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Potential use of 3D-printed models in endovascular aorta surgery

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Abstract

Background: Three-dimensional (3D) printing has become recognized for multiple medical purposes. The aim of this literature review was to investigate if there is value in usage of 3D printed models for surgeons performing endovascular procedures and if the models can be used as an educational tool for patients, students and healthcare professionals.

Method: The electronic database PubMed was searched with MeSH terms only. A systematic selection process generated seventeen articles that were included in the study.

Results: The 3D printed models were used for surgical strategy and education of patients, healthcare professionals and students. The models were found valuable for preoperative planning, intraoperative guidance, patient education, medical student education and clinical training. 3D printed models might reduce procedural time and cost. The models were accurate and feasible.

Conclusion: 3D printed models may be valuable regarding endovascular procedures and possibly other surgical practice. Patients, health professionals and students may have educational use of 3D printed models. It is feasible to produce 3D models for a wide range of purposes in clinical and educational practice.

Keywords: three-dimensional printing, aortic disease, endovascular procedures, education

Abbreviations

3D – Three dimensional

3DP – Three-dimensional printing/three-dimensional printed

AAA – Abdominal aortic aneurysm

AAP – Ascending aortic pseudoaneurysm

CAD – Computer aided design

CHD – Congenital heart disease

CT – Computed tomography

EVAR – Endovascular aortic repair

MRI – Magnetic resonance imaging

PCI – Percutaneous coronary intervention

STL – Standard tessellation language

TAAD – Type A aortic dissection

TAVI – Transcatheter aortic valve implantation

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1. Background

3D printing, also called additive manufacturing, has become more incorporated in surgical practice. It is a process where a solid model is constructed from digital images by stacking material layer by layer (1). There is a variety of materials that can be used to suit different purposes (2). The fields of application range from preoperative planning and intraoperative guidance to custom implants (3). They can also be a useful tool for education and training purposes (4).

Cardiovascular disease is a major cause of mortality in the developed world (5). The field of endovascular surgery has in the last years obtained a more important role in treatment of vascular disease because of its minimally invasive approach. In general, endovascular aortic repair (EVAR) is a minimally invasive method to treat aortic aneurysms, using catheter and avoiding laparotomy. Endovascular aortic repair is associated with avoidance of respiratory and abdominal complications, as well as shorter hospital stay (5).

1.1 3D-printing

To generate a physical 3D model computed tomography (CT) or magnetic resonance imaging (MRI) scans are saved in a suitable format. Then, a virtual 3D model is crated based on the patients' data. The image is then segmented, which implies selection of the desired anatomical structures to be printed. The virtual model is exported to a Standard Tessellation Language (STL) format (1). This format shows the models surface as a triangular mesh (6). The virtual 3D model is not suitable for printing because of topological roughness. The surface can be smoothened and the model file can be simplified for more effective printing (1). By importing the image a Computer-Aided design (CAD) software, it is possible to further refine or alter the model. For example, openings can be formed, thickness can be reformed and support structures can be added (6). The final product is sent in STL format and printed by a 3D printer. The models have great accuracy (7). The potential of 3DP might be vast and the field is currently evolving rapidly.

There are different types of 3D printers. They can be classified by method, material deposition process. Stereolithography apparatus is the most commonly used printer in medicine. It uses photosensitive resin and an ultraviolet laser to build the model layer by layer. Other materials that can be used in 3D printers are metal powder, photopolymers and thermoplastics among others. Layer thickness depends on printer model and ranges from

0.016 – 0.33 mm (1) compared to a CT scanner can capture an image of the human body with a precision of 0.5mm (8). Deposition of material can be continuous or one drop at a time (1).

1.2 Aortic disease

Some of the most important pathologies of the aorta are dissections and aneurysms. The major components of the pathogenesis are atherosclerosis and hypertension (9).

Aneurysms are defined as a localized dilation of a vessel or the heart due to weakness in the organ wall. They can be divided into different categories depending on their histology, shape and location. True aneurysms arise due to a thinning of an intact arterial wall whereas false aneurysms or pseudo-aneurysms are hemorrhagic expansions into the extravascular space through a defect or tear in the vascular wall. There are two common shapes of aneurysms: saccular aneurysms have a spherical appearance while fusiform aneurysms involve the whole circumference and longer portions of vessels. The most common location for aneurysms is the thoracic or abdominal aorta but they can also arise in other places, for example Willi's circle in the brain, popliteal artery, visceral arteries or other locations (9).

Aside from hypertension and atherosclerosis, other etiologic factors that can contribute to the pathogenesis are inflammation, ischemia in tunica media and a number of syndromes that affect the connective tissue of vessel walls, for example Marfan syndrome. Aneurysms may expand and compress adjacent structures or obstruct neighboring vessels. The most serious event is aneurysm rupture, which may lead to massive, potentially mortal bleeding (9).

Aortic dissection is a condition where layers of the aortic wall are separated and a blood-filled channel is formed. The dissection may rupture through the adventitia and cause cardiac tamponade or aortic dysfunction due to colossal hemorrhage. The most common risk factor is hypertension which contributes to degenerative changes in tunica media. Blood flow through vasa vasorum is diminished because of hypertrophy of its medial layer and hypertension, which leads to ischemia of the vessel wall. Ehlers-Danlos syndrome, Marfan syndrome and other conditions that affect connective tissue of vessels are less common risk factors for dissection (9).

