from the manufacture of simple prosthetic tools to complex tissues. Thus, 3D printing has gained considerable interest among medical professionals.[2] The specific 3D models, which are created using exclusive imaging data from the patient, can be used to assist the training of medical trainees, reduce surgery time, tutor patients for upcoming surgery, as well as guide clinicians to improve therapy. Owing to all the advantages, the usage of 3D printing is escalating in health care.[3] This article discusses the role of the medical imaging department in 3D printing and the basic physics behind it, in addition to its applications in the medical field.

## *Methodology*

articles issued between 2012 to 2024 were included. This review has been organized using publications from PubMed. Phrases such as "3D printing", "dimensional printing", "three-dimensional printing," "3D printing in medicine", and "3D printing applications" were used to search the articles. Relevant articles were used after reading the titles from the list of shortlisted articles. New articles were searched using the references from the selected articles. Articles that had essential data about 3D printing in addition to its applications in medicine were included in the review. The final result comprised an introduction, basic physics, applications, and advantages, along with the limitations of 3D printing.

## *Process of 3d printing*

the basic procedure of 3D printing can be classified grossly into three stages. These include data acquisition from the anatomy, followed by processing of the acquired image, and finally, printing the 3D model. An additional step may be required in certain cases to post-process the printed model.

### Image Acquisition

The procedure of 3D printing initiates with the acquisition of CT, MRI, and/or USG data. In theory, a volumetric image dataset that possesses adequate contrast to separate tissue types can be used to manufacture an anatomical 3D model. Data from different imaging modalities may be used for the same.[1] CT scans are preferred to fabricate 3D models of the bony anatomy or tough tissue. MRI on the other hand has leverage for imaging soft tissue and cardiovascular structures and is used for 3D printing models of the same.[4]

CT has become a widely exploited imaging modality that is used by the medical imaging department for diagnosing a variety of pathologies as it has excellent resolution and can easily locate several pathologies.[5] Since CT scans have a wide range of applications, along with easy post-processing of data, it has been commonly used for 3D printing. An added advantage is the excellent contrast, spatial resolution, and additionally high signal-to-noise ratio, which helps in reducing partial volume artifacts as well as enables excellent differentiation of tissue, which enhances 3D printing.[1] For improving the model accuracy, isotropic voxels (1.25 mm or lower) should be used to reconstruct the CT images.[6] The thicker the sections, the lesser the model accuracy. On the other hand, if the slices are extremely thin sections, excessive segmentation, and standard tessellation language (STL) refinement may be required, especially if image artifacts are present.[1]

MRI is another image acquisition modality that is commonly utilized for 3D printing. However, proper choice of the MRI sequence is required to obtain proper tissue contrast and thereby help in the fabrication of a good model. For instance, to obtain good myocardial images, a black-blood sequence is appropriate, for segmenting intra-cranial sutures AMPRAGE sequences may be advantageous, etc. Also, a 3D acquisition may be preferred over a 2D acquisition since the prior offers higher SNR and isotropic voxels also benefit the models. MRI also provides exceptional contrast of soft tissue, uses non-ionizing radiation, and also has the ability to acquire images in different planes.[7]

USG uses ultrahigh sound waves to image the patient non-invasively. It has been used to construct 3D-printed models of the fetal heart, valves, and septal defect. This was possible due to advances in three-dimensional and four-dimensional USG imaging. USG imaging is less expensive and utilizes non-ionizing radiation, which makes it appropriate for younger subjects. However, its application in producing 3D models is limited owing to its lower spatial

