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Radiology-Driven 3D Printing: Imaging Workflows and Clinical Applications

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Abstract

Advances in medical imaging and 3D printing have made this technology a powerful tool in modern healthcare. Combining imaging methods like computed tomography (CT) and magnetic resonance imaging (MRI) with 3D printing allows for the creation of precise, patient-specific anatomical models. This has a significant impact on radiology, surgical planning, education, and personalized medicine. This review looks at recent studies on medical 3D and new four-dimensional (4D) printing technologies. It focuses on workflow, manufacturing methods, materials, and clinical uses. The process involves capturing radiological images, segmenting anatomy, converting DICOM data into stereolithography (STL) files, and making prints using additive manufacturing techniques like fused deposition modeling, stereolithography, and selective laser sintering. The review covers applications in radiology, dentistry, pediatrics, forensic medicine, pharmaceuticals, and medical education. It also discusses related quality assurance and regulatory issues. The review shows that 3D printing improves preoperative planning, surgical precision, and anatomical visualization. This leads to better clinical outcomes. In radiology, it helps with interventional planning, training, phantom development, and clearer patient communication. Customized implants, prosthetics, surgical guides, and drug delivery systems show the technology's flexibility. The development of 4D printing introduces smart materials that respond to stimuli and can change over time. This enables dynamic implants, tissue scaffolds, and

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1. Introduction

Indeed, modern medical practice has witnessed a revolution as a result of the integration of medical imaging technologies and additive manufacturing. While initially additive manufacturing was considered an industrial design tool in the 1980s, it has evolved to become an important tool for creating real anatomy from virtual anatomy. In particular, modern radiology practice has been completely transformed by the ability of additive manufacturing to create 3D physical models from 2D imaging data (Soliman SMA, et al.,2024). The radiologist has become the center of customized medicine thanks to the use of additive manufacturing in CT and MRI imaging for precise body models that conform to each patient's unique anatomy by "locking in" each patient's unique morphology. The radiologist's expertise in image interpretation has evolved from image interpretation to surgical planning and design (Pérez-Sevilla M et al.,2025). Recently, 4D printing technology has been seen as an evolutionary step in 3D printing technology. 4D printing technology differs from 3D printing technology in that smart materials are used. 4D printing technology has been seen as having huge potential in drug delivery, regenerative medicine, and smart implants that can sense any change in the body. (Siddique MF et al.,2026) Despite this technology's significant advances, there is still a great deal to be achieved, especially in relation to standardization, quality, and regulation [1-3]. Patients' outcomes are unpredictable because this technology does not yet have a recognized set of standards in picture segmentation, conversion, and manufacturing. Technology is progressing so fast, and this is something that the current regulatory system is unable to keep up with (Long T, et al., 2025). The goal of this paper is to give a thorough overview of radiology-driven 3D and 4D printing technology, covering its technical, production, and clinical features as well as its problems.

2. Imaging Workflows and Technical

2.1. Image Acquisition Protocols

The highest quality radiological imaging is the starting point for medical 3D printing. Because of their excellent spatial resolution, geometric correctness, and quick scanning periods, CT scans are the method of choice for bone or high-contrast structures. Overlap, the right kernel, and thin slices of 1 mm or less are the optimum CT protocols for 3D printing. Because CT angiography makes it possible to see both bone and veins simultaneously, it can also be used, particularly in orthopedic and face conditions. (Pérez-Sevilla M et al.,2025). MRI is crucial when working on projects requiring nerves, muscles, or organs since, as previously indicated, it offers better soft tissue contrast than CT. While T2-weighted or contrast-enhanced sequences are utilized when examining malignancies or inflammatory processes, T1-weighted images offer superior anatomical features. Modern MRI methods, such as diffusion tensor imaging, which makes it possible to see nerve tracks, are advancing 3D modelling (Long T, et al., 2025). Cone-beam CT has also become indispensable, particularly when working on dental or face cases because it reduces the radiation dose needed, making it perfect for corrective jaw surgery or dental implants [4-6]. Additionally, we have been able to work on fetal modeling through four-dimensional ultrasonography, which has made prenatal surgery planning possible. Furthermore, the direction of bio-printing could be influenced by the most recent photoacoustic imaging techniques (Velu A, et al., 2025).