A dissection occurs when a tear develops in tunica intima which leads to an intramural hemorrhage. One way to classify dissections is into type A and type B, but there are also other classifications. Type A consist of DeBakey I; dissection in the aorta ascendens that proceeds to aorta descendens and DeBakey II; dissection isolated to aorta ascendens. These are more severe regarding complications and mortality. Type B includes DeBakey III which are lesions that do not include aorta ascendens (9).

1.3 Endovascular procedures

Endovascular surgery is a group of minimally invasive procedures performed in several vascular pathologies. Angioplasty, angioscopy, catheterization and percutaneous coronary intervention (PCI) are examples of endovascular procedures. They are performed to improve the condition of cardiovascular diseases. Needles are used to gain access to the vessels, most commonly the femoral artery. Needle size is selected based on the diameter of the guidewire which is used to manage catheters. There are many different types of catheters, various configurations allow the operator to access vessels of diverse shapes and angles. Angioplasty balloons are used to treat stenosis as well as to deploy and expand stents. To treat various vessel pathologies stents and stent grafts can be used. Stents are metallic nets that can be inserted in a vessel to treat dissection or stenosis. They can be self-expandable or balloon-expandable. Stent grafts are metallic nets covered with, for example, polyester fabric and are mostly used for traumatic lesions in vessels or aneurysms (5).

Endovascular repair of aortic aneurysms, or EVAR, was first introduced in 1991 (10). It is conducted by inserting a graft with a metal stent into the aorta through the femoral arteries and inserted into the lumen to exclude the aneurysm. There are anatomical conditions that are essential for a case to be suitable for endovascular treatment. The tortuosity of the femoral arteries must be low enough to allow guidewires and delivery systems to be conveyed. It is also important that the aorta proximal to the aneurysm have a cylindrical shape of at least 15 mm to ensure adequate stent graft placement. This is called aneurysm exclusion and ensures that blood will not leak into the aneurysm. Compared to conventional repair, patients treated endovascularly have shorter hospital days, less morbidity and blood loss during surgery. The long term benefits are not yet clear considering mortality (11).

Aortic dissections can also be managed endovascularly. It is debated whether endovascular treatment in uncomplicated cases of acute and chronic descending dissections is more efficient than non-operative management, however endovascular approach is commonly used in cases with complications, such as malperfusion syndrome, with positive results. Numerous other procedures can be performed with endovascular techniques, but are not considered in this study (5).

1.4 Objective

The aim of this study was to investigate if there is value in the usage of 3D-printed models for surgeons performing endovascular procedures and if the models can be used as an explanation tool for the patient or teaching material for students and other healthcare personnel.

2. Method

2.1 Design

Systematic literature review.

2.2 Search

This systematic literature review was executed in the electronic database PubMed, 2017-04-26. The advanced search builder in PubMed was used to perform a systematic search that was followed by a selection process.

MeSH terms were used in the search which was conducted by combining “3D-printing” using “AND” with the terms “aortic disease”, “endovascular procedures”, “education” and “economics”. The pairs were then added to one search using “OR”.

The search resulted in sixty-five studies. First, the filters “human” and “English” were added in the PubMed search function. Second, all reviews and comments were excluded. The third step in the selection process was carried out by evaluating the relevance of the abstract to the objective and the inclusion criteria of this study, which resulted in eighteen articles (Figure 1). One study whose abstract was not available was excluded once the analysis started, though the title was misleading and the study was not relevant to the objective of this systematic review.

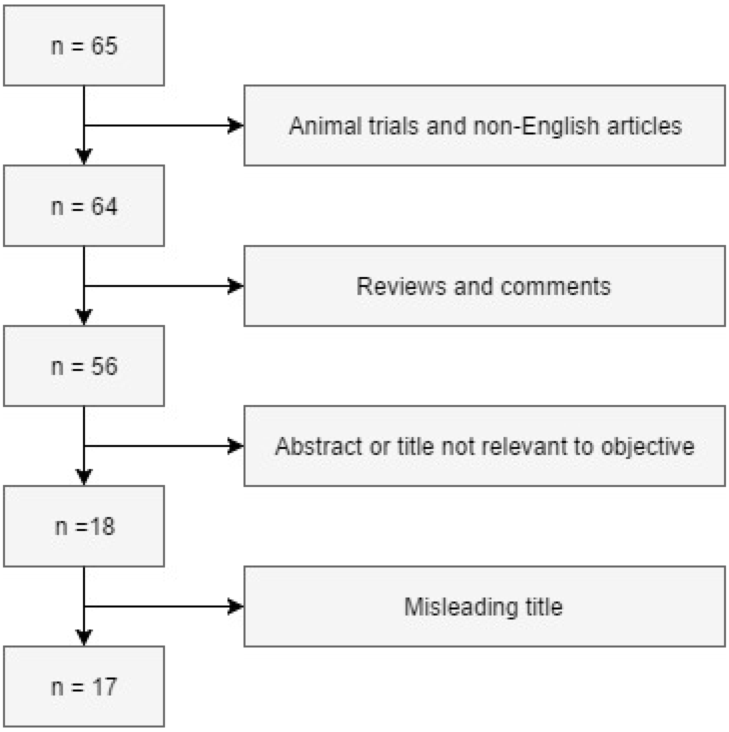

Figure 1. The electronic database PubMed was searched 2017-04-26 in the advanced search builder. Sixty-five results were generated by the search. The selection process consisted of the steps shown and resulted in seventeen final articles.