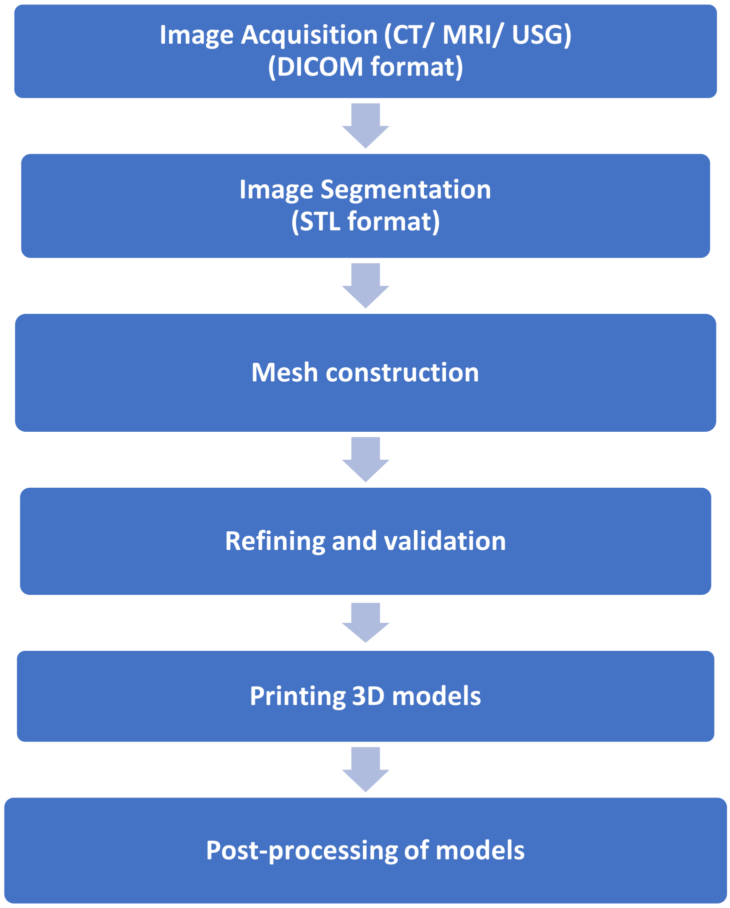


***Figure 1:*** *Outline of the process of 3D printing*

resolution as well as image artifacts.[8]

The CT, MRI, and/or USG data, is subsequently recorded in the DICOM (digital imaging and communications in medicine) format. This format is the accepted form of communicating and managing medical imaging data in addition to other information. It enables a fast, robust collaboration among medical imaging specialists.[9]

**Processing of the Image**

The DICOM data that is acquired cannot be used directly by the 3D printer. To design 3D models of the anatomy, the data acquired from the patient's CT/US/MRI scan requires to be changed to STL format from DICOM. A variety of software can then be used to create as well as edit this data.[9] Formation of digital models from DICOM images grossly includes the following steps: a) Image segmentation to generate an STL file, b) mesh construction, c) removing unwanted anatomy, and lastly, d) refining and surface conditioning to produce the final model.[8]

The processing of the image begins with segmentation. It may be preceded by the integration of datasets from different modalities. Segmentation basically involves obtaining the data of required anatomy and then refining it to form an STL file. Commercially available software packages can be used to perform segmentation.[8] Segmentation is done using a tool that uses a range of threshold Hounsfield units, which depend on the area of interest (e.g., fat, fluid, blood, bone, etc). An initial mask is now created which is refined using additional tools.[5]

The 3D mask, which has been generated by segmentation, describes the region of interest. Following this, triangulated surface meshes are used to demarcate an enclosed volume. This procedure is called mesh generation.[8] Triangle approximations are used because of their flexibility along with their simplicity. Basically, multiple small or large triangles will be used to produce the entire 3D shape. This depends on the thickness of the slice; as such, good quality of the radiographic image is necessary.[5] Ensur-

| Table 1: Comparing the technologies of 3D Printing | | | |
|---|---|---|---|
| **Technique** | **Process in brief** | **Advantages** | **Disadvantages** |
| Vat photopolymerization | Deposition of liquid resin in successive layers which is then subjected to laser light solidifying the resin | • Accurate print<br>• Manufactured in different colors & transparency levels | • Expensive<br>• Longer printing time |
| Material Extrusion | Materials such as metal, polymer, or plastic are wound around a coil and Supplied to a printer. Heat is used to melt it as it deposits on a platform, which then stiffens as it cools down | • Stronger<br>• More durable<br>• Allows the use of different colors | • Resolution for minute details is low |
| Material Jetting | A liquid photopolymer is sprayed on a build platform, which is dried using UV light | • Different materials and colors can be combined to obtain variable flexibility and strength | • Expensive |
| Binder Jetting | A liquid-binding agent is jetted upon a fine powder bed which bonds the powder wherever it has been deposited | • Less expensive | • Models are not translucent<br>• Only one material can be used |
| Powder Bed Fusion | Minute particles made of glass powder, ceramic, metal such as titanium alloy, or thermo-plastic are fused using an electron beam or high-power laser to form a 3D shape | • Durable models | • Expensive |
| Sheet Lamination | Layer-by-layer cutting and bonding of materials such as plastic films, paper, or metal. | • Less expensive<br>• High speed | • Fabrication time is higher |

ing proper imaging parameters like the dimensions of the pixels, the thickness, and the increment of the slice is required to ensure optimal image quality.[9] In order to estimate the shape of the object, the position as well as the size of triangles, which are essential in forming the model, can be altered. Smaller triangles improve the image quality and vice versa.[5]

