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Chapter

Application of Three-Dimensional Printing in Surgical Planning for Medical Application

Wei-Ling Chen, Tsung-Lung Yang, Jieh-Neng Wang and Chung-Dann Kan

Abstract

Three-dimensional printing (3DP) is an evolving technology with a wide range of medical applications. It complements the traditional methods of visualizing the cardiovascular anatomy and assists in clinical decision making, especially in the planning and simulation of percutaneous surgical procedures. The doctor–patient relationship has changed substantially, and patients have become increasingly aware of their rights and proactively make decisions regarding their treatment. We present our experience in using 3DP for aortic repair, preoperative surgical decision making for congenital heart disease, and simulation-based training for junior vascular surgeons. 3DP can revolutionize individualized treatment, especially for congenital heart disease, which involves unique anatomy that is difficult to examine using traditional computed tomography. As cardiovascular medicine and surgery require increasingly complex interventions, 3DP is becoming an essential technology for surgical instructors and trainees, who can learn to become responsible and humane medical doctors. 3DP will play an increasingly crucial role in the future training of surgeons.

Keywords: doctor–patient relationship, patient-specific geometry, three-dimensional printing (3DP), surgical decision making, personalized 3D-printed cast

1. Introduction

A thorough preoperative evaluation of anatomy and proper surgical planning are essential to successful operations. Clinicians must be able to assess the patient's anatomy to quickly make surgical plans and provide information to reduce surgical risk and operating time [1]. However, the availability of imaging modalities (computed tomography [CT] and magnetic resonance imaging [MRI]) and the cost of technology affect the acquisition of information and images for surgical plans. Clinicians can usually rely on their experience and two-dimensional (2D) medical imaging to guide their decision-making process. Although three-dimensional (3D) postprocessed images improve upon traditional 2D image sets, they usually do not provide sufficient information for surgical simulation. Medical 3D printing (3DP) is a rapidly advancing technology that can provide innovative solutions to problems

in preoperative planning [2, 3]. The doctor–patient relationship may change substantially as patients become increasingly aware of their rights and proactively make decisions about their treatment; medical 3DP can help patients select their treatment from the available options [4]. Surgeons' decisions may sometimes be questioned. Therefore, surgeons must inform patients and their families about treatments, the process of the operation, and the pros and cons of the operation to help patients select their desired treatment method.

Because of considerable improvements in surgical intervention and the development of endovascular stent grafts since 2000, the use of 3DP for surgical planning may reduce surgical risk and improve outcomes and the doctor–patient relationship. Before any examination or surgery, clinicians should discuss the risks, benefits, and alternatives with patients. Although informed consent is integral to high-quality medical practice, doctors should advise their patients of all risks; negligence during this process can lead to a breakdown in the doctor–patient relationship [5–10]. However, this represents a challenge for many providers of healthcare services. Fortunately, 3DP has improved surgical processes and the quality of information on which patients may base their consent. However, the following limitations remain [11, 12]:

1. Accurate image capture by transthoracic echocardiography, MRI, and CT is essential for 3DP.

2. Risk scores are suboptimal for individuals with anatomical diversity or unique traits because they provide population estimates rather than patient-specific estimates, even though risk scores represent all potential variables.

3. Complex disorders make imaging, therapy, and intervention more challenging, which has an impact on the results.

The following chapters discuss clinical applications of 3DP in medicine, including a wearable orthopedic brace that can monitor vascular access stenosis dysfunction; the use of 3DP to enable zone zero thoracic aortic endovascular repair for ascending aorta disease; a case report of surgical planning for congenital heart disease; a simulation-based training program for junior vascular surgeons; and additional clinical cardiovascular applications.

2. History of 3D printing in clinical application

The term "3D printing" has come to refer to a group of related manufacturing processes that use digital data to produce physical models. In the broad spectrum of additive manufacturing techniques now used in the industry, 3D printing stands out. The term refers to the procedure through which a three-dimensional physical object is created from a digital model [13]. Nowadays, 3D printing technology represents an opportunity to help pharmaceutical and medical companies create more specific drugs, enabling rapid production of medical implants and changing how doctors and surgeons plan procedures [1]. In addition, 3D printing can significantly improve the research knowledge and skills of the new generation of surgeons. Improving patient and surgeon relationships [14] and medical applications was initially reported in the early 2000s [15]. Initially, these reports focused on custom prostheses [16], but as the

technology improved, reports of using anatomic models for preoperative planning began appearing [17]. The recent rapid growth of 3D printing in medicine has been staggering. Specifically, the anatomic data radiologists receive and interpret daily can be used in 3D printing to provide tailored medication. Offering such a service could be a method for radiology to show its worth in in-patient treatment and a new avenue for interaction with referring clinicians. Moreover, radiologists have seen the development of medical imaging that enables 3D printing. CT and MRI's multiplanar imaging led to 3D reconstructions, which enhanced the assessment of intricate anatomy [18–20]. As described, 3D printing transfers digital image data from a flat-screen into the physical world's third dimension [20].

Yearly, the scope of applications for 3D printing in the medical field broadens, making it possible to save lives and improve quality of life in ways that were previously imagined. In point of fact, three-dimensional printing has been put to use in a wide variety of medical specialties, including cardiothoracic surgery, cardiology, gastroenterology, gastroenterology, neurosurgery, oral and maxillofacial surgery, orthopedic surgery, plastic surgery, podiatry, pulmonology, radiation oncology, transplant surgery, urology, and vascular surgery [21–34].

Below we list some of the most prominent direct uses of 3D printing in the clinical and medical arena [35–37]:

1. Integrating clinical and imaging data will be an integral part of the multi-step process that will determine the optimal treatment choice via personalized pre-surgical planning.