2.3 Inclusion criteria

The inclusion criteria used for this systematic review was original studies carried out on humans and English language was to be used. Articles should discuss 3D printing in relation to cases of cardiovascular disease where a model was to be used for preoperative planning, intraoperative guidance or visualizing complex anatomy. Education of medical students or any health care personnel using 3D printed models was to be related to cardiovascular pathology or endovascular procedures. Articles that attended 3D printed models and economics or education of patients were included regardless of link to cardiovascular disease or endovascular surgery.

2.4 Exclusion criteria

All reviews and comments were excluded from this systematic review. Animal trials were also excluded because they were not relevant to the purpose of this study.

2.5 Quality rating

A quality rating of the included studies was performed. Three different properties of each study were assessed and rated by a scoring system, described in Table 1. The scores from the different categories were added to a total. A high total score implicates high quality of the study. The scores are stated in 8.1 Overview of the studies included in this systematic review, in Attachments.

Table 1. Scores and properties included in the quality rating

Score	Study design	Relevance*	Clinical implications**
4	Randomized controlled trial	High relevance	Certain impact
3	Observational cohort study	Moderate relevance	Possible impact
2	Case-control study	Low relevance	Unlikely impact
1	Case report/Other	No relevance	No impact

*Relevance to the purpose of the present study
**Property where a study's potential to affect standard clinical practice is assessed

2.6 Ethical consideration

No individual personal data was used in this study. Since all published articles must follow the international guidelines of Council of Science Editors (CSE) or International Committee of Medical Journals Editors (ICMJE) it is assumed that each study has considered ethical and individual confidentiality aspects (12).

3. Results

Seventeen articles generated by the search in the electronic database PubMed met the inclusion criteria and aim of this study. The results were categorized into five subjects; surgical strategy, patient education, health professional education, medical student education and cost.

3.1 Surgical strategy

Surgical strategy comprises cases in which the 3DP model was used in relation to a surgical intervention. Ten of the studies included considered surgical strategy. The most common use of 3DP models was preoperative visualization of the patient’s anatomy and planning of the procedure as well as intraoperative guidance. In three studies the models were used to test the deployment of a stent graft prior surgery (13–15). Another two studies used the models to customize equipment to the patient’s anatomy (16,17). The model was also used to conduct an experiment (18) and to select optimal equipment (14,19). Results regarding surgical strategy are summarized in Table 2.

Several studies also considered subjective statements made by the professionals regarding the 3D printed models used in the case. The most frequent statements described the models as “useful” and “helpful” (6,14,15,19–21). Some articles presumed that 3DP models could potentially decrease procedural time (14,15,17), procedural cost (17), radiation time and contrast administration during a procedure (15).

Table 2. Potential use of 3D printed models in surgical strategy

Study (Reference)	n*	Patients' conditions	Aim	Use of 3D printed models	Conclusion of study
Occlusion of an ascending aortic pseudoaneurysm with intraoperative echocardiography and a printed model - Li, F. et al. (16)	1	Ascending aortic pseudoaneurysm	Report first trial of treatment of AAP with TEE and a 3D printed model.	- Visualizing the aneurysm - Cusomized occluder was constructed using the 3D model.	- Better matching of the occluder based on the 3DP model led to successful sealing of the AAP.
Use of a 3D Printed Hollow Aortic Model to Assist EVAR Planning in a Case with Complex Neck Anatomy - Tam, MD. et al. (13)	1	Abdominal aortic aneurysm. Complex anatomy.	Illustrate potential 3DP models for EVAR planning in a case with complex anatomy.	- Stent graft was deployed and inspected prior EVAR procedure.	- EVAR assisted by 3DP models may set a new industry standard, and use may extend to TAVI and neurovascular surgery. - Furture studies need to investigate the role of 3DP further.
A Pilot Study Assessing the Impact of 3-D Printed Models of Aortic Aneurysms on Management Decisions in EVAR Planning - Tam, MD. et al. (20)	6	Aortic aneurysm. Complex anatomy.	To assess the impact of a printed model on management decision in cases of aortic aneurysms with challenging anatomy.	- 28 endovascular operators made 144 management plans prior handling the 3D models. 29 plans changed after considering the model.	- The majority stated that they would find models useful in some cases. - 20% of decisions changed after model handling. - In 41% of cases confidence increased.
Modelling of aortic aneurysm and aortic dissection through 3D printing - Ho, D. et al. (6)	2	One patient with aortic aneurysm and one patient with Stanford B aortic dissection	Determine the accuracy by which 3DP models of aortic pathology, involving the aortic arch, resemble contrast-enhanced CT	- The mean difference between the physical model and the CT scan was 1.0 mm and 1.2 mm for cases.	- 3DP models can be constructed from CT scans and may be useful in surgery and education. - Further research need to investigate recreation of internal aortic details.
Using 3D printed models for planning and guidance during endovascular intervention: a technical advance - Itagaki, MW. (14)	1	Multiple splenic artery aneurysms. Complex anatomy.	Describe a technique where a 3DP model was printed to visualize complex anatomy and to test off-label equipment prior surgery	- The 3DP model facilitated testing of stent placement and optimal catheter combination for the procedure. Approach decision was made based on the model. - Luminal model optimized angiographic angles which saved contrast and time.	- 3DP models is helpful to determine spatial anatomy and operative procedure. - 3DP models can lessen complication rate and surgery time. - Models can be used at least in complex cases.
Rapid prototyping in aortic surgery - Bangeas, P. et al. (19)	1	Abdominal aortic aneurysm.	To create an anatomically correct model of an aortic aneurysm to support management decisions and preoperative planning	- Exact anatomy resemblance supported understanding of aneurysm configuration and selection of the appropriate stent graft. Helped forecast potential complications.	- 3DP models are useful for preoperative planning and intraoperative guidance. - It is achievable to create anatomically valid vascular models it be used in medical practice.
Three-dimensional virtual surgery models for percutaneous coronary intervention (PCI) optimization strategies - Wang, H. et al. (18)	1	Restenosis after PCI.	To investigate optimal stent implantation strategies through simulation and experiment with a 3D printed model	- The 3D printed model was used to perform hydrodynamic experiments imitating coronary vessel conditions and stent graft position. The trial was consistent with computer simulation and measurement.	- 3DP models were successfully applied to construct vessel structures for the experiment.
Custom Fenestration Templates for Endovascular	1	Abdominal aortic aneurysm.	To investigate optimal stent implantation strategies through simulation and	- A 3D printed model of the aorta was printed to customize patient specific	- Using a 3DP template saves time and eliminates measurement errors.

