



3D PRINTING IN RADIOLOGY: SHAPING THE FUTURE OF IMAGING IN INDIA

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ABSTRACT

Radiology serves as a crucial pillar of modern medicine, with advancements in imaging technology continuously reshaping diagnostic and therapeutic practices. Recent technological advancements have introduced 3D reconstruction techniques to produce high-resolution anatomical models that aid in diagnosing complex conditions. This article traces the evolution of Three-dimensional printing, highlighting its applications in medical fields. Three-dimensional (3D) printing has emerged as a transformative force in radiology, bridging the gap between digital imaging and physical reality. This review explores the dynamic interplay between 3D imaging and 3D printing within the Indian healthcare landscape, focusing on how these innovations enhance imaging methods and improve patient outcomes. Despite the potential of 3D printing in healthcare, the literature on its implementation in India is limited. While adoption remains in the early stages, 3D printing has shown potential in various applications. However, implementation faces significant challenges; despite the obstacles, the technology offers a unique opportunity to address India's healthcare challenges, particularly in providing personalized medical solutions to its large population. Few studies have been published, highlighting the need for greater exploration of this technology's benefits in clinical settings. This review aims to synthesize existing research, address the challenges faced in adoption, and discuss the innovative applications of 3D printing.

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INTRODUCTION

Radiology has long been the eyes of medicine, playing a critical role in every medical scenario and offering diagnosis and treatment plans (Zhou et al., 2021). From detecting something as small as a calculus to addressing the complexities of a pandemic, imaging has consistently proven to be a cornerstone of accurate diagnosis and a reliable pillar in healthcare. Decades have gone by, but no advancement in imaging has been as bold as the innovations we see today. Recent technological progress has resulted in the development of 3D imaging methods that provide enhanced and more thorough representations of anatomical features. 3D reconstruction has been a significant leap forward in enhancing our understanding of anatomy and diagnosing major health conditions, particularly in cases of trauma and genetic deformities of all kinds. The "three dimensional (3D) Laboratory" serves as the foundation for advancements made by pioneering academic radiologists, utilizing sophisticated software tools to reconstruct two-dimensional (2D) data from imaging modalities. Computed tomography (CT) stands out among these modalities, demonstrating its superiority through high-resolution imaging capabilities. Volume rendering (VR) images displayed on a 2D screen have facilitated three-dimensional visualization of anatomical and pathological conditions. This

advancement has significantly impacted radiology, offering a crucial tool for radiologists to effectively share important findings with healthcare teams (Mitsouras et al., 2015).

This transition from 3D imaging not only enhances visualization but also lays the groundwork for innovative applications, such as 3D printing, which can create tangible models based on these images. Three-dimensional (3D) printing, often referred to as additive manufacturing, is an innovative production technique that enables the rapid transformation of digital 3D designs into physical models. Unlike traditional manufacturing processes, which typically involve subtractive methods like cutting or milling, 3D printing builds objects by sequentially layering materials. This method encompasses various techniques that focus on constructing items through precise layering, utilizing a diverse range of materials, each with distinct properties, depending on the intended application (Smith & Dasgupta, 2020). The use of 3D printing in radiography especially, has created innovative new opportunities that will improve the precision and personalization of healthcare. 3D printing enables physicians to better plan surgeries and diagnose illnesses in previously unimaginable ways by converting medical imaging data into tangible, patient-specific models. With a population of over 1.4 billion, India is especially affected by this technology. The nation's healthcare system has particular difficulties, including a lack of qualified medical personnel, restricted access to state-of-the-art diagnostic equipment, and inequities in medical facilities. These problems can be resolved with the speedy creation of personalized 3D models for diagnostics or surgical preparation, which would improve treatment accuracy and relieve the burden on the healthcare system (Haleem et al., 2021).

Beyond its use in clinical settings, 3D printing holds promise for transforming medical research and education in India. It can empower medical institutions, particularly in underprivileged areas, by providing easily available and reasonably priced technologies that enable students and healthcare providers to innovate and enhance patient care. In addition to encouraging a fresh wave of innovation and advancement in medical practices nationwide, this technology can aid in closing gaps in healthcare access. The purpose of this review is to examine how 3D printing and radiology work together dynamically in Indian healthcare. We will look at how this technology might improve imaging methods and patient outcomes as technological developments change the paradigms of diagnosis and treatments. This analysis attempts to shed light on the revolutionary potential of 3D printing in transforming radiological practices and meeting the specific needs of the Indian population by identifying creative applications, problems, and future prospects.

