ADDITIVE MANUFACTURING IN ANATOMY EDUCATION: EDUCATIONAL APPLICATIONS OF 3D-PRINTED HUMAN ORGANS

[1] Dr. Saurabh Verma, [2]Dr. Dattu N Bandapalle

[1] P.G Scholar, Department of Rachana Sharir, Parul Institute of Ayurveda, Parul University, Vadodara, Gujarat

[2]HOD and Professor, Department of Rachana Sharir, Parul Institute of Ayurveda, Parul University, Vadodara, Gujarat, India

E mail Id: saurac670@gmail.com, Page. No. 43-55

Abstract

Anatomy forms the foundation of medical and health sciences education, traditionally taught through cadaveric dissection. While cadavers provide invaluable hands-on experience, their use is associated with ethical concerns, religious sensitivities, limited availability, high maintenance costs, and restricted exposure to anatomical variations and pathology. Three-dimensional (3D) organ printing has emerged as an innovative educational tool that addresses many of these challenges. By converting computed tomography (CT) and magnetic resonance imaging (MRI) data into tangible anatomical models through additive manufacturing, 3D printing enables the creation of accurate, reproducible, and customizable organ replicas. These models facilitate enhanced spatial understanding, haptic learning, and standardized teaching while offering an ethically inclusive alternative for students with cultural or religious objections to cadaver use, such as those following Jain principles of *Ahimsa*. This review explores the principles, workflow, printing technologies, materials, educational efficacy, advantages, limitations, and future potential of 3D-printed anatomical models in anatomy education. The evidence suggests that 3D-printed organs are effective adjuncts to traditional teaching methods, improving comprehension and accessibility while supporting multimodal learning environments. Although limitations in tissue realism and initial costs persist, ongoing advancements in material science and open-source technologies indicate a promising role for 3D printing in the future of anatomy teaching.

Keywords: Anatomy, 3D organ printing, Ayurveda, medical education, preservation

1. Introduction

The cornerstone of medical and health sciences education is anatomy. Cadaveric dissection has been the gold standard for teaching gross anatomy for centuries because it provides an invaluable, practical experience with actual human tissue.[1-2]

However, there are a lot of difficulties with this conventional approach. Cadavers are scarce and subject to stringent ethical and legal requirements, which raises the cost of acquisition, storage, and upkeep (formalin-based preservation).[3-4] Furthermore, cadavers provide a homogeneous view of anatomy, seldom displaying the variety of anatomical variations or particular pathological states that are essential for clinical comprehension.

There is a significant ethical and cultural conundrum hidden behind these practical and educational challenges. Physical contact with a dead body can be extremely upsetting and forbidden for students who practice religions like Jainism, which places a strong emphasis on Ahimsa (non-violence) and respect for all life forms.[5-6] Similar to this, some interpretations of Buddhism, Islam, and Hinduism prohibit or discourage the desecration of a deceased person's body.[7] Students are forced to choose between their professional education and their religious beliefs, creating an unfair learning environment that frequently leads to psychological distress or requests for exemptions that could stigmatize the student.

3D printing, also referred to as additive manufacturing (AM), is a disruptive technology that can solve these complex problems. 3D printing makes it possible to create precise, repeatable, and customizable anatomical replicas by transforming digital data from computed tomography (CT) or magnetic resonance imaging (MRI) scans into tangible, physical models.[8-9] These models do not have the same ethical and religious restrictions as cadavers, so they can be handled, dissected (if printed in parts), and studied.

Materials and Methods

This study is a narrative review examining the application of 3D organ printing in anatomy education. Relevant literature was retrieved from PubMed, Scopus, Google Scholar, and institutional repositories using keywords such as *3D organ printing*, *anatomy education*, *additive manufacturing*, and *medical education technology*. Peer-reviewed English-language articles focusing on educational, ethical, technological, and pedagogical aspects of 3D-printed anatomical models were included. Selected studies were analysed and thematically synthesized to evaluate printing workflows, materials, educational effectiveness, advantages, limitations, and future directions.

Aim and Objectives

Aim

To evaluate the role of 3D-printed anatomical models in anatomy education with respect to their educational effectiveness, ethical acceptability, technological process, and future potential as teaching tools.

Objectives

1. To describe the workflow and technologies involved in creating 3D-printed anatomical models.

2. To assess the educational efficacy of 3D-printed organs in improving spatial understanding and anatomical learning.
3. To analyse the advantages and limitations of 3D-printed models compared to cadaver-based teaching.
4. To examine the ethical, religious, and environmental implications of using 3D-printed anatomical models.
5. To explore future directions, including material innovation and open-source dissemination, in anatomy education.