Repair of Juxtarenal Aortic Aneurysm - Leotta, DF. et al. (17)			experiment with a 3D printed model	fenestrations in a standard commercial stent graft.	- May save surgical cost and make EVAR available to more patients where the anatomy is challenging.
The Interactive Use of Multi-Dimensional Modeling and 3D Printing in Preplanning of Type A Aortic Dissection - Hossien, A. et al. (21)	3	Type A aortic dissection.	To create digital and physical 3DP models of TAAD and evaluate if these are useful in preoperative planning and operative repair.	- Three case specific models were made to visualize the dissection. The models clearly showed the anatomy with true and false lumen and the intimal flap.	- 3DP could potentially be a valuable tool to refine procedural technique, both for surgeons and trainees. - Model can be used to educate surgeons, medical students and patients about aortic pathologies.
The use of a three-dimensional print model of an aortic arch to plan a complex percutaneous intervention in a patient with coarctation of the aorta - Ghisiawan, N. et al. (15)	1	Coarctation of the aorta and a pseudoaneurysm.	To describe percutaneous intervention approach on coarctation of the aorta and a pseudoaneurysm in the aortic arch, guided by a 3DP model	- A 3D model of the patients' aorta was made to plan the deployment of the stent graft to cover the pseudoaneurysm and planning an intervention to reestablish blood flow to the left subclavian artery.	- 3DP likely reduced radiation dose, contrast administration and procedural time. - It is a useful tool for preoperative planning and performing percutaneous intervention in patients with CHD.

*n = number of patient cases reviewed by the study.

3.2 Patient education

Two studies considered 3DP models for patient education, and shown in Table 3. The models were found valuable, both by the test subjects and the physicians (22,23).

In one study, the overall understanding of general aspects of the condition and treatment improved by 37.6%. Four different aspects were considered and the increase of correct responses after explanation with the model was statistically significant in understanding regarding kidney anatomy (+50%), physiology (+16.7%) and surgical procedure (+44.6%). Understanding of pathology also improved (+39.3%) (22).

Table 3. Evaluation of 3D models as a tool for patient education

Study (Reference)	Number of participants	Cost	Understanding	Satisfaction	Conclusion
Personalized 3D printed model of kidney and tumor anatomy: a useful tool for patient education - Bernhard, J-C. et al. (22)	7	560 USD per model	Understanding of - kidney anatomy* - kidney physiology* - surgical procedure* - pathology improved after intervention with 3DP models in the group.	Mean satisfaction was 9.4/10.	- 3DP models are valuable for understanding in surgical patient education. - Numerous fields of use may achieve cost efficiency.
3D-manufactured patient-specific models of congenital heart defects for communication in clinical practice: feasibility and acceptability - Biglino, G. et al. (23)	97	64 USD per model	Perceived knowledge improvement was slightly higher in the model intervention group than in the control group.	Overall, parents found model very useful.	- The physicians found the model very useful and that parents interacted well with the model.

* Statistically significant.

3.3 Healthcare education

Two studies considered 3DP models as an educational tool for pediatric residents (24,25). When compared to standard 2D curriculum, knowledge acquisition was similar but the increase in learner satisfaction was statistically significant ($P = 0.03$). Self-efficacy also improved but the raise was not statistically significant ($P = 0.39$) (24). 3DP models were useful in a simulation based curriculum. Structural conceptualization ($P < 0.0001$) and knowledge acquisition ($P = 0.0082$) improved significantly. Understanding and management of post-procedural complications also increased (25).