2. 3D-printed models educate medical students, residents, and patients.

3. Lowered expenditures associated with healthcare, shorter hospital stays after surgery, and fewer cases requiring further medical attention are all benefits.

4. With 3D printing, it is possible to choose the precise dimensions of prosthetic parts before implantation.

5. 3D printing may make personalized implants or surgical guidance and devices for specific procedures.

6. To follow a pharmacological treatment, 3D printing helps invalidate the results achieved by the patient.

7. The viability and efficacy of a cardiovascular system in preventing and treating peripheral and coronary artery disease.

8. Patient education: patients may not fully understand 2D images (CT or MRI) representation of a 3D anatomy. Therefore, 3D printing may improve doctor-patient communication by showing the anatomic model directly.

9. Boosting medical training using 3D-printed models of individual patients, which may improve outcomes and facilitate quick comprehension.

10. Bioprinted by pharmaceutical industries to replace animal models for analyzing the toxicity of new drugs.

3. 3D printing methods

3.1 Image acquisition modalities

Surgical outcomes depend on experience and technical skills. However, outcomes and operative times can be improved if anatomical information is acquired before surgery. MRI, CT, and echocardiography enable clinicians to obtain valuable information regarding the physiology and structural details of patients with cardiovascular disease. 3DP analysis software can help inform less-experienced surgeons. For example, the Mimics Care Suite (Materialize, Leuven, Belgium) is medical software that offers an effective and efficient method of evaluating stent appositions by using 3D imaging. Advances in 3DP technology have enabled clinicians to examine 3D structures in pre-operative planning [38]. 3D Slicer is free, open-source, extensible operating software for medical image visualization and computation (www.slicer.org). 3D Slicer supports CT, MRI, positron emission tomography, X-ray, and ultrasound images [3, 38, 39].

3D models can be viewed from any angle. In preoperative planning, 3D models can be used to determine the proper location for an endograft and reduce surgical risk. Surgeons can apply the detailed anatomical information provided by 3D models to solve critical problems. Surgeons can also use 3D models to accurately determine the location of a pseudoaneurysm lumen and whether an aneurysm entrance may be covered by a stent during thoracic endovascular aortic repair [40–43]. 3DP software can also facilitate stent sizing. We used 3D Slicer to create an STL file for 3DP.

3.2 Methodology- creating an STL file for medical printing using 3D slicer

Cardiovascular images were obtained from contrast-enhanced CT scan data in accordance with standardized scanning protocols [44]. These CT images were used to build an STL package. 3D Slicer has function that exports reconstructed 3D images as STL files for 3DP. **Figure 1** shows the 3D printing framework: first, gather CT or MRI pictures of the patient; second, import DICOM images of the scanned component into the 3D Slicer; third, model generation; fourth, construct a printable 3D model; and fifth, print 3D objects.

3.3 CT with digital imaging and Communications in Medicine file format as the standard for storing images

Digital Imaging and Communications in Medicine (DICOM) is the most widely used standard for sharing information about medical imaging worldwide. Using
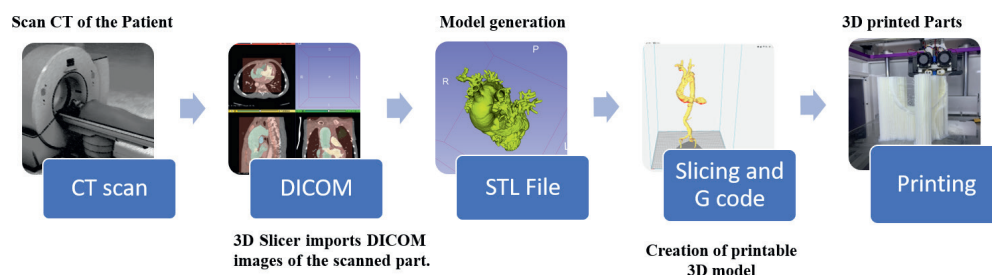
Figure 1.
3D printing framework. (A) Gather CT or MRI pictures of the patient (B) import DICOM images of the scanned component into the 3D slicer (C) model generation (D) construct a printable 3D model (E) print 3D objects.

DICOM images to print in 3D has become more popular. With the growth of technologies like medical and imaging engineering, as well as the improvement of hardware and software and their falling prices, life has become more accessible. For example, more and more patient-specific 3D models, such as teaching, planning, and simulating surgery, are used in cardiovascular areas. DICOM image 3D printing uses 2D pictures stacked on top of each other and then broken up into the data format that the 3D printer needs. DICOM pictures are being split into a 3D computer-aided design format for intermediate data, which can be used for first-stage processing, like setting up an ROI. Out of the roughly 100 file formats of 3D CAD data that are used as 3D native files and intermediate files, STL is the most common format for 3D printing. There are several commercials (paid) and open-source (free) software tools for converting DICOM images to STL data, and all of them can be run on a regular personal computer.

After creating a 3D picture, the following phase is to convert it into a mesh structure for verification before printing. The subsequent step of segmenting the pictures into regions of interest based on characteristics such as brightness or contrast is a crucial part of the process. The decision of how to segment a picture can be helped by virtual rendering. 3D Slicer is equipped with a virtual rendering module for rapid 3D modeling, enabling medical professionals to inspect lesions and see photographs quickly. On the other hand, virtual rendering models cannot be immediately transformed into the STL format necessary for 3D printing. The segmentation process can be carried out using a variety of approaches, the most common of which are completely automatic, semiautomatic, and entirely manual. The segmentation process is based on the built-in tools available in 3D Slicer for sketching and coloring tissue outlines and lesions. Layered structures can be helpful for segmentation because they enable medical professionals to distinguish tissues and highlight connections between lesions and neighboring healthy tissues using different colors. Segmentation may now be finished more rapidly as a result. 3D Slicer may also be used to do this.