METHODS

This review employs a systematic literature review approach to explore the dynamic interplay between 3D printing and radiology in the context of Indian healthcare. The objective is to examine the impact of 3D imaging advancements, particularly the development of 3D printing, on medical practices, diagnosis, and treatment planning. The review involves an extensive analysis of published articles, research papers, and case studies focusing on the application of 3D imaging technologies, including computed tomography (CT) and volume rendering (VR), in enhancing radiological practices.

To gather relevant data, the review focuses on peer-reviewed journals and academic publications from reputable databases, ensuring a comprehensive understanding of the topic. Articles were selected based on their relevance to the intersection of 3D printing and radiology, with a particular emphasis on studies conducted within the Indian healthcare system. The inclusion criteria for the studies included discussions on technological advancements in 3D imaging, the application of 3D printing in healthcare, and its potential to address challenges faced by the healthcare system in India, such as access to quality diagnostic tools and personalized care. The review synthesizes the findings of these studies, identifying key trends, challenges, and opportunities for integrating 3D printing into radiology to improve patient outcomes and healthcare practices.

RESULTS AND DISCUSSION

History Of 3d Printing: From Digital Models To Physical Creation

In 1970, Herbert Voelcker made a pivotal contribution to 3D modeling, developing a mathematical theory and algorithms that allowed solid objects to be represented digitally. This

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groundbreaking work laid the foundation for countless innovations in engineering and computer graphics. A decade later, in 1981, Dr. Hideo Kodama took things a step further by experimenting with photopolymers and ultraviolet light, unknowingly setting the stage for stereolithography (SLA). Although Kodama's work didn't immediately lead to commercial success, it was an important first step toward the 3D printing revolution. In the mid-1980s, Charles Hull built on Kodama's experiments, perfecting and commercializing SLA. He co-founded 3D Systems and introduced the now-iconic STL file format, which would become the standard for 3D printing. But the innovation didn't stop there. In 1989, Carl Deckard developed Selective Laser Sintering (SLS), a technology that allowed objects to be printed from powdered materials—bringing even more complexity and precision to the process. At the same time, Scott Crump invented Fused Deposition Modeling (FDM), another key technology that would change the landscape of 3D printing forever. Together, these groundbreaking innovations—FDM, SLA, and SLS—became the core technologies that would go on to revolutionize industries across the globe, from manufacturing to healthcare and beyond. (Jakus, 2018; Salazar-Gamarra et al., 2022). Table 1 gives a brief overview on the major milestones achieved in the history of 3D printing.

Table 1: Major milestones in the history of 3D printing

Period	Event/Development	Description
1970s	Voelcker's Theory	First mathematical theory and algorithms for modeling solid objects in 3D.
1981	Kodama's SLA Paper	Hideo Kodama published the first paper on stereolithography (SLA) process.
1984	Charles Hull Develops SLA	First commercialized rapid prototyping technology.
1987	Carl Deckard Invents SLS	Selective Laser Sintering (SLS) introduced, based on powder-bed fusion.
1988	Scott Crump Invents FDM	Fused Deposition Modeling (FDM) process, filament-based additive manufacturing.
1991	Commercialization of RP Machines	Companies like Stratasys, Cubital, and Helisys commercialize rapid prototyping systems
1993	MIT Invents 3D Printing	MIT develops inkjet-style 3D printing technology
1993	Helisys Develops LOM	Laminated Object Manufacturing (LOM) process introduced, using laser-cut sheet materials
1996	3D Printing Terminology Established	The term "3D Printing" becomes the official term for rapid prototyping technologies.
2000s	Technological Maturation & Medical Use	3D printing technologies evolve, particularly for use in medicine (e.g., craniomaxillofacial surgeries).
2010s	Maker Movement & Government Support	The rise of consumer 3D printers (MakerBot), and US government initiatives (America Makes) support rapid adoption of 3D printing.
2012-2017	FDA Approves 3D Printed Medical Devices	First 3D printed medical devices, including implants, approved for use
2020s	Advancements in Bioprinting & Biofunctional Materials	Focus shifts to bioprinting, using hydrogels, live cells, and even full tissues and organs

These very technologies are employed in 3D printing to date. The process begins with the creation of a digital model, which is then subsequently divided into layers and sent to the printer. The printer constructs the object layer by layer until it is fully formed. Materials for 3D printing can include plastics, metals, ceramics, or composites, typically provided in the form of filaments, resins, or powders. The choice of material and printing technology influences the final characteristics of the printed item, including its strength, flexibility, and surface quality (Kantaros et al., 2023).