Since the imaging data contains noise, refining and processing the initial mesh is very crucial. Several software tools can be used for the same to create more accurate models.[8] The post-processing of the image includes several steps, such as correcting the mesh model, removing errors, connecting parts and closing ends, correcting gaps, filling internal spaces, creating supports, etc. To end, this finished STL file is relayed to the printing device to complete the process of fabrication.[10]

### Technologies of 3D Printing

To fabricate the 3D models, the data that has been converted in the STL format is used by the 3D printers, and thin 2-dimensional layers of special materials are deposited successively and then fused to form the anatomical model. Several groups of technologies for 3D printing exist. Some of these include vat binder jetting, photopolymerization, material extrusion, material jetting, powder bed fusion, etc.[5]

**Vat photopolymerization:** Also known as digital light processing or stereolithography, this process basically includes a high-power source of light, e.g., a laser and liquid resin vat, which is photo-curable. The liquid resin is deposited in successive layers and then subjected to light. Exposure to light solidifies the resin. Once the final layer is deposited and cured, any excessive resin is taken off, and the 3D model that is made is cured a final time inside an Ultra Violet (UV) cell. Light sanding might be required to smoothen out any step edges for the final finishing. A common application is fabricating bony models.[1] An advantage of the model is that they are accurate and can be manufactured in different colors as well as transparency levels. [10]  The disadvantage of these printers is that they are quite expensive; the photopolymers are comparatively fragile, and the vat should be sustained at a precise level.[1]

**Material Extrusion:** This is a commonly used cost-effective hardware. Successive coats of either metal, polymer, or plastic are deposited on a platform by an extrusion head. These materials, which are wound around a coil, are then unraveled to feed the printer head. Heat is used to melt as it deposits on the plane, which then stiffens as it cools down.[1] These materials are stronger, more durable, and allow the use of different colors. They are also easy to use and more cost-effective. However, the resolution for minute details is low thus affecting the final quality of the models in comparison to material jetting and vat photopolymerization. Also, overhanging model parts may require additional support until hardened since it is initially soft.[10]

**Material Jetting:** Similar to ink-jet printing, these printers use a liquid photopolymer that sprays on a build platform, which is subsequently dried using UV light. These printers make use of two jetting heads; one head sprays the model while the other head sprays a support substance, like gel or wax which is subsequently removed. A common application is for the manufacture of dental implant guides and dental casts.[1] Advantages include the feasibility of combining different materials as well as colors in order to obtain variable flexibility and strength. Also, binder jetting is the only method to obtain clear models with colors ingrained in them.[10] The disadvantage is that these materials are comparatively expensive.[1]

**Binder Jetting:** This printer utilizes a cartridge that jets an adhesive agent upon a fine powder bed. This liquid-binding agent bonds the powder wherever it has been deposited. After binding one layer, more powder is deposited for binding the new layer. Once the model is ready, it is vacuumed, and any unbonded powder is blown off. Infiltration with cyanoacrylate, wax, etc., helps in achieving deformable models and also helps in determining the final strength of the model. These materials are comparatively less expensive. This method of 3D printing is used in order to color code different anatomical parts. Color coding may be necessary to separate blood vessels from adjacent structures, for example, to distinguish the Circle of Willis from structures in the base of the skull. [1] The drawbacks of this technique are that these models are not translucent, only one material can be used and they may be more prone to breakage before infiltration.[10]

**Powder Bed Fusion:** In this method, minute particles made of glass powder, ceramic, metal such as titanium alloy, or thermo-plastic are fused using an electron beam or high-power laser to form a 3D shape. Implants and fixations are commonly fabricated by this method. These models are durable but quite expensive.[1]

**Sheet Lamination:** This method involves layer-by-layer cutting and bonding of materials such as plastic films, paper, or metal. Upon completion, any extra material is peeled of to clean the model. The advantage of this technique is that it is inexpensive. However, the fabrication time is higher than other methods. Also, cleaning of complex models may be difficult.[1]