The software that can be used to segment images and the software that creates STL files from DICOM data differ. Therefore, the characteristics of each must be understood (**Figure 2**).

Step A: The first step requires dragging and dropping the folder containing the DICOM images onto the 3D Slicer's welcome window.

Step B: To add layers, users must utilize the Segment Editor. Each Segment Editor module has a collection of default parameters matching a specific anatomical component.

Step C: Paint each layer using the paint tool (growing for seeds). The algorithm makes each seed grow at the same time. Since growth is faster in areas where everything is the same, the lines between segments are where there is a significant change in image intensity. Therefore, If the wrong segment is grown anywhere, then paint some more seeds there with the correct segment. Since this usually happens in low-contrast regions, typically, users need to paint with two colors on both sides of hardly visible boundaries.

Step D: A preview.

Step E: A new layer must be combined with an existing one using logical operators, and then the combined layer must be used before moving on to the next step.

Step F: Create 3D-printable vessel walls from contrast-CT volumes. "hollow" has been added to the Segment editor to create hollow objects from solid objects in a straightforward step.
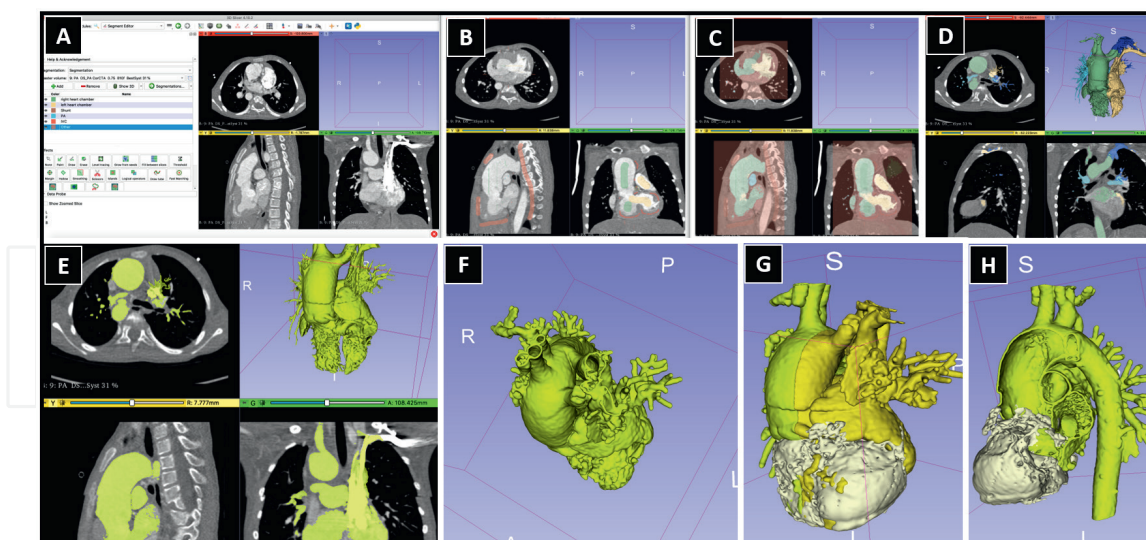
Figure 2.
Computer tomography uses DICOM as the standard format for storing patient images (A) drag and drop the folder containing your DICOM images onto the slicer welcome window (B) (C) (D) "segment editor" modules have a series of presets for different anatomy structures. (E) Using a new layer to join the layer just done logical operators. (F) Hollowing (G) ventricular wall (H) smooth tool.

Step G: Create a mask layer. Paint the ventricular wall by using the spherical brush tool. The primary goal of this step is to make a mask so that paint may be applied using a spherical brush to the ventricular compartment's wall.

Step H: Using the smoothing tool, make it even in this step (median, hole closing).

4. Using on-demand, multi-sensor wearable 3d-printed medical device for hemodialysis patient care

According to the 2020 Annual Data Report of the US Renal Data System, Taiwan has the highest end-stage renal disease (ESRD) prevalence. HD accounts for about 69% of all renal replacement therapies and 88% of all dialysis worldwide. According to Taiwan's National Health Insurance (NHI) Administration, chronic kidney disease is the most expensive to treat. The National Health Insurance (NHI) annually spends NT$53,3 billion ($1.8 billion) on hemodialysis (HD) for 87,000 patients, placing considerable pressure on the healthcare budget. Moreover, almost ninety percent of Taiwanese patients select hemodialysis as their primary dialysis treatment [45, 46].

Long-term dialysis effectiveness in HD patients depends on preserving Arteriovenous access (AVA) [47]. The high prevalence of AVF maturation failure is the first persistent issue in HD patients; AVA patency loss is also prevalent. Arteriovenous graft (AVG) has a much lower useful life than arteriovenous fistula (AVF) (AFV). With a combined incidence of 66–73% in AVF and 84% in AVG, stenosis, and thrombosis are the primary causes of access dysfunction. Juxta-anastomotic venous stenosis affects between fifty percent and seventy-one percent of AVAs [48, 49]. For hemodialysis therapy to be deemed efficient, AVA flow rates must reach between 600 and 1000 mL/min. After continuous use of these methods, pathogenic alterations occur (e.g., high venous pressure or insufficient blood flow). When the arterial lumen is decreased by 70%, the stenotic segment must be dilated, or the intraluminal thrombus must be removed.