2.2. Image Segmentation Strategies

The vital link between the imaging data and the 3D models that are prepared for printing is anatomical segmentation. It is the procedure of precisely identifying and separating the diseases or abnormalities from the surrounding anatomical structures while closely observing their boundaries and their alignment. In complex anatomical regions and situations, manual segmentation—performed by radiologists and skilled technologists—is the gold standard. The judgment of the tissue's borders is provided by manual segmentation, especially when there are several tissue interfaces or unclear borders. The most widely used method is semi-automatic segmentation since it strikes a balance between speed and technologists' and radiologists' judgment. The most popular methods are threshold-based segmentation and region growth, where the borders are established using the signal intensity in MRI images and the Hounsfield values in CT scans. By offering the ability to define reference points in various anatomical locations, the Grow from Seeds tool facilitates the simultaneous segmentation of numerous entities, such as a tumor and the surrounding parenchyma [7-10]. As convolutional neural networks demonstrate a high level of accuracy that is comparable to that of experts, deep learning has been proposed as a significant advancement in the segmentation process. When compared to manual segmentation, a potential reduction in processing times of up to 30% is possible (Schulze, et al., 2024).

2.3. DICOM-to-STL Conversion Workflow

An open-source, validated method has been established to enable the conversion of medical imaging in DICOM files to STL files for 3D printing. This conversion is a well-understood, standardized process that can be completed with 3D Slicer. Importing the DICOM data is the first stage in this process. Next, a Four-Up view is created, which enables the presentation of all three axes and a 3D view in a single window. The area of interest can then be quickly examined by activating the Volume Rendering option, which offers a variety of alternatives for different tissue types according to the customizable transfer functions. When compared to unaltered data from CT Angiography, which is used for benchmarking, validation studies have proved a high level of accuracy in terms of structure using metrics such as Dice Similarity Coefficient, with a range of error from 0.20% to 0.72% in terms of dimensions. Finally, the models can be exported from the Segmentations module as STL files, which are ready for 3D printing (Pérez-Sevilla M et al., 2025). The figure number must appear well outside the boundaries of the image itself. Multipart figures should be indicated with uppercase and bold font letters (A, B, C, etc.) without parenthesis, both on the figure itself and in the figure legends [11-13].

2.4. Software Ecosystem and File Preparation

Medical 3D printing software comes in a variety of commercial, open-source, and free software programs, each with a different feature set and price. While commercial software like Mimics (Materialise), Seg3D, and OsiriX has more sophisticated functionality and can help with regulatory compliance, open-source programs like 3D Slicer, InVesalius, and MeshLab are excellent choices for a location with a restricted budget (Pérez-Sevilla M et al.,2025).

3. Additive Manufacturing Technologies

3.1. Material Extrusion (FDM)

The most widely available and economical 3D printing process is fused deposition modeling, which solidifies thermoplastic filaments like PLA, ABS, PETG, and nylon after melting them. It is a rudimentary 3D printing technique that is frequently used in surgical applications as a basic planning tool and as a teaching tool.

3.2. Vat Photopolymerization (SLA/DLP)

The foundation of SLA and DLP 3D printing technology is photopolymerization, which produces precise, detailed models with a finish as fine as 25–50 micrometers by curing liquid resins with a light source. It works best for creating accurate surgical guides and anatomical reproductions.

3.3.Powder Bed Fusion SLS/MJF/SLM/EBM)

The materials utilized in this 3D printing process are either metal or polymer and are fused together in a bed of powder to make single-piece items. Functional models are best produced using polymer-based SLS and MJF 3D printing technology, while implants are best produced using metal-based SLM and EBM 3D printing technology (Al Qassab, et al., 2025).