Another study where nurses, ancillary providers and physicians in training valued simulation based training using 3DP models showed that the session enhanced anatomy understanding, procedural understanding and clinical managing ability. Scores were made on a scale that ranged from 1 (strongly disagree) to 10 (strongly agree). Enhancement of post-operative management ability in nurses following the session was statistically significant. Overall, the participants found simulation training with 3DP models more effective than verbal hands-off training (26). These results are summarized in Table 4.

Table 4. Evaluation of 3D printed models in education of healthcare professionals

Study (Reference)	Group	Knowledge acquisition			Learner satisfaction
		Anatomy	Surgical procedure	Post-op management	
''Just-In-Time'' Simulation Training Using 3-D Printed Cardiac Models After Congenital Cardiac Surgery - Olivieri, LJ. et al. (26)	Physicians in training	8.9/10	8.9/10	8.8/10	7.7/10 found simulation with 3D models was more effective than verbal hand-off training
	Nurses	9.3/10	9.2/10	9.5/10*	8.7/10 found simulation with 3D models was more effective than verbal hand-off training
	Ancillary care providers	9.1/10	8.9/10	8.6/10	8.4/10 found simulation with 3D models was more effective than verbal hand-off training
Usage of 3D printed models of teratology of Fallot for medical education: impact on learning congenital heart disease - Loke, Y-H. et al. (24)	Second year pediatric residents	Knowledge acquisition was similar in 3D intervention group and 2D control group.			- Learner satisfaction increased* - Self-efficacy was rated higher in the 3D intervention group.
Incorporating Three-dimensional Printing into a Simulation-based Congenital Heart Disease and Critical Care Training Curriculum for Resident Physicians - Costello, JP. et al. (25)	Pediatric residents	Improvement was seen in; - knowledge acquisition* - skill in conceiving VSD structure* - ability to manage post-operative complications - knowledge of VSD after handling 3DP heart models.			-

The 3DP model training was rated by the groups on a scale that ranged from 1 (strongly disagree) to 10 (strongly agree).
* Statistically significant

3.4 Medical student education

One study elaborated specifically on 3D models as an educational tool for medical students. 3D printed models were compared to cadaveric materials and a combination of both materials. All three groups showed increased test scores after the teaching session, though it was not significant in the cadaveric material only group (P = 0.083). Statistical significance was seen in the increase of test scores measuring anatomical understanding in the 3D model only group (P = 0.003) versus the cadaveric material only and the combined materials group (27).

3.5 Cost

Ten articles discussed the cost of 3DP model production, shown in Table 5. The cost per model ranged from 20 USD to 560 USD, unless an in-house printer was used. Cost of a printer was 1290 USD to 1420 USD and the cost to print a model depended on the amount of material that is used. 300g of plastic costs about 7 USD. Seven of the articles also mentioned the time that creation of the models required. These are shown in Table 5.

Table 5. Cost of 3D printers, 3D models and manufacturing time

Study (Reference)	Cost of printer	Cost per model	Time
Use of a 3D Printed Hollow Aortic Model to Assist EVAR Planning in a Case with Complex Neck Anatomy - Tam, MD. et al. (13)	-	300 USD	-
Personalized 3D printed model of kidney and tumor anatomy: a useful tool for patient education - Bernhard, J-C. et al. (22)	-	560 USD	-
Rapid prototyping in aortic surgery - Bangeas, P. et al. (19)	1420 USD	3 USD	~ 2 h 20 min
The Interactive Use of Multi-Dimensional Modeling and 3D Printing in Preplanning of Type A Aortic Dissection - Hossien, A. et al. (21)	-	20 USD	9 h
With the advent of domestic 3-dimensional (3D) printers and their associated reduced cost, is it now time for every medical school to have their own 3D printer? - Balestrini, C. et al. (28)	1290 USD	~ 7 USD	-
Usage of 3D printed models of teratology of Fallot for medical education: impact on learning congenital heart disease - Loke, Y-H. et al. (24)	-	200 USD	12 h
A Pilot Study Assessing the Impact of 3-D Printed Models of Aortic Aneurysms on Management Decisions in EVAR Planning - Tam, MD. et al. (20)	-	< 200 USD	20-30 min to process data. Additional time for printing or shipment.
3D-manufactured patient-specific models of congenital heart defects for communication in clinical practice: feasibility and acceptability - Biglino, G. et al. (23)	-	64 USD	0.5-3 h for data processing. ~24 h for printing.
''Just-In-Time'' Simulation Training Using 3-D Printed Cardiac Models After Congenital Cardiac Surgery - Olivieri, LJ. et al. (26)	-	200 USD	2-7 days.
Using 3D printed models for planning and guidance during endovascular intervention: a technical advance - Itagaki, MW. (14)	-	50.34 USD resp. 235.03 USD	11 days resp. 16 days from order, including shipping.

4. Discussion

This review analyzed seventeen published articles in which 3D printed models were used as part of the study design. The search generated studies that discussed 3DP models in surgical strategy (n = 10), patient education (n = 2), healthcare education (n = 3), medical student education (n = 1) and cost (n = 10). The main findings were;

- There are many fields of application for 3D printed models.
- When used in surgical practice, 3DP models are useful and may contribute to potentiation of surgical procedures, procedural time and materials.
- 3DP models are a valuable tool for communication and education of patients, students and healthcare professionals.
- It is feasible to produce 3DP models for medical and educational purposes.

