Journal homepage: https://medicinskiglasnik.ba
Med Glas (Zenica) 2026;23(1)
https://doi.org/10.17392/1975-23-01

Med (Zenica) Glas

ORIGINAL ARTICLE

Impact of 3D printing on vascular surgery training and preoperative planning

Haris Vukas[1,2*], Samra Kadić-Vukas[3], Sumeja Ćatić[4], Farah Dedović[2], Ruvejda Dizdarević[2], Nail Šehić[5], Merim Jusufbegović[6]

[1]Clinic of Cardiovascular Surgery, Clinical Centre University of Sarajevo, [2]Sarajevo School of Science of Technology Medical School, [3]Department of Neurology, Cantonal Hospital Zenica, [4]Health Centre Zenica, [5]Clinic of Cardiovascular Surgery, University Clinical Centre Tuzla, [6]Clinic of Radiology, Clinical Centre, University of Sarajevo, Bosnia and Herzegovina

ABSTRACT

Aim To investigate the impact of three-dimensional (3D) printing technology on vascular surgery, focusing on its role in preoperative planning and surgical training.
Methods A systematic review was conducted of studies published between 2017 and 2024 that evaluated 3D printing in vascular surgery. Databases searched included MEDLINE and CENTRAL. Eligible studies reported applications of 3D printing in preoperative planning, simulation, or surgical education.
Results Analysis of relevant studies revealed that 3D-printed vascular models improved surgical precision, reduced fluoroscopy time, enhanced technical skill acquisition, and increased trainees' confidence. Models based on computed-tomography angiography data provided accurate, patient-specific anatomy for classic or endovascular aortic aneurysm repair and other vascular procedures.
Conclusion 3D printing significantly enhances vascular-surgery training and preoperative preparation by providing realistic, patient-specific simulations that improve both technical competence and surgical outcomes.
Keywords: education, medical, models, simulation, three-dimensional, training

INTRODUCTION

Three-dimensional (3D) printing has transformed modern medical practice, particularly in vascular surgery where precision is critical. Patient-specific anatomical models generated from imaging data enable surgeons to plan procedures with greater accuracy and provide trainees with realistic simulation tools. Recent evidence confirms that 3D printing improves procedural safety, efficiency, and educational outcomes.

Endovascular procedures have greatly improved vascular disease care, but maintaining surgeon proficiency is difficult due to frequent updates and costly simulators. 3D printing technology, which allows for affordable, customized, and complex model creation, is emerging as a valuable tool in medical training and surgical planning. By integrating 3D printing with imaging data, medical professionals can visualize complex anatomies and develop patient-specific models that enhance education and clinical outcomes (1).

Mixed reality improves vascular surgery training by providing immersive visualization of complex aortic anatomy, especially useful during COVID-19. A Chinese study compared its effectiveness to traditional methods in teaching residents about aortic diseases (2). Similarly, cardiac catheterization with central vein cannulation can pose risks such as thrombosis and infections due to multiple attempts or improper placements (3). A cost-effective cardiovascular simulator was developed to improve training and device testing for cardiac procedures, replicating realistic heart anatomy and blood flow. It serves as a valuable tool for practicing interventions like catheterization and TAVR, enhancing preclinical evaluation. The system addresses limitations of commercial simulators by being more affordable and comprehensive for educational and development purposes (4).

A 3D-printed model was successfully developed and used for endovascular simulation, with development stages and applications (5). Patient-specific 3D models aid in planning intracranial aneurysm treatment and enhance residents' understanding of vascular anatomy and procedures (6).

***Corresponding author:** Haris Vukas
Clinic of Cardiovascular Surgery, Clinical Centre, University of Sarajevo
Bolnička 25, 71000, Sarajevo, Bosnia and Herzegovina
Phone: +387 33 29 79 41;
E-mail: haris.vks77@gmail.com
ORCID ID https://orcid.org/0000-0001-5061-6661

| Submitted: 13. Feb 2025. Revised: 15. Oct 2025, Accepted: 29. Oct 2025.

Transparent 3D models of aortic disease, created from anonymized CT-angiography images using Vat-photopolymerization, showed that these models are feasible as teaching tools. Preliminary data indicate they help improve understanding of aortic disease among surgical trainees (7). 3D-printed tissue constructs, incorporating stem and endothelial cells with appropriate bioinks and printing methods, offer a less invasive treatment option. Proper selection of bioink and printing techniques is essential for developing functional bioprinted tissues and promoting vascularization (8).
The aim of this study was to analyse current literature to evaluate how 3D printing influences vascular-surgery training and preoperative planning.