Recent developments in wireless ultrasonography have made rapid scans possible. Although these devices are not yet suitable for independent professional use or comprehensive testing of AV operation, they may serve as an alternative, cost-effective portable device for stenosis identification. Clinicians have tried qualitative and quantitative investigation of bruits since 1970, resulting in the creation of AVA dysfunction monitoring devices. However, the sensitivity of present monitoring equipment varies from 35–80% due to the spectral characteristics of functional and dysfunctional vascular access [50–52]. The audible sound of turbulent blood flow is known as a bruit. Phonoangiography (PAG), the recording and statistical analysis of bruits, has been utilized to assess vascular access in HD patients for many decades. The features of turbulent blood flow induced by a restricted channel are objectively described by spectral analysis of bruits.

On the other hand, the acoustic approach correctly reflects the directions of hemodynamic changes related to the turbulence state. From the perspective of Spencer's and Reid's curve [53], if the cross-sectional area decreases by more than 96% or the diameter decreases by more than 85%, the velocimetry may underestimate the cross-sectional area by 90% or less or the lumen diameter reduction by 70%. To understand any blood flow velocity, one needs to consider whether it was measured on the upslope, downslope, or "opposite side" of Spencer's curve. Therefore, it is vital to ensure that flow volume and velocity changes correspond. The flow volume falling to or below 20–30% of the usual flow suggests a greater degree of stenosis than anticipated. Consequently, combining PAG and flow volume changes may boost the probability of early and accurate stenosis prediction.

Photoplethysmography (PPG) is a low-cost, non-invasive, and straightforward optical technology that detects changes in peripheral circulation volume. However, wearable PPG sensors can only be positioned at specific skin sites. The light source of a PPG device transmits light to a tissue, and the photodetector analyses the light reflected from the tissue. The light reflected is proportional to fluctuations in blood volume. PPG sensors that measure blood flow volume are often powered by an infrared light-emitting diode (IR-LED) or green LED.

In recent years, several medical institutions have used 3D printing technology to create personalized external prostheses, surgical guides for implant placement, simulated implants, and other devices for preoperative planning [45]. In 2018, we developed a prototype to capture AVA hemodynamic data using AVA-targeted sensors implanted in a customized 3D-printed cast. In addition, we will request on-duty nursing personnel to evaluate sensor readings using their stethoscopes qualitatively. In addition, statistically, we will employ Doppler and grayscale ultrasonography as the gold standard to determine the AVA stenosis's ultimate status. In situations of severe blockage (i.e., 95% occlusion), however, noises may not be heard due to limited blood flow, resulting in a significant chance of false-negative findings. For improved and more accurate stenosis diagnosis, we integrated PPG (for detecting volumetric changes in AV accesses) and PAG (for detecting changing pitch patterns in AV accesses).

In recent years, the use of 3D printing has expanded significantly. Certain medical institutions have used this technology to create bespoke external prostheses, surgical guides for implant placement, simulated implants, and other preoperative planning assistance. The device's position is an essential aspect that might influence the accuracy of PAG and PPG instruments. 3D-printed, multi-sensor, wearable medical devices are a feasible method for minimizing or eliminating the influence of location.

Chen et al. combined PPG and PAG sensors to create a wearable device with increased diagnostic accuracy for detecting AVA malfunction (**Figure 3**) [54, 55].

5. Surgical predictive plan to assistant the spatial relationship of patient-specific geometry

5.1 Case 1 effective thoracic endovascular repair in acute type a aortic dissection

Acute type A aortic dissection (ATAAD) is a catastrophic disease. The risk of death without surgery is approximately 65%; the mortality rate increases by 1–2% per hour in the first 24 hours. Surgical options are often limited by open interposition grafts through median sternotomy wounds [56]. The global prevalence of ATAAD ranges from 5 to 10 cases per 1 million people, and the estimated incidence is approximately 11.9 cases per 100,000 person-years. However, approximately 25% of cases with ATAAD are considered inoperable [57–60]. Open repair surgery for patients with critical illness can entail high surgical risks and operative and hospital mortality rates and long hospital stays. Thoracic endovascular stent graft implantation is an alternative for patients with certain types of ascending aortic disease who are not suitable for traditional open surgery.
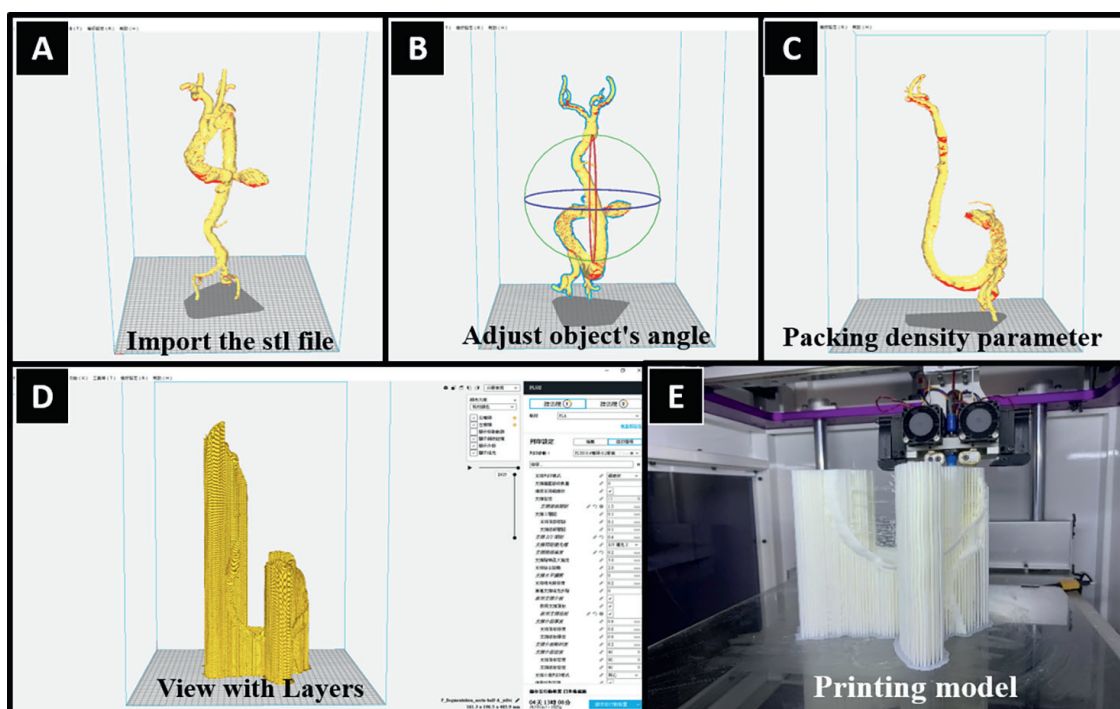