3D Imaging In Medical Imaging Imaging Requirements

3D Biomodels are created using diagnostic imaging techniques like CT or MRI, employing specialized biomodelling software that processes data rather than using raw data directly. To ensure high-quality biomodels, imaging studies must consist of isovoxel volume datasets saved in DICOM format. Most available CT scanners produce volumetric images, but it is crucial to apply appropriate post processing techniques to achieve a section thickness that is equal to or less than the pixel size (isovoxel). High-quality biomodels can be generated with a section thickness under 1 mm. To minimize artifacts in bone 3D biomodels, it is advisable to derive them from soft tissue CT reconstructions. In contrast, 3D volumetric sequences are rarely included in standard MRI acquisition protocols, so planning is often necessary for MRI studies that will require biomodelling. While biomodels can be created from MRI sequences obtained in various planes, volumetric acquisitions tend to take longer, making it essential to adopt a case-specific approach to determine which sequence to acquire volumetrically to avoid unnecessary delays (Zabala-Travers, 2021).

Biomodelling process

Post-processing involves refining DICOM images using specialized medical image processing software. The primary aim is to simplify the original image dataset while preserving the region of interest and eliminating unnecessary structures and any residual noise from the imaging technique used. This selective process, known as segmentation, is typically performed by a trained professional, such as a radiologist. Depending on the software employed, segmentation can be carried out manually, automatically, or semi-automatically, with a range of both free and commercial software options available. After segmentation, additional adjustments may be necessary to correct any errors or imperfections that emerge during the process, as these could compromise the quality of the resulting virtual 3D models and affect their suitability for final printing applications (Smith & Dasgupta, 2020).

When trying to precisely biomodel bones, CT images are ideal. An MRI or CT scan can be used to obtain soft tissue organs. While soft tissue lesions can occasionally be obtained by CT, MRI often yields superior contrast with adjacent tissues. Softwares can be used to blend CT and MRI images to create composite biomodels of the two datasets (Figure 1.0). However, this integration presents its own challenges as it requires manual adjustments and validation to ensure precision in the final models (Zabala-Travers, 2021).