4.1 Use and value of 3D printed models

The use of 3DP models in the studies varied considerably. The most common use of the models was planning or guidance of a surgical procedure. There were several advantages to this. A 3D printed model permitted a tactile dimension, which made it easier to visualize the pathology. By doing so, it helped the development of management decisions and confidence of the surgeons. 3DP models also contributed to better forecasting of complications, both intraoperatively and post-operatively.

The models were also used to try out optimal equipment prior surgery. To test equipment is especially valuable in aortic endovascular surgery where the patient outcome depends greatly on choice of the right equipment. Today, the choice is made based on the surgeon's experience and by trial and error during the procedure. There is also variance in which approach is used between institutions and surgeons. By using 3DP models, the industry could move towards consensus in patient specific management of aortic disease.

Another interesting field of 3DP model application is customization of already available resources, for example stent grafts and occluders, which are used to treat aortic aneurysms. Fenestrated or multi-branched endografts are available on the market, but are more expensive and take additional time to deliver (17). It is possible that anatomical adjustment of standard materials used in surgery can improve patient outcome without increasing the cost or management time. One study discussed that this could make endovascular treatment available to more patients with complex abdominal aortic aneurysms (17). Endovascular procedures' minimally invasive nature has advantages and thus could potentially lead to improved patient outcome and fewer complications.

The search did not generate studies that used 3DP models specifically for endovascular training, only management and critical care of heart conditions. However, research has been performed on 3DP models as an educational tool for simulation of endovascular procedures. Results of one questionnaire based study showed that endovascular simulation with 3D models was realistic compared to live patients and virtual reality training. The participants answered that their catheterization skills improved and that they would recommend the model as a tool to trainees and colleagues. The models were found to be valuable for endovascular education (4). Results of the present study regarding 3DP models as an educational instrument agrees, for findings suggest that knowledge acquisition, learner satisfaction and effectivity of education may improve by incorporating 3DP models.

One study elaborated on the value of 3DP models not only for physicians, but also for nurses and ancillary care providers. It showed that all groups benefitted from the simulation training with the models. Nurses in particular reported enhanced ability of clinical management. It is of interest to invest this further, though improvement of post-operative clinical care may result in less complications and better patient outcome. Since 3DP models were beneficial to all groups included in the study, it is possible to use the models to facilitate patient transfer. The model is a valuable communication tool and holds patient specific information regarding anatomy, pathology and surgical procedure. This might reduce communication errors amongst care providers and contribute to enhanced care delivery (26).

Regarding the value of 3DP models for medical students, one study elaborated on the efficiency compared to cadaveric material. A significant improvement in test scores was seen in the group who only handled 3DP models, thus 3DP does not demerit anatomical education. Human cadavers are not only expensive and have low availability, but there are also cultural and ethical factors that contribute to the difficulty of maintaining cadavers as a part of anatomy curriculum. Plastic anatomical models are commonly used as a compensation, but do not show anatomical variation and the cost can range up to 150 USD per model (28). 3DP models of anonymized CT scans would sufficiently show the spectra of anatomical variation and may be less expensive than cadaveric material and anatomical models.

Two studies focused specifically on 3DP models as a tool in communication with patients. Knowledge acquisition when using models varied between the studies, but they were not inferior to conventional methods and could in some cases enhance the patient's understanding of their medical situation. The two studies did agree on that patients were more satisfied when a model was used in the explanation. Education of patients about their condition could contribute to better understanding of pathophysiology and risk factors which can contribute to better long term patient outcome. There is also a possibility that better satisfaction in the patient can lead to increased compliance. Future research must explore the matter further (22,23).

4.2 Cost

The results of this study suggested that it is feasible to produce 3DP models for usage in endovascular surgery regarding the economical aspect. Material costs for an aortic stent graft reach 6000 USD (13). 3DP models might decrease procedural time, material cost and forecast possible complications, thus use of 3DP models in surgical practice could be economically supportable. One study even implies that a unit that performs 200 EVARs a year might see an economical return of material costs, including an in-house printer of 50 000 USD (13).

3D printed models can be used by different specialties such as orthopedics, neurosurgery and general surgery (3). Since the cost of a model depends on the amount of material used and not the complexity of the structure printed, it might be efficient for larger hospitals to have their own printer to avoid shipping costs. Another advantage of having an in-house printer is decreased production time, since shipping is not necessary.

One down side to an in-house printer is that maintenance is needed and the acquisition price can be high. There is also a limitation of materials that could be used since most printers only use one material. These disadvantages are avoided by using a 3D printing service, but at a higher price per model and additional shipping time.

4.3 Limitations of the study

There are few studies composed on 3DP models in endovascular surgery. This makes it difficult to include enough studies to draw certain conclusions. Most studies regarding 3DP in endovascular surgery are case reports that have a very limited study population. With a greater number of articles and larger study populations, the possibility to define the influence and value of 3DP models would increase.

In this study, only one database was used, thus there is a possibility that relevant articles could have been missed. This study did not consider unpublished data. This means that there might be additional aspects to the subject that were not comprised in this study.

Further research need to investigate the effect on patient outcome with a greater number of patients. There is also a need for a formal cost-analysis and cost-efficiency investigation.