4. Clinical Applications by Specialty

4.1. Diagnostic Radiology

3D-printed models have a number of applications in diagnostic radiology, many of which can enhance our day-to-day clinical tasks. For example, these models can be used to develop strategies and evaluate risks for complex procedures including vascular embolization’s, tumor ablations, and percutaneous biopsies. Phantom models can be very helpful in establishing precision and dependability for dose verification, changes, and calibration.

The models can be especially helpful for training and simulation, giving fellows and residents the opportunity to practice conducting different procedures on human anatomical replicas without putting patients at any risk. Patient communication is another novel use for these models, where patients can view replicas to gain a better understanding of their disease and treatment options (Schulze, et al., 2024).

4.2. Surgical Specialties

Certain surgical specialties have undoubtedly advanced due to three-dimensional printing technology, which enables us to prepare in great detail, act precisely, and provide superior outcomes. For example, in orthopedic surgery, we are able to obtain superior outcomes in preoperative anatomy planning, surgical guidance, and implants customized for each patient. This leads to shorter surgical timeframes, less blood loss, better fracture alignment, and better implant incorporation. Additionally, patient-specific anatomy design for complex surgical paths, tumor surgery, and cranial reconstruction improves safety and aesthetics in neurosurgery. Heart anatomy planning for congenital heart problems, surgical techniques, and innovative methods like 4D printing for cardiac patches are all improved in cardiothoracic surgery. With virtual surgical planning and implants, we can improve outcomes in trauma care, corrective jaw surgery, and exact jaw anatomy in maxillofacial surgery (Neussl, et al., 2025).

4.3. Dentistry

Stereolithography-based 3DP provides sub-millimeter accuracy in dental implant placement for dental implant guides[14-17]. Treatment planning and appliance manufacture benefit from the usage of orthodontic models. In craniomaxillofacial reconstruction, patient-specific gadgets enhance the procedure's results (Oberoi G, et al., 2018).

4.4. Pediatrics

Surgery for complicated congenital anomalies such craniosynostosis, congenital diaphragmatic hernia, and heart problems can be planned using modeling of congenital malformations. Upper limb impairments and facial anomalies can be corrected using reasonably priced prosthetic limbs that can be made to grow with children using 3D printing technology (Starosolski, et al., 2014).

4.5. Forensic Medicine

Facial reconstruction from skull bones can be aided with tissue-depth markers and 3D-printed skull replicas. Trauma patterns can be examined using physical models for legal proceedings. Anthropological research and age estimation can both benefit from high-resolution 3D representations of the human skeleton (Ebert, et al., 2021).

4.6. Medical Education and Training

With the development of cadaver-free models, cadavers are no longer required for medical student training. 3D-printed models and force-sensing technology can be combined to build haptic simulators that offer a realistic feel for manipulating tissue. Medical students can learn about uncommon congenital abnormalities and diseases by using anatomical variation libraries (Haleem, et al., 2021).

5. Four-Dimensional Printing

Since the technique incorporates a temporal dimension, four-dimensional printing is an advancement of additive manufacturing. To put it another way, anything made with 4D printing can adapt to their surroundings by changing their shape, characteristics, or functioning. The procedure makes use of smart materials, which may react or respond in a specific way under specific circumstances. Three key components underpin the 4D printing process: stimulation, smart materials, and spatial control made possible by additive manufacturing. 4D-printed medical equipment may react dynamically to physiological situations, in contrast to 3D models (Taylor, et al., 2024).