Figure 3.
Using on-demand, multi-sensor wearable 3D-printed medical device for hemodialysis patient care.

In the past two decades, endovascular aortic repair (EVAR) has been successfully proved and largely used to be a good alternative strategy for abdominal aortic and descending thoracic diseases. Due to the development of fenestrated and branched stent-grafts, diseases involving the visceral branches of the descending aorta and even diseases on the aortic arch have become diseases that can be treated with stent-grafts [61]. However, there is a fundamental difference between the ascending aorta and the descending aorta diseases. The ascending aorta is challenged by hemodynamic and anatomical limitations, especially under the condition of aortic dissection. The geometry of the ascending aorta is greatly affected by the aortic dissection, which leads to an increase in the diameter of the ascending aorta and loss of structural wall integrity through delamination. Therefore, it complicates the identification of a stable landing zone. At present, empirical reports on the endovascular repair of the ascending aorta are just limited to case series or case reports. Since there is no aortic stent-graft design specifically for the ascending zone, the FDA has not approved any commercial aortic stent-graft devices for the ascending aorta [62, 63].

We can try to use computed tomography 3D reconstruction and 3D Slicer software version 4.13.0 (3D Slicer contributor, http,//www.slicer.org) to help clarify the spatial relationship of the patient's specific geometry, and then successfully apply the aortic stent graft system to treat the type II acute aortic dissection diseased patient. In order to accurately understand the applicability of the TEVAR devices in patients, we can also use three-dimensional printing (3DP) technology to reconstruct the real condition of the specific landing zone (**Figures 4** and **5**). In this way, we may quickly gain the goals of early diagnosis and the tasks of meticulous planning, thereby achieving successful treatment results.

An 88-year-old man suddenly lost consciousness at the scene and was rushed to the emergency room by emergency medical services. He has a history of hypertension

Figure 4.
(A) Import stereolithography of the patient (B) adjust the object's orientation (C) set the packing density parameter (D) view the model with layers (E) print the model.
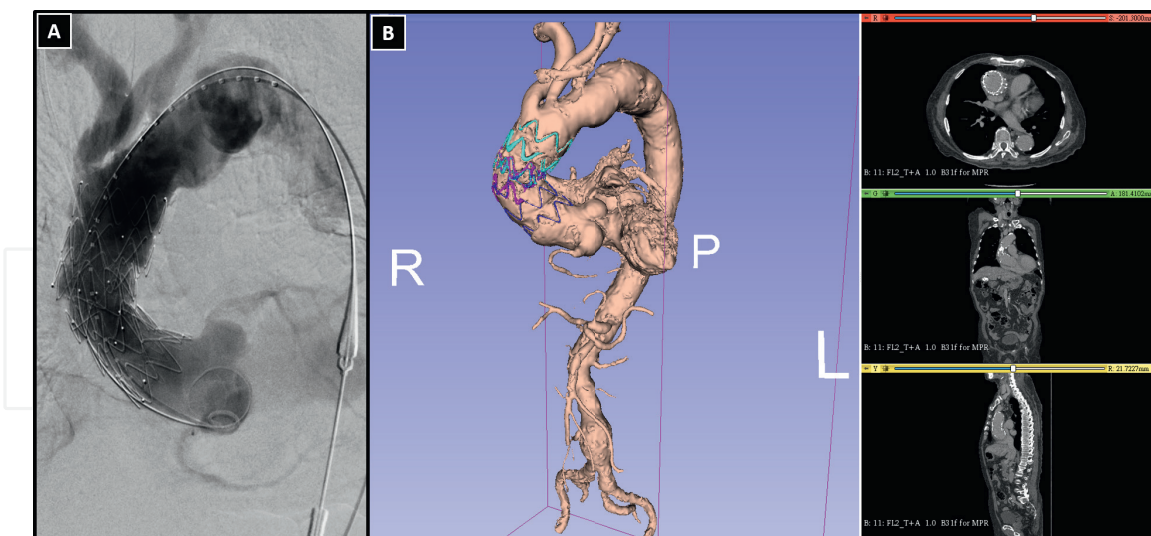
Figure 5.
3D reconstruction and 3D slicer software to reconstruct the 3D image of the aorta; (A) the patient's final aortic angiography showed complete coverage of the dissection sac orifice, satisfactory alignment of TEVAR stents, and no signs of endoleaks (B) with the assistance of computed tomography 3D reconstruction and 3D slicer software, the operation was completed as smoothly as our preoperative plan.