5. Conclusion

In conclusion, 3D printed models may be valuable regarding endovascular procedures and possibly other surgical practice. Patients, health professionals and students may have use of 3D printed models as communication, education and training tools. It is feasible to produce models for a wide range of purposes in clinical and educational practice.

6. Acknowledgements

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8. Attachments

8.1 Overview of the studies included in this systematic review

Study	Publication	Purpose	Design	Population	Results	Quality rating*
Occlusion of an ascending aortic pseudoaneurysm with intraoperative echocardiography and a printed model	Li, F. et al. (2016) *The Journal of Thoracic and Cardiovascular Surgery*	Report first trial of treatment of AAP with TEE and a 3D printed model	Case report	44-year-old man with AAP	Transthoracic occlusion of the aneurysm was performed with a custom occluder that was created based on the printed model. Surgery was successful, no complications	1+4+3=8
Use of a 3D Printed Hollow Aortic Model to Assist EVAR Planning in a Case with Complex Neck Anatomy	Tam, MD. et al. (2014) *Journal of Endovascular Therapy*	Illustrate potential 3D printed models for EVAR planning in a case with complex anatomy	Case report	Patient with AAA and complex aortic neck anatomy	Preoperative placing of stent-graft was performed on the model. Clinical intervention was successful, no post-operative complications. Cost 300 USD.	1+4+3=8
Usage of 3D printed models of teratology of Fallot for medical education: impact on learning congenital heart disease	Loke, Y-H. et al. (2017) *BMC Medical Education*	Evaluate impact of 3D printed models in the understanding of teratology of Fallot by pediatric residents.	Prospective randomized trial	Thirty-five second year pediatric residents	Residents taught with 3D model reported better satisfaction ($P = 0.03$) and higher self-efficacy ($P = 0.39$. Knowledge acquisition was similar in both groups.	4+4+3=11
A Pilot Study Assessing the Impact of 3-D Printed Models of Aortic Aneurysms on Management Decisions in EVAR Planning	Tam, MD. et al. (2016) *Vascular and Endovascular Surgery*	To assess the impact of a printed model on management decision in cases of aortic aneurysms with challenging anatomy	Qualitative analysis	Twenty-eight endovascular operators	144 management plans were made based on CTA. After viewing the model 29 management plans changed. Endovascular approach reduced from 73.6% to 67.4%. Open surgery increased from 22.9% to 27.8%. Second opinion increased from 3.5% to 4.8%. Off-label techniques decreased from 19.4% to 15.2%. Confidence generally improved.	3+4+3=10
''Just-In-Time'' Simulation Training Using 3-D Printed Cardiac Models After Congenital Cardiac Surgery	Olivieri, LJ. et al. (2016) *World Journal of Pediatric and Congenital Heart Surgery*	Evaluate the effect of a 3D model in postoperative care simulation training in a "Just-In-Time"-regime.	Qualitative analysis	70 clinicians; 22 physicians-in-training, 38 nurses, 10 ancillary providers	Nurses and physicians reported higher ability to describe the anatomy, surgical procedure and clinical postoperative management after simulation training with 3D model. Faculty of clinical management was perceived higher by nurses ($P = 0.02$).	3+4+3=10
Personalized 3D printed model of kidney and tumor anatomy: a useful tool for patient education	Bernhard, J-C. et al. (2016) *World Journal of Urology*	To evaluate impact of 3D printed models on patient education; patient´s understanding of their condition and surgical treatment	Prospective pilot study	Seven patients considered for partial nephrectomy because of kidney tumor	Significant improvement was seen in understanding of kidney anatomy ($P = 0.026$)/50%, physiology ($P = 0.018$)/16.7% and surgical procedure ($P = 0.026$)/44.6%. Understanding of pathology improved by 39.3%. Mean satisfaction 9.4/10. Cost $560 per model.	3+3+3=9
Use of 3D Printed Models in Medical	Lim, KHA. et al. (2016)	Compare the effectiveness of 3D printed cardiac	Double-blind	52 first year medical students	Overall improvement of test scores. Not significant for cadaveric	4+4+3=11