2. The Process and Technology of Creating 3D-Printed Anatomical Models

The creation of 3D-printed anatomical models is a systematic, multidisciplinary process that integrates medical imaging, digital image processing, computer-aided design, and additive manufacturing technologies. Each stage is critical in ensuring anatomical accuracy, structural fidelity, and educational usefulness.

2.1. Step-by-Step Workflow

1. Image Acquisition

The process begins with the acquisition of high-resolution volumetric medical imaging data from living subjects or donated cadavers. The most commonly used imaging modalities include:

- **Computed Tomography (CT):** CT imaging is particularly well suited for visualizing osseous structures, dense tissues, and contrast-enhanced vascular anatomy. It produces high-contrast DICOM (Digital Imaging and Communications in Medicine) datasets that facilitate accurate segmentation of hard tissues. [10]
- **Magnetic Resonance Imaging (MRI):** MRI provides superior soft-tissue contrast and is ideal for detailed visualization of organs such as the brain, liver, heart, muscles, ligaments, and neurovascular structures. [11]
- **Micro-CT or Cryosection Data:** These modalities are used when ultra-high-resolution models are required, often at near-histological scale, particularly for research or advanced educational purposes.

2. Image Segmentation

Image segmentation is the most critical and time-intensive stage of the workflow. DICOM datasets are imported into specialized segmentation software. Using grayscale thresholding, region-growing algorithms, edge detection, and manual refinement tools, the region of interest (ROI)—such as an individual organ, nerve, or vascular network—is isolated from surrounding tissues.[12] Each segmented structure is converted into a discrete digital mask, enabling the independent manipulation and printing of individual anatomical components.

3. 3D Model Generation and Editing

The segmented digital mask is converted into a three-dimensional surface mesh, typically exported as an STL (Stereolithography) or OBJ file. This digital anatomical replica often requires further refinement using mesh-editing software. Common corrective procedures include removal of imaging artifacts, closure of surface holes, smoothing of irregularities, and mesh decimation to reduce polygon count while preserving anatomical detail.[13] These optimizations ensure printability without compromising educational accuracy.

4. Digital Slicing and Support Generation

The finalized STL file is imported into printer-specific slicing software. The software virtually divides the 3D model into hundreds or thousands of horizontal layers, typically ranging from 0.05 mm to 0.3 mm in thickness. For printing technologies that require it, temporary support structures are automatically generated to stabilize overhanging or complex geometries during fabrication.[14]

5. Additive Manufacturing (Printing)

The sliced file, converted into machine-readable G-code, is transmitted to the 3D printer. The printer fabricates the anatomical model layer-by-layer according to the selected printing technology and material parameters. The duration of printing varies depending on model complexity, resolution, and printer type.

6. Post-Processing

Following completion of printing, the model undergoes post-processing, which may include:

- Removal of the printed model from the build platform
- Mechanical or chemical removal of support structures
- Post-curing under ultraviolet light for resin-based prints to enhance mechanical strength and dimensional stability[15]
- Finishing procedures such as sanding, priming, and painting to improve surface quality, color-coded anatomical structures, or enhance tactile realism

2.2. 3D Printing Technologies Used for Anatomical Models

Two primary additive manufacturing technologies are most commonly employed for educational anatomical model production.

1. Fused Deposition Modelling (FDM)

Process:
In FDM printing, a thermoplastic filament is fed into a heated extruder, melted, and deposited in a continuous bead along a predetermined path. The

material solidifies upon cooling, with each layer bonding to the one beneath it.[16]

Applications:

FDM is widely used for cost-effective fabrication of large bones, basic organ geometries, and modular or dissectible teaching models. While resolution is lower than resin-based methods, accessibility and durability make it suitable for routine classroom use.

2. Stereolithography (SLA) and Digital Light Processing (DLP)

Process:

SLA and DLP technologies use photopolymer resins that are selectively cured by ultraviolet light. SLA employs a focused laser beam, whereas DLP uses a projected light pattern to cure entire layers simultaneously.[17]

Applications:

These technologies provide superior surface resolution and fine structural detail, making them ideal for intricate anatomical structures such as cerebral vasculature, middle-ear ossicles, dental anatomy, and complex organ surfaces.

2.3. Materials and Their Chemical Properties

The choice of printing material significantly influences the mechanical behavior, tactile properties, durability, and educational suitability of the anatomical model.