MATERIALS AND METHODS

Materials and study design

Systematic review followed the PRISMA guidelines. Publications from 2017 to 2024 were screened. Eligibility criteria focused on studies that reported the application of 3D printing in vascular surgery and interventions. Articles exploring the use of 3D printing in vascular surgery, medical simulation, and training were included. Only studies published in English were considered. Conference abstracts, editorial commentaries, and review articles were excluded (Figure 1).

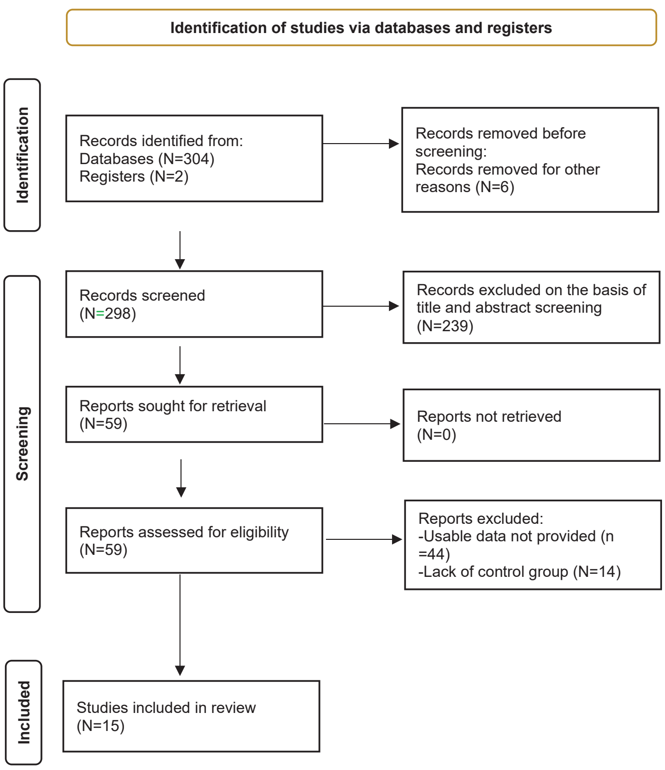

Figure 1. Preferred Reporting Items for Systematic Review (PRISMA)

Information sources and search strategy of literature published between 2017 and 2024 was conducted using various online databases, including MEDLINE (via PubMed) and the Cochrane Central Register of Controlled Trials (CENTRAL). Furthermore, reference lists from systematic reviews and other relevant articles were screened to identify additional information and research results. Additional sources, such as international clinical trial registries (9), were also reviewed. The search strategy incorporated terms such as "Vascular Surgery," "3D Printing," "Surgical Education," "Training Simulation," and "Anatomical Models." Data extraction was performed using a structured Excel spreadsheet, capturing essential information, including study characteristics (e.g., first author, publication year), primary research focus, and key findings.
Study selection and data extraction were systematically organized using Zotero 6.0.30 for efficient management (10). Titles and abstracts were screened to identify potentially relevant studies, followed by a comprehensive full-text review to confirm eligibility based on established inclusion criteria. Any disagreements between reviewers were resolved through discussion. Data extraction was performed using a structured Excel spreadsheet, capturing essential information, including study characteristics (e.g., first author, publication year), primary research focus, and key findings (Table 1).