and infra-renal aortic dissection. An emergency computed tomography (CT) scan of the head showed no significant findings. However, his chest CT showed a small amount of pericardial effusion and acute DeBakey type II dissection. An extensive tear hole lesion originated in the middle of the ascending aorta, and the obvious giant pseudoaneurysm and hematoma extended down to the coronary ostium and up to the proximal orifice of the innominate artery. The maximum diameter of the pseudoaneurysm of the ascending aorta was measured to 55.6 mm. The sinotubular junction (STJ) measurement value is 34.6 mm × 31.9 mm. The distance from the edge of the tear hole at the proximal end of the greater curvature of the aorta to the STJ was 67.5 mm, and the distance from the side of the minor curvature was 38.0 mm. And, the distance from the edge of the distal tear hole to the innominate artery is 23.8 mm. The diameter of the possible landing zone at the distal end measured at the level of the innominate artery is approximately 40.8 × 40.3 mm.

5.2 Case 2 surgical planning for congenital heart disease

5.2.1 Double outlet right ventricle

Most cases of double outlet right ventricle (DORV) present a unique challenge to congenital cardiac surgeons. The relationships among the ventricles, ventricular septum, and great arteries can vary in DORV, and the condition presents a range of clinical manifestations secondary to changes in infundibular and intracardiac morphology. The unique spatial arrangement of these structures determines the optimal type of intervention. Although traditional 2D imaging can effectively represent these structures, the preoperative 3DP of models in case 2 substantially affected the time to extubation and length of stay in the intensive care unit. Zhao et al. operated on 25 patients with DORV and studied preoperative 3D-printed models for one-third of the patients [64]. Although whether these patients were selected randomly was unclear, cardiopulmonary bypass and cross-clamp times were lower in the 3DP group; however, these differences were nonsignificant. Significant differences in

time to extubation and length of stay in the intensive care unit were observed, possibly suggesting improved surgical outcomes. In our case, a 7-year-old boy presented with complex congenital heart disease (DORV with a large subaortic ventricular septal defect [VSD], and d-looping transposition of the great arteries [D-TGA]), infundibular pulmonary stenosis, had received a modified Blalock–Taussig (BT) shunt at 6 months of age. His condition was stable after a palliative operation, but he was admitted for surgical evaluation and intervention after progressive exercise intolerance and cyanosis. Echocardiography revealed (1) situs solitus and levocardia; (2) a large VSD; (3) atrioventricular concordance and ventricular arterial discordance; (4) the aorta and pulmonary trunk arising from the right ventricle (RV) with the aorta right-anterior to the pulmonary trunk, compatible with D-TGA; (5) severe infundibular pulmonary stenosis; and (6) left-side aortic arch. Chest CTA revealed similar findings. Cardiac catheterization hemodynamic data revealed that aortic pressure was 116/75 mmHg with 90.7% oxygen saturation (SaO_2), superior vena cava (SVC) pressure was 8 mmHg (mean) with 78.5% SaO_2, inferior vena cava (IVC) pressure was 9 mmHg (mean) with 80.6% SaO_2, right atrium (RA) pressure was 8 mmHg (mean) with 80% SaO_2, RV pressure was 119/12 mmHg with 82.2% SaO_2, and pulmonary artery (PA) pressure was 12/2 mmHg (mean) with 84.1% SaO_2. Our surgical plans were total cavopulmonary connection (TCPC) or physiological biventricular repair (VSD patch repair with an intracardiac tunnel or right ventricular outflow tract reconstruction with RV-to-PA valved conduit [Rastelli operation]). We used CTA data for surgical simulation through 3DP (**Figure 6**). The 3DP analysis indicated that physiological biventricular repair with left BT shunt ligation was most feasible for the patient. The surgical procedure was conducted as planned, and the results were satisfactory. Currently, the patient's condition is stable. He has received regular follow-up in the outpatient clinic for 2 years and does not require further intervention.
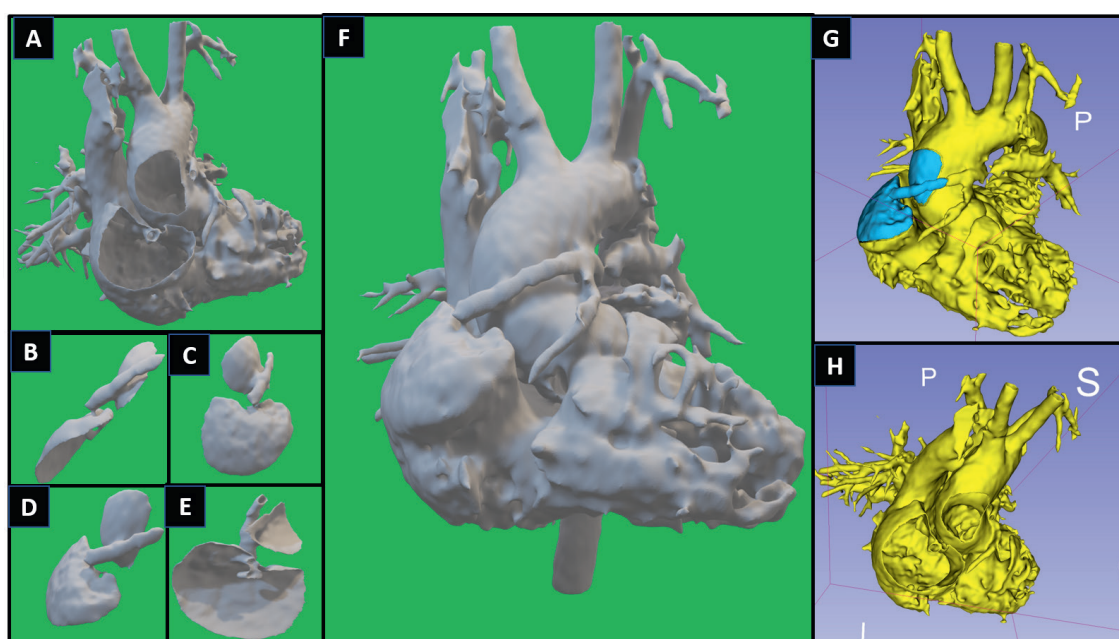
Figure 6.
Congenital heart for surgical planning; (A) 3D printing (B) cutting the 3D model for surgical planning (C) (D) (E) ventricular wall (F)3D dimensional printing congenital heart (G) (H) reconstruct the real condition of the congenital heart.