### Post-processing of 3D Printed models

The 3D models may require post-processing after fabrication such as cleaning, sterilization, or removing the supports from the models.  Post-processing may depend on the type of manufacturing method. For example; models with overhanging parts which are manufactured by Vat photopolymerization may need support structures which has to be manually removed following printing. [11] They also require a solvent rinse and manual separation of extra material or resin followed by UV curing.[1] The gel/wax support material which is used in material jetting undergoes manual elimination using high-pressure spray water. Any residual material can be subsequently removed by melting it or drenching the anatomical model in a solution of soap. Models manufactured binder jetting have to be vacuumed and/or air blown to eliminate any unbonded powder. These models are then infiltered with wax, resin or cyanoacrylate for strength.[1]

## *Overview of medical applications*

3D printing currently has numerous clinical applications. A few of the applications have been discussed below under the following headings: Preoperative Planning, Simulation models, and Therapeutic uses**.**

**Preoperative Planning/ Simulation Models:**

The anatomic models, which are 3D printed, are based on anatomy which is patient-specific. Thus, this can aid surgical planning as the surgeons can better understand the complex and unique anatomical makeup of each individual.[12]

*Orthopedics:*

In a research conducted by **Chung et al**., a real-sized 3D replica of the calcaneus was used as a minimally invasive tool for preoperative as well as intraoperative plate fixation of fractures of the calcaneus. Patients who presented with a unilateral intraarticular fracture of the calcaneus underwent a CT examination of bilateral calcanei. The mirror imaging technique was utilized for preoperative planning, which simply refers to the technique of printing real-sized models of the uninjured, contra-lateral side of the anatomy (which are probable to be of the same dimensions as the injured side). Prior to the surgery, a real-size 3D replica of the non-injured calcaneus was utilized to preshape the calcaneal locking plate so that it fits the calcaneus. The 3D model was then sterilized and subsequently used intraoperatively in order to assess the degree of fracture reduction by correlating it to the injured calcaneus using C-arm equipment.[13] Research by **Huang et al**. exhibited the ability of 3D models to decide the trajectories of the screws before internal fixation of the ruptures of the tibial plateau and help in improving the precision of plating as well as screwing of complex plateau fractures.[14]

*Neurosurgery:*

An incident of an 11-year-old child with manifold defects of the skull base, complex deformity of cranio-vertebral junction, and tortuous vascular anatomy was reported by **Pacione et al**., which required surgical treatment. The surgery was aided with a customized 3D anatomical model of base of the skull along with the proximal cervical vertebrae in order to plan the appropriate surgical approach as well as help in the success of the case.[15]

*Abdominal/ Thoracic surgery:*

3D printed anatomical models were used by **Silberstein et al.** for pre-surgical planning for determining the best approach as well as intraoperative guidance for the removal of renal tumors. These models assisted the urologists in evaluating the resection margin of the tumor in relation to the collecting system and the hilar vessels.[16]

*Cardiovascular Applications*

3D printing was used by **Hossien et al.** in order to determine the treatment options, i.e., whether to perform open surgery or proceed with endovascular intervention in patients who had aortic dissections. They created patient-specific 3D structures to facilitate the surgery and also aid in interventional repair. 3D printing was also used for follow-up post-surgery.[17] **J Hermsen et al.** used 3D printing technology in individuals with hypertrophic cardiomyopathies along with left ventricular outflow tract obstruction in order to plan and rehearse the myectomy strategies.[18] **H Wanget al.** confirmed that 3D printing technology, in combination with the reconstruction of medical images, is a promising technique for angio-cardiopathy research. They used 3D anatomical models in order to determine the optimum strategies for stenting and to evaluate the associated effects during Percutaneous coronary intervention.[19]

*Obstetrics and Gynecology*

3D printed models are utilized for pre-operative simulation as well as intra-operative supervision of several benign and malignant tumors of the ovaries, uterus, and cervix. Structures of fetal abnormalities such as cleft palate, congenital cardiovascular malformations, tumors, etc have been used to predict the disease prognosis. This can aid in decision making whether or not termination of pregnancy is required and also to provide counseling services.[20]