Methods

Outcome measures. Two reviewers (article authors) independently evaluated each study, resolving disagreements through discussion, to ensure a thorough and unbiased assessment of evidence on 3D printing in vascular surgery training and preoperative planning. The aim of this study was to review surgical skill and competency, as measured by the Objective Structured Assessment of Technical Skills (OSATS) score (11).
Primary outcomes. a) Improvement in surgical skill competency. The primary aim of this study was to evaluate changes in surgical skill competency, measured using the Objective Structured Assessment of Technical Skills (OSATS), before and after training with 3D-printed models, in order to quantify enhancement in trainees' surgical skills. b) Improvement in preoperative planning accuracy. This was assessed by comparing the alignment of preoperative plans developed using 3D-printed models with the actual surgical outcomes, providing evidence for the practical value of these models in refining surgical precision.
Secondary outcomes. Composite technical metrics encompasses several technical improvements, including reduced operative time, fewer intraoperative errors, and enhanced accuracy during procedural steps. Together, these metrics provide a comprehensive evaluation of technical advancements facilitated by 3D printing in vascular surgery.
Eligibility for performing complex procedures were determined if a training with 3D-printed models enables trainees to qualify for more advanced vascular surgeries:
a) monitoring serious adverse events –it compared the prevalence of serious adverse events in surgeries planned with and without 3D -printed models;
b) prevalence of treatment-emergent adverse events arising specifically from the introduction of 3D-printed models into surgical planning and training was recorded and evaluated;
c) boost in trainee confidence levels among trainees was measured before and after training sessions involving 3D models using a Likert scale (12), highlighting the models' impact on psychological preparedness and self-assurance;
d) reduction in surgical completion time and effect of 3D preoperative planning on efficiency was examined by comparing the time required to complete surgeries before and after using 3D-printed models;
e) fluoroscopy time during endovascular procedures was evaluated before and after training with 3D models to determine

Table 1. Overview of studies regarding 3D printing in vascular surgery

Author	Year	Focus of study	Key findings
Foresti R., et al.	2024	3D Vascular modelling/ practice	A new 3D-printed modular system for endovascular training was developed using real patient data. In a small study, trainees using a stepwise difficulty approach completed sessions faster and reported high satisfaction, demonstrating that the system is an effective, customizable, and accessible simulation tool to improve training efficiency.
Raffaele A., et al.	2024	3D Vascular modelling/ practice	A 3D-printed arm model was created using CT scans, including bones and vessels, with latex dipping for veins and Material Jetting for arteries. The model also included a silicone skin mould. Experts rated it highly for realism and functionality, demonstrating its potential as a training tool for paediatric ultrasound-guided vascular procedures, despite some limitations in ultrasound appearance.
Li W., et al.	2023	Teaching tool for trainees	The study found that MR-assisted training combined with 3D-printed models improved residents' understanding of aortic anatomy and pathophysiology, boosted their confidence, and increased enthusiasm for learning about aortic diseases. Most residents rated the models as realistic and effective for training.
Mir A., et al.	2023	3D Vascular modelling/ practice	The study reviews methods for 3D bioprinting vascularized tissues, highlighting the importance of using appropriate bioinks, incorporating stem and endothelial cells, and selecting suitable printing techniques to improve tissue development and address current technical challenges.
Nguyen P., et al.	2023	3D Vascular modelling/ practice	The study found that 3D-printed patient-specific vascular models made with FDM, SLA, SLS, and PolyJet techniques are highly accurate, with minimal errors, making them suitable for clinical planning and training.
Rynio P., et al.	2022	3D Vascular modelling/ practice	This accuracy study evaluated 3D-printed templates of the visceral aorta and aortic arch against CT angiography images. The results showed high reliability and excellent agreement between measurements of aortic and branch diameters, with minimal bias. The models demonstrated very close geometric accuracy, indicating they are reliable tools. These findings support their use in endovascular and interventional radiology practices for guiding the fabrication of customized stent-grafts.
Magagna P., et al	2022	3D Vascular modelling/ practice	This pilot study demonstrated that 3D printing is a feasible and useful tool for preoperative planning, simulation, and patient communication in complex aortic and vascular surgeries. Further research is recommended.
Göçer H., et al.	2021	3D Vascular modelling/ practice	The study found that 3D-printed vascular models closely matched actual measurements and influenced procedural planning, leading to more accurate access site and device choices. Practicing with these models can improve success rates, reduce errors, prevent unnecessary procedures, and serve as valuable educational tools in vascular interventions.
Matyjas M., et al	2021	3D Vascular modelling/ practice	The 3D-printed embolization simulator was highly effective for training, improving beginners' confidence and reducing procedure times, making it a valuable educational tool.
Kiraly L., et al	2021	3D Cardio-Vascular modelling/ practice	This study demonstrates that 3D-printed models of the heart and vessels improve diagnosis, surgical planning, and safety in complex congenital cardiac surgeries. Preoperative rehearsals on these models led to modified operative plans and no increased complications, highlighting their value despite resource requirements. The partnership also suggests a potential for future bioprinted patient-specific implants.
Kärkkäinen JM., et al	2019	3D Vascular modelling/ practice	A 3D-printed AAA model was used to simulate EVAR procedures, demonstrating that experienced operators completed the procedure faster and more independently than less experienced trainees. The model effectively replicates all steps, making it useful for training and assessing endovascular skills in vascular surgery.
Spinelli D., et al	2019	3D Vascular modelling/ practice	3D-printed, disassemblable aortic models based on patient CT images were used to enhance training for 37 surgical trainees. Evaluation showed that demonstrating these models significantly improved trainees' understanding of aortic disease, indicating that 3D models are a feasible and effective teaching tool in surgical education.
Torres I., et al	2018	3D Vascular modelling/ practice	3D printing of vascular models enhances endovascular training by improving surgical planning and skill development, especially for complex procedures. Different methods are reviewed, and the process takes about a week, showing that these models are effective tools for surgical education and confidence.
Rotman OM., et al	2018	3D Vascular modelling/ practice	A new, cost-effective cardiovascular flow simulator was developed to train medical professionals and test devices in central vein catheterization. It features realistic anatomy, pulsatile blood flow, and variable arm positions, enabling catheter insertion and navigation. The simulator aims to improve training, reduce risks, and support device development before animal testing.
Mafeld S., et al	2017	3D Vascular modelling/ practice	The study demonstrated that creating and using a 3D-printed anatomically accurate human aorta for endovascular training is feasible. Feedback from 96 physicians indicates the models are valuable, but further validation is needed.
Park CK.	2017	3D Neuro-Vascular modelling/ practice	This review discusses how advancements in 3D printing technology have enabled the creation of precise, realistic neurosurgical disease models. These models improve spatial understanding, aiding in surgical planning, simulation, and training, and are now ready for routine clinical use.