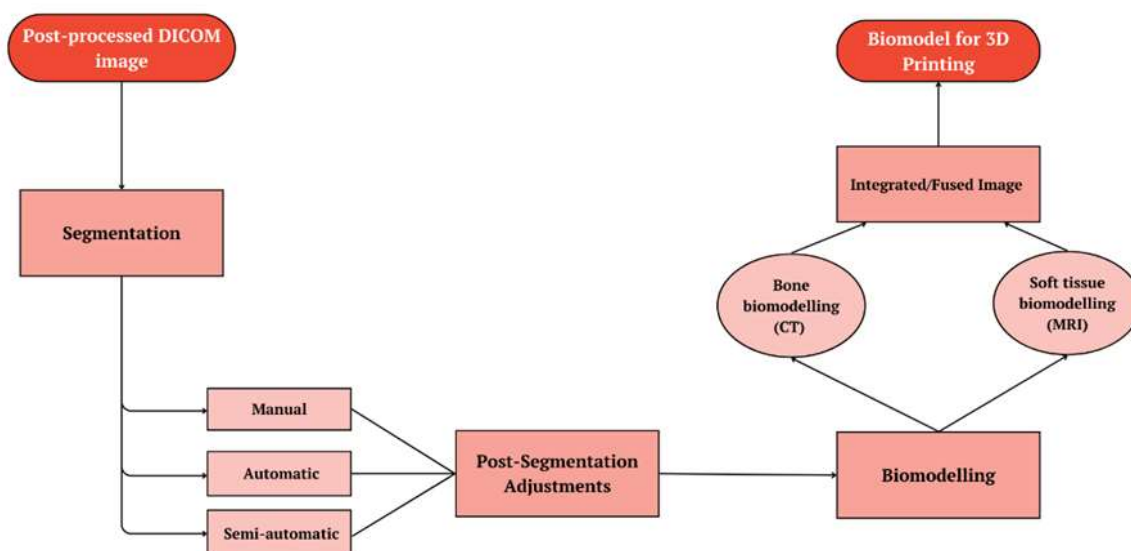


Figure 1: Biomodelling processing from Image to 3D objects

Applications Of 3d Printing In Radiology

Currently, 3D printing is revolutionizing practically every sector of the economy because of its many uses. It is used to make everything from clothing and exquisite artwork to simple toys and models. It is also essential to the production of modern-day components for spacecraft and airplanes (Jakus, 2018). During the COVID-19 pandemic, due to the increase in the number of patients, 3D printing was successfully used to print several items such as personal protective equipment (PPE), masks, valves, and other devices that had a shortage in hospitals (Longhitano et al., 2021).

The following are a few of the primary direct uses of 3D printing in the medical and clinical fields, which are made possible by the various advantages that this technology could bring about: used for pre-operative planning and customized pre-surgical instruments and prosthetics, testing of devices: for quick development of devices (Aimar et al., 2019).

Pre-surgical planning

3D printing can be used to print out anatomical models, which are utilized to prepare fixation plates for surgical procedures. It enables the analysis of the patient's anatomy and injury and, to derive from this, a reference to plan the surgery. Based on this, fixation plates can be precontoured to meet the patient's anatomy. Using patient-specific 3D printed pre-contouring templates has benefits, including reduced blood loss and time during surgery, enhanced fracture configuration assessment, and selection of screws and fixation plates based on the patient's anatomy (Marinescu et al., 2020).

3D printing can be combined with 3D computed tomography, bronchography and angiography to precisely identify the pulmonary segmental structures, prevent intraoperative injuries and blood loss, shorten the duration of the procedure and increase safety of thoracoscopic pulmonary segmentectomy in non-small cell lung cancer (Hu et al., 2021).

With 3D printing, it is possible to create models of small vessels, which are helpful for both surgical assistance and preoperative preparation. A study successfully created a model and used pre-operatively to test catheter equipment for a patient with multiple splenic artery aneurysms, helping identify the optimal puncture site. The same model served as an intraoperative reference, facilitating a successful and unconventional procedure that preserved splenic function. The results indicated that 3D printing of small vascular models is feasible and valuable for both pre-operative planning and intraoperative guidance, thanks to advancements in accessible technology. This method, however, has drawbacks. Testing should take into account the fact that 3D-printed models might not have the same endovascular flow, wall fragility, softness or resistance as an actual vascular system (Itagaki, 2015).

3D printing has demonstrated the ability to speed up, improve accuracy, and reduce invasiveness in patient-specific plastic surgery, leading to lesser scars. This is particularly crucial for children, whose finer, more compact anatomy and the possibility of blood loss during longer surgeries are essential factors. 3D printing can lower risks and improve results by increasing surgical precision, especially in specializations like plastic surgery and craniomaxillofacial surgeries. Beyond this, patients' quality of life is significantly impacted by 3D printing in plastic surgery. It significantly improves patients' recuperation and general wellbeing by assisting in the restoration of not only outward appearance but also vital abilities like speaking and social interaction (Lin & Yarholar, n.d.).

Education and training

In terms of education, 3D-printed simulators mark a substantial change in the way that training is carried out. Traditionally restricted by time and space, skilled surgeons can now teach a variety of techniques or procedures outside the operating room. With this method, more trainees can acquire expertise at the same time. Furthermore, every case be 3D printed as many times as necessary, giving surgeons several chances to practice with the same case (Zabala-Travers, 2021).

Using 3D printing, a silicone model was created for ERCP training, enabling semipermanent repetition of different ERCP procedures. The silicone model allowed for successful practice of procedures like calculus extraction, biliary cannulation and stent implantation without causing damage to the model, allowing for real-time endoscopic and fluoroscopic studies. The model's robust and economical construction makes it a great training aid for certain ERCP approaches (Kwon et al., 2020).

Bioprinting

3D bioprinting is an emerging technology that is expected to transform tissue engineering and regenerative medicine, impacting various fields, including tissue engineering, regenerative medicine, and pharmaceuticals. Bioprinting involves the process of creating biomaterial that contains living cells through the use of 3D printing. The exact build of cells, tissues, and even organs is made possible by this method, which enables the layering of polymers and living cells. Because of its adaptability, bioprinting has been widely used in fields like cancer research, tissue engineering, regenerative medicine, and drug screening. The capacity of this technology to precisely deposit cells, hormones, medications, and growth factors can improve tissue regeneration, making it one of its many important advantages. Biomaterials for bone, cartilage, cardiac tissues, heart valves, neural tissues and even skin have been successfully printed to date. This technology shortens treatment times considerably (Aljohani et al., 2018; Zhang et al., 2021).