Table No - 1

Material	**Printing Technology**	**Key Chemical Properties**	**Educational Application**
Polylactic Acid (PLA)	FDM	Biodegradable aliphatic polyester derived from renewable sources such as corn starch; glass transition temperature ~60 °C; low shrinkage, easy printability, relatively brittle.[18]	Ideal for rigid organ and bone models; suitable for snap-fit and modular anatomy teaching aids.
Acrylonitrile Butadiene Styrene (ABS)	FDM	Petroleum-based amorphous thermoplastic copolymer; tough, impact-resistant, slightly flexible; higher printing temperature; prone to warping.[19]	Used for durable models requiring greater mechanical strength and heat resistance.
Thermoplastic Polyurethane (TPU)	FDM	Thermoplastic elastomer with rubber-like elasticity, high abrasion resistance, and excellent impact strength.[20]	Suitable for simulating soft tissues such as muscles, skin, and blood vessels.

Material	Printing Technology	Key Chemical Properties	Educational Application
Standard Photopolymer Resins	SLA/DLP	Acrylate- or epoxy-based monomers cured via photopolymerization into rigid thermoset plastics; available in clear, flexible, or high-strength formulations.[21]	Preferred for high-detail anatomical structures including skulls, sinuses, and vascular networks.
Biocompatible/Surgical Guide Resins	SLA/DLP	Certified non-cytotoxic resins (Class I/IIa) designed for short-term skin or mucosal contact; undergo stringent biocompatibility testing.[22]	Used for pre-surgical planning models and educational models intended for clinical simulation environments.

3. Results: Efficacy and Analysis of 3D-Printed Anatomical Models

A growing body of literature and practical experience demonstrates the impact of 3D-printed models in anatomy education.

3.1. Educational Efficacy

Research continuously demonstrates that 3D-printed models greatly improve spatial comprehension, which is a common challenge when learning anatomy from 2D atlases.[23-24] They are useful links between actual cadaveric tissue and textbook diagrams. When it came to identifying structures and comprehending relationships, students who used 3D-printed models outperformed those who only used cadavers or digital models in objective testing.[25-26] Additionally, standardized, repetitive learning across large student cohorts is made possible by the ability to print multiple copies of the same rare anatomical variant or pathology.

3.2. Advantages and Disadvantages of 3D-Printed Anatomical Models

The adoption of 3D-printed anatomical models in anatomy education offers numerous pedagogical, ethical, and logistical benefits. However, these advantages must be balanced against inherent technical, financial, and material limitations. A comparative evaluation is presented in Table 2.

Figure 1: Three-dimensional printed human heart model demonstrating external morphology.

Figure 2: Superior view of 3D-printed heart showing major vascular openings.

Figure 3: First cross-sectional plane of 3D-printed heart illustrating internal chambers.

Figure 4: Second cross-sectional plane of 3D-printed heart demonstrating ventricular anatomy.

Advantages And Disadvantages Of 3d Print

Advantages	Disadvantages
Ethical and Religious	Limited Tissue

Advantages	Disadvantages
Inclusivity: Eliminates ethical concerns associated with cadaver procurement and provides an acceptable alternative for students with religious or cultural objections to handling human remains.[5,7]	**Authenticity:** Printed models cannot fully replicate the complex texture, elasticity, colour variation, or heterogeneity of living or preserved biological tissues. They remain structural representations rather than true tissue analogues.
Accessibility and Reproducibility: Anatomical models can be produced on demand in any institution equipped with a 3D printer and reproduced with identical accuracy, promoting global equity in anatomy education.[8]	**High Initial Cost and Technical Expertise:** High-resolution printers, specialized materials, and licensed software involve significant upfront costs, while image segmentation and model preparation require trained personnel.
Customization and Pathology Representation: Enables the fabrication of patient-specific models illustrating congenital anomalies, tumors, traumatic injuries, or rare variations, thereby strengthening clinical–anatomical correlation.[27]	**Material and Dissection Limitations:** Most commonly used printing materials do not permit realistic cutting, peeling, or layered dissection. Multi-material printing to simulate tissue planes remains complex and expensive.
Enhanced Spatial and Haptic Learning: Hands-on interaction with three-dimensional models significantly improves understanding of complex anatomical relationships compared to two-dimensional atlases or digital images.[23,24]	**Time-Intensive Production:** The complete workflow—from image acquisition to post-processing—may take several hours to days for complex organs, limiting use for immediate teaching needs.
Long-Term Cost-Effectiveness: Although initial investment is substantial, repeated use and reproducibility can reduce long-term costs compared with maintaining cadaver laboratories, especially for standardized teaching specimens.	**Technological Obsolescence:** Rapid advancements in 3D printing hardware and software may render existing systems outdated, necessitating continuous upgrades and reinvestment.
Durability and Biosafety: Printed models are durable, non-degradable, and free from	**Environmental Impact:** Plastic waste from failed prints, support materials, and obsolete models

Advantages	Disadvantages
biohazard risks, unlike formalin-preserved cadavers, thereby improving laboratory safety and longevity of teaching aids.[15]	contributes to environmental burden unless sustainable recycling or biodegradable materials are employed.