the models' role in minimizing radiation exposure during endovascular procedures;
f) understanding of anatomical models change in trainees' comprehension of vascular anatomy was assessed through pre- and post- training tests, demonstrating the educational impact of 3D-printed models;
g) measuring the consistency and agreement among surgeons.

RESULTS

Clinical applications and benefits analysis reported significant enhancements in surgical performance among trainees who utilized 3D-printed aneurysm models, noting marked reductions in fluoroscopy time and contrast volume, which contributed to improved safety and efficiency (3,5).

The study involved participants aged 19-75 (median age 54), including 43 women and 33 men. The most common aneurysms were in the internal carotid artery (30%), anterior communicating artery (26%), middle cerebral artery (23%), and posterior circulation (21%). Without 3D printed models, the inter-observer agreement among Medical Doctors (MD1, MD2, MD3) was good, with kappa values of 0.703 (MD1 vs. MD2) and 0.64 (MD1 vs. MD3). After using 3D models, the agreement improved to very good levels: kappa values (k) increased to k=0.85 (MD1 vs. MD2), k=0.70 (MD1 vs. MD3), and k=0.72 (MD2 vs. MD3). The k measures the consistency among surgeons, with higher values indicating better agreement (6).

Six anonymized CT angiography cases of aortic disease were converted into reassemblable 3D models using vat photopolymerization. These models were shown to 37 surgical trainees after a seminar, and a validated questionnaire assessed their understanding before (T0) and after (T1) viewing the models. Participants (average age 28, mostly male) demonstrated a significant increase in understanding, from a median score of 7.25 at T0 to 8.00 at T1 (p=0.002). It emphasized the educational value of 3D-printed aortic models, which helped trainees better comprehend the intricate anatomy of aortic diseases, a critical aspect for precise surgical planning and execution (7).

Successful vascularization depended on integrating stem and endothelial cells, choosing appropriate bioinks, and selecting suitable printing methods (such as extrusion, inkjet, stereolithography, and laser-based techniques) for both scaffold and scaffold-free constructs. Scaffold materials include hydrogels and polymers, while scaffold-free methods use decellularized matrices, spheroids, and protein-based inks (8).

Additionally, it was found that 3D-printed models for arteriovenous malformation surgery not only facilitated more effective preoperative planning but also boosted surgeons' confidence, a vital factor for successful outcomes. Over 18 months, 3D printed models of arteriovenous malformations from CT angiography scans of six patients were created. These vascular models showed precise details of the nidus, vessels, and skull relationship, aiding in surgical planning. Despite clear visualization of vessels, differentiating arteries from veins by colour was a limitation. The models, placed beside surgeons during procedures, improved identification and surgical preparation (13).