6. Transposition of the great arteries (TGA)

A 10-year-old girl presented with complicated congenital heart disease, situs inversus, levocardia, a large VSD, an atrial septal defect (ASD), and corrected transposition of the great arteries with pulmonary atresia. She had received a right modified BT shunt at 1 month of age and a left modified BT shunt at 3 years of age. Her condition stabilized after these palliative operations, but she was admitted for surgical evaluation and intervention because of progressive exercise intolerance and cyanosis. Echocardiography revealed (1) situs inversus and levocardia; (2) a large type II VSD with a bidirectional shunt; (3) atrioventricular discordance and ventricular arterial discordance, with the aorta right-anterior to the atretic PA; and (4) right aortic arch with patent bilateral BT shunts and bilateral SVCs. Chest CTA revealed similar findings. Cardiac catheterization hemodynamic data revealed that aortic pressure was 106/58 mmHg, SVC pressure was 9 mmHg (mean) with 75.1% SaO_2, IVC pressure was 9 mmHg (mean) with 79.1% SaO_2, RA pressure was 8 mmHg (mean) with 78.4% SaO_2, RV pressure was 87/14 mmHg with 88.2% SaO_2, left atrium pressure was 9 mmHg (mean) with 99.9% SaO_2, LV pressure was 93/14 mmHg with 85.5% SaO_2, and PA pressure was 16 mmHg (mean) with 93.4% SaO_2. Our surgical plan involved TCPC, physiological biventricular repair (morphological LV-to-PA valved conduit), and physiological biventricular repair with anatomical repair (double [arterial plus atrial] switch). We used the CTA data for surgical simulation through 3DP (**Figure** 7). We discovered that physiological biventricular repair with VSD and ASD repair was the most feasible option for this patient. The position for the bilateral BT shunt was identified using the 3D-printed anatomical structure, facilitating identification of the structure and adhesion tissue during surgery. The surgical procedure was conducted as planned, and the results were satisfactory. Currently, the patient's condition is stable. She has received regular follow-ups in the outpatient clinic for 2 years without requiring further intervention.
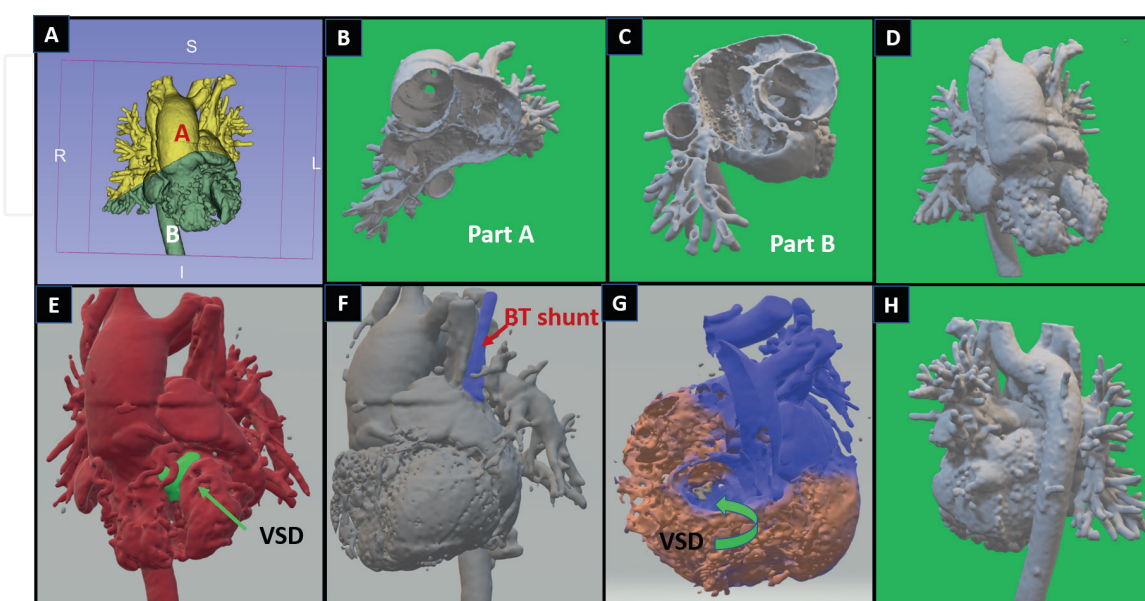
Figure 7.
Surgical planning in medical application; (A) (B) (C) (D) 3D printing for congenital heart, (E) ventricular septal defect (VSD), (F) BT shunt, (G) 3D printing model.