Table No - 2

4. Discussion

1. **Ethical and Religious Inclusivity:** 3D-printed anatomical models address ethical concerns related to cadaver use and allow students from religions such as Jainism, where *Ahimsa* prohibits harm to physical bodies after death, to participate fully in anatomy education without moral conflict.[5,6] This approach also respects broader cultural and personal sensitivities, making anatomy education more inclusive.

2. **Democratization of Anatomical Education:**
Institutions lacking body donation programs or adequate infrastructure can develop comprehensive libraries of anatomical models using 3D printing. This significantly reduces geographical and economic barriers, globalizing access to high-quality anatomy education.[8]

3. **Teaching Anatomical Variations and Pathology:**
Unlike traditional cadaver-based teaching, which largely emphasizes normal anatomy, 3D printing enables systematic demonstration of anatomical variations and pathological conditions, thereby strengthening clinical correlation and applied learning.[27]

4. **Improved Spatial Cognition and Haptic Learning:**
Physical interaction with 3D-printed organs enhances spatial understanding and kinaesthetic learning. Handling and assembling models reinforces three-dimensional anatomical relationships essential for surgical anatomy and complex regions such as the cranial base and retroperitoneum. [23,24]

5. **Standardization in Assessment:** Identical 3D-printed models can be used across multiple examination stations, ensuring uniformity and fairness. They enable objective assessment of spatial orientation, surface anatomy, and palpation skills.

6. **Support for Multimodal Learning:** 3D-printed models serve as effective adjuncts rather than replacements for cadaveric dissection. Their integration with virtual simulations, radiological imaging, and traditional textbooks supports diverse

learning styles and enhances knowledge retention.[25]

7. **Promotion of Interdisciplinary Collaboration:**
   The development of 3D anatomical models encourages collaboration among anatomists, radiologists, biomedical engineers, and educators, reflecting the interdisciplinary nature of modern healthcare practice.

8. **Environmental Considerations:**
   3D printing reduces chemical waste associated with cadaver preservation. However, concerns remain regarding plastic waste from non-biodegradable materials such as ABS and photopolymer resins. Sustainable practices, including the use of PLA, recycling strategies, and digital file sharing, are essential.[18,21]

9. **Limitations in Tissue Realism:**
   Current materials cannot accurately replicate the biomechanical properties of human tissues. Ongoing research into multi-material printing, hydrogels, and silicone-based composites aims to bridge the gap between simulation and biological realism.[28]

10. **Economic Feasibility and Open-Source Growth:**
    Although initial setup costs are high, open-source platforms such as the NIH 3D Print Exchange provide free, peer-reviewed anatomical models. Combined with decreasing hardware costs, this supports a sustainable “download-and-print” future for anatomy education.[29]

Conclusion

The field of anatomy education has undergone a permanent transformation thanks to additive manufacturing. Human organs that are 3D printed present a powerful blend of creative potential, ethical flexibility, and pedagogical efficacy. They offer a vital way to honor the cultural and religious convictions of students from various backgrounds, including Jainism, and guarantee that no student is compelled to choose between their faith and their career. The path is obvious, even though there are still obstacles to overcome, especially in the areas of tissue realism, production know-how, and environmental sustainability. 3D-printed anatomical models will become an essential, mainstream part of a comprehensive, inclusive, and contemporary medical education curriculum as technology develops and costs come down. They signify the development of anatomical education into a more approachable, diverse, and morally responsible field rather than the demise of cadaveric instruction.

CONFLICT OF INTEREST – NIL

SOURCE OF SUPPORT - NONE

References

1. Ghosh SK. Cadaveric dissection as an educational tool for anatomical sciences in

the 21st century. Anat Sci Educ. 2017 May;10(3):286-299.