Fluid pumps have been integrated to simulate a pulsatile circulatory system, creating a realistic environment for practicing techniques such as percutaneous transluminal angioplasty and ultrasound-guided femoral artery access. All trainees completed the task, with an average final simulation time of 16.24±8.05 minutes. The total training time, including non-evaluated sessions, was shorter for the SS group (23.13±9.2 minutes) compared to the random simulation (RS) group (44.6±12.8 minutes), with a significant difference (p=0.0075). In the standard simulation (SS) group, training times increased progressively over three sessions, while times in the RS group remained steady, indicating that the SS group's difficulty levels increased gradually. The second training session for the SS group used a stepwise difficulty 3D model, whereas the RS group's second session involved a random difficulty 3D model (14).

In several cases, simulations were conducted under fluoroscopy, providing realistic radiological guidance for the trainees. The simulator, designed with computer-aided tools and 3D printed, was used for embolization training. The trainees completed pre- and post- training questionnaires assessing their expertise and confidence levels. Participants watched an instructional video and performed four embolizations on the simulator. Five experts and twelve novices participated, with experts being experienced radiology residents and fellows, and novices being medical students and less experienced residents. Experts rated the simulator highly for embolization training. Performance times differed significantly between experts (189±42s) and novices (235±66s) with a p-value of .001. The simulation effectively replicated the embolization process, including complications, and enhanced educational outcomes. Notably, novices reported a significant boost in confidence (p=0.001) (15).

Simulating endovascular aortic replacement (EVAR) procedures using a 3D-printed aneurysm of aorta abdominalis (AAA) model connected to a fluid pump, two expert implanters and 20 vascular surgical trainees with different level of experience performed the procedures. Results showed that experienced trainees had significantly shorter total procedure times (32±9 minutes) and fluoroscopy times (13±5 minutes) compared to less experienced trainees (44±6 minutes and 23±8 minutes, respectively). All experts completed the procedure within 45 minutes and did so independently, whereas only 46% of the less experienced trainees achieved this, with only 15% completing the entire procedure independently. Benchmark implanters consistently outperformed trainees in nearly all EVAR metrics, highlighting their higher proficiency and the simulator's potential to differentiate skill levels effectively (16).

In the study that evaluated the dimensional accuracy of patient-specific vascular models created using various 3D printing technologies Fused-Deposition Modelling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS) and PolyJet 3D printing, models demonstrated a high level of dimensional accuracy, indicating they are suitable for clinical use in surgical planning and training. All methods produced high-quality models with overall errors ranging from approximately -0.72% to 0.53% compared to original CT angiography data. The digital segmentation process introduced a small average error of about -0.83%. Errors due to the printing process themselves were minimal, with models slightly underestimated on average (17).

The accuracy of 3D-printed models of the visceral aorta and aortic arch, compared to CT angiography images, showed measurements at key landmarks with excellent reliability, with intraclass correlation coefficients above 0.9. Bland-Altman analysis revealed minimal measurement biases, ranging from 0.05 to 0.47 for arch templates and 0.06 to 0.38 for abdominal templates. Hausdorff mean distances averaged 0.47 mm for the

aortic arch and 0.24 mm for the abdominal models, indicating high geometric accuracy suitable for clinical applications. Additionally, the ability to rapidly design and print patient-specific stents addresses delays associated with traditional manufacturing, which often takes 12–15 weeks (18).
In a study describing the reconstruction of an 8-year-old girl's left arm from CT scans—including bones, arteries, and veins—using semi-automatic segmentation, different 3D printing methods were tested. Latex dipping produced vessels that closely resembled real paediatric veins in echogenicity and flexibility, while arteries were printed using material jetting technology. An external mould was also printed to create soft tissues with silicone. Twenty experts evaluated the model, rating it highly realistic in morphology and function for simulation purposes, particularly for vessel and soft tissue response to puncture. However, its ultrasound appearance received lower scores (19).
The Vicenza "San Bortolo" Hospital and the University of Padova created 20 patients 3D-printed aortic models for education, aiding in planning, training, and patient communication. These models improved device customization, surgical accuracy, and surgeon confidence, especially in complex surgeries. They also provide realistic practice for young surgeons to develop open surgical skills outside the operating room. Although cadaveric and virtual simulations are useful, 3D models offer a more accessible and precise way to understand patient-specific anatomy, potentially reducing operative times and radiation exposure (20).
A retrospective analysis of 16 patients (avg. age 72) who underwent superficial femoral artery balloon angioplasty compared pre-procedural CT images with 3D-printed models. Measurements from manual and software segmentation methods were similar and both smaller than the actual balloon sizes used. Stenosis severity assessments were consistent between methods but lower than angiographic reports. The use of 3D models led to changes in vascular access site selection in 31.2% of patients and altered wire and catheter choices in eight cases, demonstrating the models' influence on procedural planning (21).