Education: A Randomized Control Trial Comparing 3D Prints Versus Cadaveric Materials for Learning External Cardiac Anatomy	*Anatomical Sciences Education*	models to cadaveric materials in anatomical surface education of first year medical students	randomized control trial		only (P = 0.083) and combined group (P = 0.080). Statistically significant improvement for 3D model group (P = 0.003). Reduced cost compared to cadaveric materials.	
3D-manufactured patient-specific models of congenital heart defects for communication in clinical practice: feasibility and acceptability	Biglino, G. et al. (2014) *BMJ Open*	Evaluate potential use 3D printed models as a tool for communication in clinical practice	Questionnaire-based study	97 parents of children diagnosed with congenital heart conditions	Both groups found the explanation of the condition very clear. Improvement of perceived knowledge in the model group was not statistically significant (P = 0.2). Parents and physicians found model very useful. Visits in the model group lasted on average 5 min longer (P = 0.02).	2+3+3=8
Modelling of aortic aneurysm and aortic dissection through 3D printing	Ho, D. et al. (2017) *Journal of Medical Radiation Sciences*	Determine the accuracy by which 3D models of aortic pathology, involving the aortic arch, resemble contrast-enhanced CT	Case report	One patient with aortic aneurysm and one patient with Stanford B aortic dissection	Compared to the CT scan, the mean vessel diameter differed 1.0mm for Model 1 and 1.2mm for Model 2. The intimal flap in the dissection could not be printed continuously.	1+2+3=6
Using 3D printed models for planning and guidance during endovascular intervention: a technical advance	Itagaki, MW. (2015) *Diagnostic and Interventional Radiology*	Describe a technique where a 3D model was printed to visualize complex anatomy and to test off-label equipment prior surgery	Case report	62-year-old female patient with multiple splenic artery aneurysms	Pre-operatively, a cerebrovascular stent was successfully placed in the model and optimal catheter combination and approach was determined. An intraoperative luminal model helped optimizing angiographic angles which saved contrast and time. Equipment worked as predicted by model trial. Successful treatment, no complications post-op.	1+3+3=7
Rapid prototyping in aortic surgery	Bangeas, P. et al. (2016) *Interactive CardioVascular and Thoracic Surgery*	To create an anatomically correct model of an aortic aneurysm to support management decisions and preoperative planning	Case report	68-year-old male patient with AAA	Construction time was 138 min. The cost of the printer was 1300 euros, material for one model costed 3 euros. The anatomy was resembled well by the model which helped with selection of graft and operative strategy. The patient had no peri- or post-operative complications.	1+4+3=8
Three-dimensional virtual surgery models for percutaneous coronary intervention (PCI) optimization strategies	Wang, H. et al. (2014) *Nature*	To investigate optimal stent implantation strategies through simulation and experiment with a 3D printed model	Retrospective case study	Patient with restenosis one year after PCI	The printed model used in hydrodynamic experiments was highly consistent with the simulated trials. It could be a useful method for future studies of coronary disease.	1+2+1=4
Custom Fenestration Templates for Endovascular Repair of	Leotta, DF. et al. (2015) *Journal of Vascular Surgery*	To describe a technique where 3D printed hollow models with openings representing vessel	Case report	Patient with a juxtarenal AAA	Time for preprocessing was 30 min and printing time was 9 hours. Using models to customize standard stents gives accurate placement and	1+4+3=8

Juxtarenal Aortic Aneurysm		origins are used as templates to customize stents preoperatively			saves surgery time. They can also potentially save procedural costs.	
The Interactive Use of Multi-Dimensional Modeling and 3D Printing in Preplanning of Type A Aortic Dissection	Hossien, A. et al. (2016) *Journal of Cardiac Surgery*	To create digital and physical 3D models of TAAD and evaluate if these are useful in preoperative planning and operative repair.	Retrospective study	Three patients with Type A aortic dissection	The physical models accurately visualized the pathology of each patients' dissection. The 3D models were used while interpreting CT scans, which was useful for surgeons and learners. Production time was 9 hours and cost was 20 USD.	2+4+3=9
The use of a three-dimensional print model of an aortic arch to plan a complex percutaneous intervention in a patient with coarctation of the aorta	Ghisiawan, N. et al. (2016) *Cardiology in the Young*	To deescribe percutaneous intervention approach on coarctation of the aorta and a pseudoaneurysm in the aortic arch, guided by a 3D model	Case report	19-year-old, male patient with coarctation of the aorta and a pseudoaneurysm	Model was used preoperatively value the stent placement. This showed that the left subclavian artery would be blocked by the stent which led to a new surgical plan that involved penetrating the stent to reestablish flow through the left subclavian artery. Successful procedure.	1+2+3=6
Incorporating Three-dimensional Printing into a Simulation-based Congenital Heart Disease and Critical Care Training Curriculum for Resident Physicians	Costello, JP. et al. (2015) *Congenital Heart Disease*	To evaluate if 3D printed heart models can be used in simulation training of CHD a critical care for more advanced learners	Qualitative analysis	23 pediatric residents	Printing material was modified to allow surgical incisions and sutures. Knowledge acquisition was beneficial ($P = 0.0082$), knowledge of VSD was enchanted ($P = 0.01$) and their skill in conceiving VSD structure improved ($P < 0.0001$)	3+2+3=8
With the advent of domestic 3-dimensional (3D) printers and their associated reduced cost, is it now time for every medical school to have their own 3D printer?	Balestrini, C. et al. (2015) *Medical Teacher*	To elaborate on the potential use and cost of 3D printers in medical schools	Personal view	-	The cost of a 3D printer is ca 1000 GBP. Printed models are not priced by complexity but by amount of material, unlike anatomical models. Anatomical models can range 23 GBP – 116 GBP whereas an equivalent printed model using 300 g of plastics costs 5.62 GBP. Accuracy of printed models to CT scans are 0.2 mm. An advantage is that anatomical variations can be visualized which is a valuable resource for medical students	1+2+1=4

*Study design + relevance + clinical implications = total score. Scoring system is explained in Table 1.

8.2 Search terms used in PubMed

(("aortic diseases"[MeSH Terms] AND "printing, three-dimensional"[MeSH Terms])

OR

("endovascular procedures"[MeSH Terms] AND "printing, three-dimensional"[MeSH Terms])

OR

("education"[MeSH Terms] AND "printing, three-dimensional"[MeSH Terms])

OR

("economics"[MeSH Terms] AND "printing, three-dimensional"[MeSH Terms]))