Impact On Indian Healthcare

Having explored the various applications of 3D printing, it is important to examine how these technologies influence healthcare outcomes, particularly in the Indian context. As seen previously, incorporating 3D printing in healthcare not only improves the accuracy of diagnosis but also enhances patient-specific treatment methods. As we explore how 3D printing is affecting Indian healthcare, it is evident that these developments deal with crucial challenges the system is facing, like accessibility or cost.

Adoption of 3D printing in Indian healthcare

In India, 3D printing is a relatively new technique in forensics. Although its applications are limited so far, most of the research is still in the proof-of-concept phase, focussing on the pros and cons of the technology. One study explored the use of 3D printing to reconstruct the missing teeth from post-mortem samples, while other studies successfully reassembled fractured dental and bone fragments, obtaining high accuracy with small error margins. Employing this technique with the help of post-mortem computed tomography has also assisted forensics in many other aspects, such as human identification, bite mark/pattern analysis, crime scene reconstruction etc.(Jani et al., 2021).

A study conducted in India surveyed orthodontists to assess their awareness in the usage of 3D printing in the dental-maxillofacial department. Most of the study population said they were familiar with 3D printing. Numerous others mentioned they learned about the technology from workshops and the internet. Even with this awareness, the majority of the respondents said that the main obstacle to using 3D printing clinically was its high cost and complexity. Nevertheless, a significant percentage indicated that they would like to use 3D printing in the future and acknowledged its benefits over conventional digital imaging techniques. To improve diagnostic and treatment planning, a deeper comprehension of this new technology is necessary (Dr. Maitry Parikh, 2019). By making it possible to create personalized implants, surgical guides, and prosthetic devices, 3D printing, also known as additive manufacturing, has completely transformed the area of oral surgery. Surgeons can now create patient-specific models courtesy of this technology, which enhances procedure planning and precision (Kodlipet et al., 2023).

3D printing was used to print molds of patients who underwent cranioplasty, created by software that makes use of computer-assisted design. PMMA implants were made intraoperatively using these molds. The process involved preoperatively creating the molds and then intraoperatively preparing the implant to repair the defect caused by craniectomy. The fundamental method here was to recreate the patient's skull from the unaffected side using a mirrored imaging technique (Gopal et al., 2021).

Despite the potential of 3D printing technology, limited research has been conducted in India, particularly in clinical settings, and although studies have been undertaken, no significant work in Indian healthcare has been published on this technology. There is a pressing need for further investigation and experiments to explore the practical applications and benefits of 3D printing in Indian healthcare.

Challenges in the Indian context

Adopting 3D printing presents a number of significant hurdles for Indian enterprises, most of which fall into the categories of infrastructure, finance, and human resources. The lack of orientation and training is one of the main obstacles. Additionally, High costs, a lack of qualified workers, poor infrastructure, and the challenge of balancing benefits with costs all contribute to it. As businesses get ready for the future, these difficulties point to a larger mentality marked by risk aversion and a lack of faith and confidence in both people and technology (Marak et al., 2019).