DISCUSSION

This systematic review can even underscore the transformative role of 3D printing in vascular surgery, highlighting its potential to revolutionize both training and preoperative prospects and illustrate the feasibility and utility of 3D-printed models in endovascular simulations, demonstrating their capacity to replace costlier and less accessible traditional approaches. 3D printing provides vascular surgeons with tangible, patient-specific representations that facilitate personalized planning and rehearsal of complex interventions (). The technology improves comprehension of vascular anatomy, optimizes stent-graft selection, and enhances communication within surgical teams. Simulation-based education using 3D models standardizes skill acquisition and bridges the gap between theory and clinical practice. Specific applications include preoperative rehearsal for congenital heart surgery (1,14), TAVR valve testing and procedural simulation (2,3). Computational modelling has improved process optimization. Despite advancements, challenges remain in cell maintenance, printing thick tissues, replicating tissue complexity, and scaling. Exploring newer technologies like 4D printing may help overcome these limitations and improve vascularized tissue fabrication (12).
3D strengths lie in its focus on innovative and promising cell encapsulation techniques using hydrogels, covering a range of versatile technologies and providing a broad overview (). It addresses a critical unmet medical need by exploring potential therapies for limb ischemia and emphasizes the ability to tailor hydrogel properties for specific applications (). However, it has weaknesses in that it lacks detailed discussion of clinical trial results and real-world efficacy, providing limited insight into biological challenges such as immune responses and long-term cell survival ().
Additionally, the heavy focus on technical aspects may overlook important translational and regulatory hurdles, and there is little exploration of future directions, scalability, and practical implementation of these therapies (22).
However, challenges remain - high equipment costs, material limitations, and the need for trained technical staff restrict widespread adoption (2,23).
The lack of standardized workflows across institutions also contributes to inconsistent results. Continued innovation in biocompatible materials and cost-efficient production is essential for routine clinical integration. Time and cost constraints remain significant barriers, especially in emergency contexts requiring rapid production. Moreover, the lack of standardized workflows and methodologies across institutions contributes to variability in procedural durations and outcomes, complicating widespread implementation ().
In conclusion, 3D printing significantly improves both vascular-surgery training and preoperative planning. Its adoption leads to higher procedural accuracy, greater trainee confidence, and more efficient operations. Future research should focus on validating these outcomes in larger, multicentre trials and extending data collection beyond 2026 to ensure contemporary relevance.

FUNDING

No specific funding was received for this study.

TRANSPARENCY DECLARATION

Conflicts of interest: None to declare.

REFERENCES

1. Torres I, De Luccia N. Artificial vascular models for endovascular training (3D printing). Innov Surg Sci. 2018; 3(3):225-34.
2. Li W, Liu Y, Wang Y, Zhang H, Zhao Y et al. Educational value of mixed reality combined with a three-dimensional printed model of aortic disease for vascular surgery in the standardized residency training of surgical residents in China: a case control study. BMC Med Educ. 2023; 23:812.
3. Rotman OM, Kovarovic B, Sadasivan C, Gruberg L, Lieber BB, Bluestein D. Realistic Vascular Replicator for TAVR Procedures. Cardiovasc Eng Technol. 2018; 9:339-50.
4. Kiraly L, Horer J, Kottmaier M, Kovacs A, Balint A. Three-Dimensional Virtual and Printed Prototypes in Complex Congenital and Pediatric Cardiac Surgery—A Multidisciplinary Team-Learning Experience. Biomolecules 2021; 11:1703.