**Therapeutic uses**

Apart from the fabrication of patient-based 3D models of anatomy, 3D printed structures can also be employed to synthesize customized implants, surgical instruments, and various prostheses. The advantages of these are that these devices can be customized according to patient needs, manufacturing competencies, and possible cost-effective techniques.[21] Recently, 3D printing has also been used to manufacture products with materials that are drug-impregnated.[22]

*Prostheses*

Several prostheses such as hearing aids, Invisalign® braces, dental crowns, skull plates, facial implants, hip cups, knee trays, several surgical instruments, and screws have been 3D printed with FDA approval. 3D printing helps overcome several drawbacks of conventional prosthetic devices. 3D-printed prostheses are comparatively economical as compared to the conventional ones, which come at very high prices. The most important advantage over conventional prosthetics may be that 3D-printed prostheses are patient-specific; hence, they provide a better "fit" and comfort.[21] Prostheses that are fabricated in a limited number of sizes are disadvantageous as they may be uncomfortable for the patient and may also lead to a decreased lifespan of the device. Furthermore, prostheses that are not properly fitted may affect the patient's health, compliance, and comfort and may even cause depression.[23]

*Joint Prostheses:*

Customized, patient-based joint prostheses came to be extensively studied in medicine. Customized joint prosthesis helps in increasing patient comfort and also have a longer lifespan in comparison to conventional arthroplasty.[24] Some of the common implementations of 3D printing in the synthesis of the joint prosthesis have been discussed below:

A completely solid femoral implant, which has a greater stiffness than the bone, can cause considerable resorption of the bone due to stress shielding. This can lead to peri-prosthetic fracture or serious complications during or post-revision surgery. 3D-printed, completely porous implants of the hip were designed by **Arabnejad S et al.** to help diminish the loss of osseous matter by almost 75% due to stress shielding in comparison to the solid implant.[25]

**Sultan et al**. used 3D printing to manufacture cementless, titanium-coated, highly porous base plates for total knee arthroplasty (TKA) implants. Cementless TKA implants demonstrated outstanding clinical outcomes and survivorship.[26]

Custom-made prostheses are extremely expensive. 3D printing helps in manufacturing customized, lightweight, as well as affordable prostheses. Guisheng Xu et al. utilized 3D-printed structures to fabricate a prosthetic hand for a child who was diagnosed with a severely distorted right wrist following trauma. Personalized rehabilitation training helped significantly improve the function of the prosthesis.[27]

*Craniofacial and Maxillofacial Prostheses*

3D printing has also been used for reconstructing mandibular implants, skull plates, temporal bones, ear ossicles, zygomatic bones, etc.

**Mee H et al.** reported using a 3D printed extra-cranial plate in order to treat the Syndrome of the trephined, which occurs in patients post craniectomy. The patient suffering from it may develop symptoms such as headaches, cognitive disorders, motor impairments, and decreased consciousness. The application of the cranial plate helped in improving the patient's neurological state.[28]

*Bone and joint reconstruction*

Patient-specific acetabular parts which were 3D-printed were used by **M Citak et al.** to manage severe acetabular defects along with pelvic discontinuity. Critical deformities of the acetabulum, along with extensive bone loss, may impact the quality of life along with the survival rates. 3D printing showed promising results for the treatment of the same.[29]

Congenital anomalies, cholesteatoma, infection, trauma, and surgery may lead to ossicular abnormalities, which may result in Conductive hearing loss. Surgical reconstruction of the ossicles helps in correcting the ossicular defects. **Jeffrey D. Hirsch et al.** used customized 3D-printed ossicular prostheses for surgical ossicular chain reconstruction. Their study suggested that 3D printing is a reasonable solution for ossicular chain defects, which results in conductive hearing.[30]

Mandibular reconstruction not only helps in reforming the morphology of the human face but also helps the individual with biological functions of the mouth, such as pronunciation, mastication, respiration, and swallowing. **J Park et al.** Performed segmental reconstruction of the mandible by making use of 3D-printed implants, which were made of titanium, along with dental fixtures. This study demonstrated that titanium implants that are 3D-printed provide an acceptable treatment option for the reformation of the mandible.[31]

*Surgical Tools*

**J. Hooper et al.** performed research to evaluate the practicality of 3D-printed instrumentation in total knee replacement. In order to cut down the time as well as the skill required at the time of surgery, 3D-printed instruments were planned. Their study showed that the manufacture of single-use devices is an attainable aim.[32]