1. **Lack of Orientation and Training:** One of the key challenges businesses in India face when adopting 3D printing technology is the lack of proper orientation and training. Many employees lack the necessary knowledge and skills to effectively operate or manage 3D printing systems, which creates hesitation in embracing the technology. To address this, companies can collaborate with educational institutions, technology providers, or government initiatives to offer specialized training and certification programs focused on 3D printing. This approach would help upskill the workforce, making them more confident and capable in using these advanced technologies and facilitating smoother adoption across industries.
2. **High Costs:** The high costs associated with 3D printing—ranging from the initial investment in printers and materials to ongoing maintenance—pose a significant financial challenge, particularly for small and medium-sized enterprises (SMEs). To make adoption more feasible, both government and private financial institutions could offer subsidies, grants, or low interest loans to ease the financial burden on small businesses.
3. **Shortage of Skilled Workers:** Another significant is the shortage of skilled workers who can operate, maintain, and troubleshoot these advanced technologies. This gap in expertise limits the ability of companies to scale and fully leverage the potential of 3D printing. To address this, partnerships between industry and academia can be developed to create specialized training programs that equip workers with the necessary skills. In the short term, companies can also focus on upskilling their existing staff through online courses or by bringing in consultants to fill the knowledge gap, ensuring smoother integration and more effective use of 3D printing technology.
4. **Poor infrastructure:** poor infrastructure can disrupt the smooth operation of 3D printers, leading to delays and inefficiencies. To overcome this, improving local infrastructure is crucial—ensuring stable power supply, better internet connectivity, and enhanced logistics can help enterprises operate 3D printing systems more reliably.
5. **Risk Aversion and Lack of Trust:** Many businesses in India are hesitant to adopt 3D printing due to a strong aversion to risk and uncertainty about its long-term benefits. Past experiences with failed innovations have made companies cautious about embracing new technologies. To overcome this, businesses can begin by implementing pilot projects or small-scale trials, allowing them to test the value of 3D printing without committing large resources upfront. Additionally, showcasing real world case studies and success stories can help build trust in the technology, demonstrating its potential and encouraging wider adoption as companies see tangible results and outcomes from others in their industry.
6. **Regulatory Issues and Lack of Standardization:** The lack of clear regulations and standards for 3D printing in India causes uncertainty and hesitation among businesses. Issues like IP rights, safety standards, and material consistency create challenges. To address this, the government should work with industry leaders to establish clear guidelines and standards. This would reduce legal risks, ensure quality, and boost confidence in adopting 3D printing.

The Future Of 3d Printing In Indian Radiology

Bioprinting offers groundbreaking potential in organ transplantation by creating patient specific tissues and organs using the person's own cells. This could dramatically reduce the risk of organ rejection and the need for long-term immunosuppressive drugs. By enabling personalized transplants, where 3D-printed organs are custom-tailored to fit an individual's unique anatomy, bioprinting could significantly improve transplant success rates. As the technology advances, it has the

potential to address the critical shortage of organs, shorten waiting lists, and make transplants more accessible and affordable—an especially pressing need in India, where demand far outstrips supply.

Innovative materials in 3D printing, such as radiopaque substances and bioactive resins, are transforming the field of radiology by making diagnostic models visible on X-rays and more closely resembling human tissue behavior. These materials can improve the design of custom implants, surgical planning models, and prosthetics, ensuring better fit, durability, and seamless integration with the body.

Meanwhile, the integration of AI into 3D printing is streamlining the process by automating the creation of precise 3D models from radiological images. This not only speeds up workflows but also reduces the risk of human error. AI-driven 3D printing enables personalized treatment plans, enhances surgical precision, and allows for real-time adjustments during procedures, ultimately leading to better patient outcomes and more effective healthcare delivery.

To promote broader adoption of 3D printing in India, several actions can be taken:

1. **Policy and Regulations:** Establishment of clear guidelines for 3D-printed medical devices, financial incentives for innovation, and development of national standards to ensure safety, consistency, and global competitiveness.
2. **Infrastructure Development:** Investment in 3D printing facilities in hospitals and research centers, building a local supply chain for materials to reduce costs, and creation of remote collaboration platforms to connect urban and rural areas.
3. **Training and Skills:** Providing specialized training for healthcare professionals, integrating 3D printing into medical education, and partnering with companies for hands-on experience.
4. **Public Awareness:** Education of the public about the benefits of 3D printing in healthcare. In addition to these, cultural acceptance is another significant factor to be considered. As change comes with resistance, knowledge, and education about advanced technologies are crucial in fostering an environment where innovation can thrive.

CONCLUSION

3D printing has the potential to revolutionize healthcare in India, offering benefits like more accurate diagnoses, personalized treatment plans, and better patient outcomes. However, there are significant challenges to overcome, including high costs, a shortage of skilled workers, limited infrastructure, and a natural hesitancy to adopt new technologies. To unlock its full potential, India needs a concerted effort to improve training, provide financial support, build stronger infrastructure, and create clearer regulations around 3D printing. Looking ahead, more research is needed to evaluate the cost-effectiveness of 3D printing in healthcare, understand how it impacts patient outcomes, and develop standardized guidelines for its use in medical settings. By addressing these gaps, India can make 3D printing a more accessible, practical, and powerful tool in transforming healthcare for the better.

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