5. Mafeld S, Nesbitt C, McCaslin J, Bagnall A, Davey P, Bose P, et al. Three-dimensional (3D) printed endovascular simulation models: a feasibility study. Ann Transl Med 2017; 5(3):42.
6. Marciuc E, Dobrovat, B, Popescu M, Dobrin N, Chiriac A, Marciuc D et al. 3D Printed Models—A Useful Tool in Endovascular Treatment of Intracranial Aneurysms. Brain Sci 2021; 11: 598.
7. Spinelli D, Marconi S, Caruso R, Conti M, Benedetto F, De Beaufort HW et al. 3D printing of aortic models as a teaching tool for improving understanding of aortic disease. J Cardiovasc Surg (Torino). 2019; 60(5):582-588.
8. Mir A, Lee E, Shih W, Koljaka S, Wang A, Jorgensen C et al. 3D Bioprinting for Vascularization. Bioengineering (Basel). 2023; 10(5):606.
9. National Library of Medicine. National Center of Biotechnology information. https://clinicaltrials.gov/ (accessed: October 26, 2025)
10. Zotero. Personal research assistant https://www.zotero.org/ (accessed: October 26, 2025)
11. Objective Structured Assessment of Technical Skills. http://cirugiaminimamenteinvasiva.es/SurgTTT-eLearning/index.php/en/mod8-2/assess-the-resident-progression/26-page-6-objective-structured-assessment-of-technical-skills-osats (accessed: October 26, 2025)
12. Likert Scale Questionnaire. https://www.simplypsychology.org/likert-scale.html (accessed: October 26, 2025)
13. Shah A, Jankharia B, Goel A. Three-dimensional model printing for surgery on arteriovenous malformations. Neurol India 2017; 65(6):1350-4.
14. Foresti, R.; Fornasari, A.; Bianchini Massoni, C.; Mersanne, A.; Martini, C.; Cabrini, E.; Freyrie, A.; Perini, P. Surgical Medical Education via 3D Bioprinting: Modular System for Endovascular Training. Bioengineering 2024, 11, 197.
15. Matyjas M, Sauerbrey M, Wyschkon S, de Bucourt M, Scheel M. Three-dimensional simulator: training for beginners in endovascular embolization with liquid agents. CVIR Endovasc 2021; 4(1):78.
16. Kärkkäinen JM, Sandri G, Tenorio ER, Alexander A, Bjellum K, Matsumoto J et al. Simulation of Endovascular Aortic Repair Using 3D Printed Abdominal Aortic Aneurysm Model and Fluid Pump. Cardiovasc Intervent Radiol 2019; 42(11):1627-1634.
17. Nguyen P, Stanislaus I, McGahon C, Pattabathula K, Bryant S, Pinto N et al. Quality assurance in 3D-printing: A dimensional accuracy study of patient-specific 3D-printed vascular anatomical models. Front Med Technol. 2023;5:1097850.
18. Rynio P, Wojtuń M, Wójcik Ł, Kawa M, Falkowski A, Gutowski P et al. The accuracy and reliability of 3D printed aortic templates: a comprehensive three-dimensional analysis. Quant Imaging Med Surg. 2022; 12(2):1385-1396.
19. Raffaele A, Mauri V, Negrini M, Negrello E, Parigi GB, Avolio L et al. Elaboration and development of a realistic 3D printed model for training in ultrasound-guided placement of peripheral central venous catheter in children. J Vasc Access. 2024; 25(6):1767-1774.
20. Magagna P, Xodo A, Menegolo M, Campana C, Ghiotto L, Salvador L et al. Applications of Three-Dimensional Printing in the Management of Complex Aortic Diseases. Aorta (Stamford) 2022; 10(5):242-248.
21. Göçer H, Durukan AB, Tunç O, Naser E, Gürbüz HA, Ertuğrul E. Evaluation of 3D printing in planning, practicing, and training for endovascular lower extremity arterial interventions. Turk Gogus Kalp Damar Cerrah Derg 2021;29:20-6.
22. Costa ALR, Willerth SM, de la Torre LG, Han SW. Trends in hydrogel-based encapsulation technologies for advanced cell therapies applied to limb ischemia. Mater Today Bio. 2022;13:100221
23. Zasada WA, Stępak H, Węglewska M, Świątek Ł, Kluba J, Krasiński Z. The Utility of Three-Dimensional Printing in Physician-Modified Stent Grafts for Aortic Lesions Repair. J Clin Med 2024;13(10):2977.