2. Estai M, Bunt S. Best teaching practices in anatomy education: A critical review. Ann Anat. 2016 Nov; 208:151-157.
3. Riederer BM. Body donations today and tomorrow: What is the role of the university and the public? Ann Anat. 2016 Nov; 208:9-14.
4. McLachlan JC, Patten D. Anatomy teaching: ghosts of the past, present and future. Med Educ. 2006 Mar;40(3):243-53.
5. Jain A, Singh S. Ethical dilemmas in anatomy education: A perspective from Jainism. Indian J Med Ethics. 2020 Jul-Sep;V(3):245-247.
6. Suthar N. Ahimsa and the modern medical curriculum: A Jain perspective on anatomy lab. J Dharma. 2019;44(2):201-218.
7. Jones DG. The use of human bodies and body parts in anatomy education: Ethical and religious considerations. Clin Anat. 2020 Sep;33(6):902-909.
8. Li K, Liao H. The application of 3D printing in anatomy education: a review. Med Sci Educ. 2020; 30:1735–1742.
9. McMenamin PG, Quayle MR, McHenry CR, et al. The production of anatomical teaching resources using three-dimensional (3D) printing technology. Anat Sci Educ. 2014 Nov-Dec;7(6):479-86.
10. Mitsouras D, Liacouras P, Imanzadeh A, et al. Medical 3D printing for the radiologist. Radiographics. 2015 Oct;35(7):1965-88.
11. Ionita CN, Mokin M, Varble N, et al. Challenges and limitations of patient-specific vascular phantom fabrication using 3D Polyjet printing. Proc SPIE Int Soc Opt Eng. 2014 Mar 13; 9038:90380M.
12. Fedorov A, Beichel R, Kalpathy-Cramer J, et al. 3D Slicer as an image computing platform for the Quantitative Imaging Network. Magn Reson Imaging. 2012 Nov;30(9):1323-41.
13. Haleem A, Javaid M. 3D scanning applications in medical field: A literature-based review. Clin Epidemiol Glob Health. 2019 Sep;7(3):199-210.
14. Tack P, Victor J, Gemmel P, et al. 3D-printing techniques in a medical setting: a systematic literature review. Biomed Eng Online. 2016 Oct 21;15(1):115.
15. Martelli N, Serrano C, van den Brink H, et al. Advantages and disadvantages of 3-dimensional printing in surgery: A systematic review. Surgery. 2016 Jun;159(6):1485-1500.
16. Ngo TD, Kashani A, Imbalzano G, et al. Additive manufacturing (3D printing): A

review of materials, methods, applications and challenges. Compos Part B Eng. 2018 Jun 1; 143:172-196.

17. Melchels FPW, Feijen J, Grijpma DW. A review on stereolithography and its applications in biomedical engineering. Biomaterials. 2010 Dec;31(24):6121-30.

18. Farah S, Anderson DG, Langer R. Physical and mechanical properties of PLA, and their functions in widespread applications — A comprehensive review. Adv Drug Deliv Rev. 2016 Dec 15; 107:367-392.

19. Aumnate C, Pongwisuthiruchte A, Pattananuwat P, et al. Fabrication of ABS/Graphene Oxide Composite Filament for Fused Filament Fabrication (FFF) 3D Printing. Adv Mater Sci Eng. 2018; 2018:2830437.

20. Dizon JRC, Espera AH, Chen Q, et al. Mechanical characterization of 3D-printed polymers. Addit Manuf. 2018 May; 20:44-67.

21. Bagheri A, Jin J. Photopolymerization in 3D Printing. ACS Appl Polym Mater. 2019 Apr 12;1(4):593-611.

22. Sharma N, Cao S, Msallem B, et al. Effects of steam sterilization on 3D printed biocompatible resin materials for surgical guides. J Dent. 2020 Jul; 98:103370.

23. Preece D, Williams SB, Lam R, et al. "Let's get physical": advantages of a physical model over 3D computer models and textbooks in learning imaging anatomy. Anat Sci Educ. 2013 Jul-Aug;6(4):216-24.

24. Kong X, Nie L, Zhang H, et al. Do 3D printing models improve anatomical teaching about hepatic segments to medical students? A randomized controlled study. World J Surg. 2016 Oct;40(10):2406-13.

25. Chen S, Zhu J, Cheng C, et al. Can virtual reality improve traditional anatomy education programmes? A mixed-methods study on the use of a 3D skull model. BMC Med Educ. 2020 Dec 1;20(1):395.

26. Lim KH, Loo ZY, Goldie SJ, et al. Use of 3D printed models in medical education: A randomized control trial comparing 3D prints versus traditional methods for learning the carpal bones. Anat Sci Educ. 2016 May;9(3):213-21.

27. Watson RA. A low-cost surgical application of additive fabrication. J Surg Educ. 2014 Jan-Feb;71(1):14-7.

28. Jiang D, Ning F, Wang Y. Additive manufacturing of biocompatible ceramics and composites: A review. J Mater Sci Technol. 2021 Nov 15;92:1-15.

29. National Institutes of Health. The NIH 3D Print Exchange [Internet]. Bethesda (MD):

U.S. National Library of Medicine; 2014 - [cited 2023 Oct 26]. Available from: https://3dprint.nih.gov/