**Other medical Applications**

*Educating medical students/ residents:*

3D models can supplement as well as substitute cadaveric material during the training of medical students, as cadaveric material may be hard to obtain.[33] Anatomical models that are 3D printed came to be implemented in training for the repair of cerebrovascular aneurysms by **Wurm et al.** [34], abdominal aorta aneurysms repair by **Wilasrusmee et al.** [35] and percutaneous nephrolithotomy by **Bruyère et al.**.[36]

## *Advantages*

**customization of product**

Being able to produce customized products and devices on the basis of the patient's anatomy is the greatest perk of this technique, that can be a great deal for both the physicians as well as the patient.[37] These surgical tools, fixtures, and implants, which are custom-made, help to minimize the surgery time as well as the recovery time of the patient as well as increase the rate of success of the procedure.[38]

**Cost Efficiency**

Printing of 3D models has become highly cost-efficient, with the cost to print the object being as cheap as the last object.[39]

**Rapid Productivity**

3D-printed models can be manufactured within a few hour's time.[38] This makes this technology comparatively faster than the conventional method of making implants and prosthetics. Apart from the reduced manufacturing time, these models are made with high accuracy, reliability, and resolution, which is improving with further advancements.[37]

## *Limitations*

despite various applications in medicine, 3D printing still has certain limitations. A few of the challenges have been discussed below:

**Financial drawbacks**

3D printing has become cost-efficient due to its increasing popularity, yet the expense of starting the printing service can be quite enormous. The basic requirement for the setup involves the post-processing software as well as the equipment which are required for printing purposes. Labs can be established either as individual units or as an extension of a pre-existing 3D visualization lab. Additionally, the lab requires trained staff in order to fabricate the models under the guidance of a radiologist.[21] Also, an experiment conducted by **Javan et al.** demonstrated that the price of the 3D printed model is influenced by the size of the model, its complexity as well as the amount of material that is used.[40]

**Quality control**

The accuracy and the quality of the 3D models are important features when 3D printing is concerned. Research led by **Leng et al.** suggested that Quality Assurance of medical 3D structures is highly essential in order to ensure that the model is accurate and reproduces the anatomy exactly. Their study also indicated that checking segmentation for accuracy by overlapping the original source images and the STL file was necessary before printing. The authors also encouraged to scan the anatomical models with CT. The acquired images are then compared with the images from the original scan (either CT or MRI).[41]

## *Future directions and emerging issues*

The numerous clinical applications of 3D printing have opened up vast possibilities in the treatment of patients. Further clinical trials should be conducted to evaluate the influence of this technique on patient outcomes as well as clinical decision-making. Conducting multi-center studies can help in validating the results of trials. The processing time and cost can be reduced with further technical improvements which can be further incorporated in the clinical diagnosis. [42] Also with the application of 3D printing in biomedical technology, various types of cells can be printed to create complex tissues. This has paved a path for researchers and scientists to create whole human organs via bioprinting. [43]

3D printing may face several challenges in healthcare despite the numerous clinical applications. 3D-printed prosthetic devices may need approval from the FDA or other regulating bodies before they reach the general market for clinical use. Also, proper documentation of the devices manufactured must be maintained as a defense in case any litigation arises. This may be in the form of a visual inspection of the model as well as the 3D reconstruction required to generate the model followed by a detailed report of the 3D-printed device from a radiologist. Alternatively, maintaining soft copies of the 3D printed files or scanning the 3D printed model and comparing it to the reference file can also be done. [44]

### CONCLUSION

3D printing has expeditiously flourished in the preceding years in the medical domain. Several applications have been reported for cardiovascular, cerebrovascular, orthopedic, dental, and many other medical fields. 3D models have been used for simulation training, pre-surgical and intra-operative planning, manufacturing prostheses, reconstruction of bones, and educational as well as research purposes. The popularity of 3D printing has steered the manufacture of cost-effective 3D-printed models. The customized models help the medical personnel to practice the surgeries precisely, thereby increasing the success rates as well as reducing the operation times. With respect to the patient, 3D-printed prostheses help in providing a better fit for the patient, thereby increasing the comfort of the patient while ensuring that the device is cost-efficient. Radiology and medical imaging can help lead the whole process of 3D printing by processing the raw data acquired from the scans, designing the models, and finally printing it, which can be used for surgical, research, or educational motives. Embracing the budding field of 3D printing in medical setups can help in improving and providing better patient care. **R**

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