5.1. Stimulus-Responsive Material Platforms

Smart and targeted medicine is based on stimuli-responsive polymers, which change their response to certain stimuli in accordance with their environment. Polyacrylic acid, alginate, and chitosan are pH-responsive hydrogels, and they change their size to deliver targeted medicine to a certain part of the body, such as the stomach or intestines. Shape-memory polymers and PNIPAm change their response to a certain temperature to deliver targeted medicine to a certain part of the body, such as the stomach or intestines, by seeking a certain temperature. They also help in processes such as wound healing and cell dissociation. High-resolution 3D printing and drug delivery are possible with photo-responsive polymers such as GelMA and spiropyran-based polymers, which change their response with the help of light. Tissue stimulation and non-invasive drug delivery are possible with magnetic field-responsive polymers, which use magnetic nanoparticles to change their response to a certain magnetic field, opening up new avenues in tissue engineering and advanced scaffold design with the help of moisture-responsive polymers, which change their shape in accordance with a certain moisture level (Zhe Wang, et al., 2025).

5.2.Clinical applications of 4d printing

Because 4D printing is producing dynamic structures that react to stimuli similarly to how living tissues in the body do, it is revolutionizing the fields of tissue engineering and medication delivery systems. Hydrogels that change from soft to firm in terms of their mechanical properties have been developed for the repair of cartilage and bone, and scaffolds that respond to magnetic fields and use the effect of shape memory to place the scaffolds in the body minimally invasively and apply mechanical stimulation. Patches that are temperature-responsive, self-folding, and resistant to the heart's pounding have been developed for cardiac repair. Coaxial bioprinting and self-folding scaffolds have been developed to mend blood arteries and maintain their openness throughout time. Temperature and self-healing hydrogels that encourage wound contraction, prevent infection, and stimulate stem cell proliferation have been developed for skin healing, as have flexible chitosan scaffolds that cover the wound. Programmable drug delivery devices that target the issue site and are guided by pH and magnetic responses have been developed (Sheikh, et al.,2022).

6. Challenges and Limitations

Numerous interrelated factors, including technical, biological, regulatory, and economic ones, have impeded the widespread use of 3D and 4D printing in healthcare. The technological factors include the lack of automatic segmentation and common file formats for printing, as well as challenges in handling materials that can be printed in several formats and predicting the real-time performance of stimuli-responsive materials. The biological aspects that impact the viability of large tissue engineering tissues include variations in biodegradation rates, variations in material fatigue, and inadequate vascularization. Adoption at healthcare facilities, especially those with limited resources, is impacted by a number of regulatory reasons, including the lack of explicit laws for bio printed tissues, inadequate quality norms, and a lack of clinical trial data (Lambert, et al., 2022).

7. Future Directions

Future advancements in 3D and 4D printing have the potential to completely transform materials, technology, laws, and medical uses. Because AI can automate picture segmentation and modify 3D printing parameters, it has the potential to completely transform 3D and 4D printing. Volumetric and in situ bioprinting are two new technologies that could help get over speed restrictions and enable 3D printing of tissues right in the operation room. Using both additive and subtractive methods, hybrid manufacturing shows promise for improving precision. However, the mechanical and biological capabilities of 3D and 4D printed tissues could be enhanced by future bionics and smart materials due to their self-healing capabilities, multi-trigger reactions, and variable qualities. Increased restrictions through uniform norms and quality standards are another hopeful aspect of the future of 3D and 4D printing. With clear protocols and committed teams, 3D and 4D printing have the potential to completely transform the clinical uses of these materials (Srivastava, et al., 2025).

Conclusions

From being only an area of study, radiology-driven 3D printing technology has developed into a crucial component of modern patient care. Better surgical planning, training, and patient-specific care are all made possible by it. We can produce precise anatomical reproductions if we adhere to established procedures from data intake in DICOM format to the finished product made utilizing additive manufacturing. This leads to shorter operations, less blood loss, and better surgical outcomes, according to studies. The technique is also utilized in many areas of medicine, and by adding new dimensions to tissue engineering and drug administration through stimulus-responsive devices, 4D printing is creating new opportunities in this field. However, the lack of standards, material problems, legal concerns, and financial limitations are preventing this technology from gaining widespread use. In the near future, it is anticipated that advancements in technology, legislation, and interdisciplinary cooperation will make 3D and 4D printing technologies an essential component of patient care.

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