6.1 Training scenario: simulation-based training increases training efficiency for young surgeons

Simulation has been widely used in various surgical training programs for laparoscopic surgery, virtual aortic stent graft procedures, and ultrasound to allow surgeons to practice advanced surgery procedures and acquire new skills [6–8]. Various simulation platforms can be used. Anatomical simulations and presurgical planning may improve surgical results and patient safety, and 3DP can improve both. 3DP can provide anatomical information and a visualization of structural relationships. It can also be used to create a model of a patient's anatomy. We inserted silicone tubing into a printed leg structure to simulate arteries and veins and instructed participants to perform vascular exploration and anastomosis in deep and difficult-to-access areas [1–3]. We used a previous training plan to evaluate the results. A total of 28 students participated in the training course and completed a questionnaire. Most of the participants came from one of three job categories; 75% worked in medical centers, 58.3% were attending surgeons, and 66.6% had less than 5 years of working experience. The effect of the course was evaluated on the basis of the participants' perceptions of their disease familiarity, confidence, and competence, all of which improved significantly ($p < 0.001$). The effect on young surgeons was more substantial than that on attending surgeons. However, trainees from nonmedical centers progressed further than did trainees from medical centers. A total of 95.4% of the participants were satisfied with the course [6].

7. Discussion

3DP and fast prototyping have been used in the medical field since the early 2000s and gradually gained a foothold, possibly because of the widespread use of small, affordable printing units and advancements in imaging acquisition and postprocessing software [5, 8]. 3D-printed anatomical models created from imaging data are increasingly valuable in personalized precision medicine. The applications of 3DP in the medical field can be used for tissue and organ fabrication, prosthetics and implant production, and anatomical models.

In recent years, many medical institutes are already using 3D printing technology to fabricate customized external prosthetics, surgical guides for preoperative planning [45]. We worked out a prototype using AVA-targeted sensors embedded in a personalized 3D printed cast to collect AVA hemodynamic data. The wearable orthopedic brace can monitor vascular access stenosis dysfunction. The wearable medical device incorporated sensors are the PAG sensor for mainly examining vascular pitch patterns and the PPG sensor for calculating flow volume secondarily as a double-checking of the AV access status. By monitoring and detecting changes in the frequency spectrum domain, a new function of the autoregressive (AR) model was introduced to the PAG-based sensors to identify AVA stenosis and concurrently audit the state of its life cycle. It alerts hemodialysis patients about AVA malfunction early and urges them to return [5].

Although 3DP has not been applied as often to aortic surgery and congenital heart surgery as it has to orthopedic and spinal surgery because of the complexity and uniqueness of aortic surgery and congenital heart disease, research on 3DP to improve preoperative surgical planning and medical education for young surgeons is underway. 3DP can benefit almost all parties involved in patient care. Surgeons can

use 3DP to improve their understanding of anatomy, preoperatively plan, and simulate procedures. 3DP materials may help patients and their families to understand diseases. Moreover, 3DP may help medical students, trainees at all levels, and nurses to improve their understanding of certain concepts [3].

We employed DICOM imaging data. DICOM is a standardized image format and network communications protocol that allows for the interoperable transfer of medical images and related information among systems. 3D Slicer and 3D modeling can be used to visualize the aorta before surgery, thereby allowing surgeons to quickly make surgical plans and offering reference information for determining the appropriate combination of stent grafts.

Section 5.1 Case 1 demonstrates that TEVAR stents can be used to treat severe ATAAD. However, because of the complexity of the related anatomical structures and the technological limitations of current devices, utilizing TEVAR stents for ATAAD treatment remains challenging. Dorros et al. (2000) demonstrated the feasibility of treating the ascending thoracic aorta with an endoprosthesis [59]. However, research on ascending TEVAR has been limited to several single-center clinical trials and case reports. In addition, the US FDA has not approved any endovascular stents specifically for the descending aorta [62]. This lack of development may be caused by anatomical and physiological challenges, such as those presented by the opposing ascending aorta, the descending anatomy, complex pathologies, and hemodynamic alterations [60–62].

The use of TEVAR devices designed to treat ascending aortic disease has gradually become feasible; however, whether ascending aortic disease can be predicted and how failure can be avoided remain unclear. In the anatomical structure of the ascending aorta, the greater curvature can be more than 30% longer than the lesser curvature. In addition, in cases of acute ascending aortic dissection, the diameter of the ascending aorta can suddenly increase by up to 32% [63]. The size and shape of commercial stent grafts with fixed diameters and lengths make them incompatible with ascending aortic diseases. The US FDA has yet to approve any commercial devices designed explicitly for ascending aortic diseases. We used 3DP to visualize the spatial relationships in patient-specific geometry and treated patients by using a combination of three stents. However, continued follow-up is required for the evaluation of long-term outcomes.

Case 2 demonstrates the application of 3DP to DORV and D-TGA in surgical planning for congenital heart disease (**Figures 6–8**). The heart has a complicated structure, and congenital heart defects can generate limitless variation in internal and external elements, often yielding unique and highly complex structures. Therefore, the precision with which 3DP can model rhythmic structure is essential. Although comparing the dimensions of a model with those of a digital source image is easy, it can only confirm that the printing process is accurate in relation to stereolithographic input data. Therefore, Hoashi et al. tested the accuracy of 3DP by using preserved cardiac autopsy specimens and discovered that the accuracy was ≥90% [38, 64].

Surgical residents have novice open surgical skills, limited work hours, short training programs, numerous endovascular procedures to perform, high costs, and pressure caused by public expectations. Therefore, basic lectures are insufficient to prepare students for surgical practice. Every operation requires precision and reliability. Simulation-based training may improve the learning process. The purpose of such training is to allow for new surgeons to practice operations and build confidence before surgical procedures and to allow experienced surgeons maintain and refine their skills.
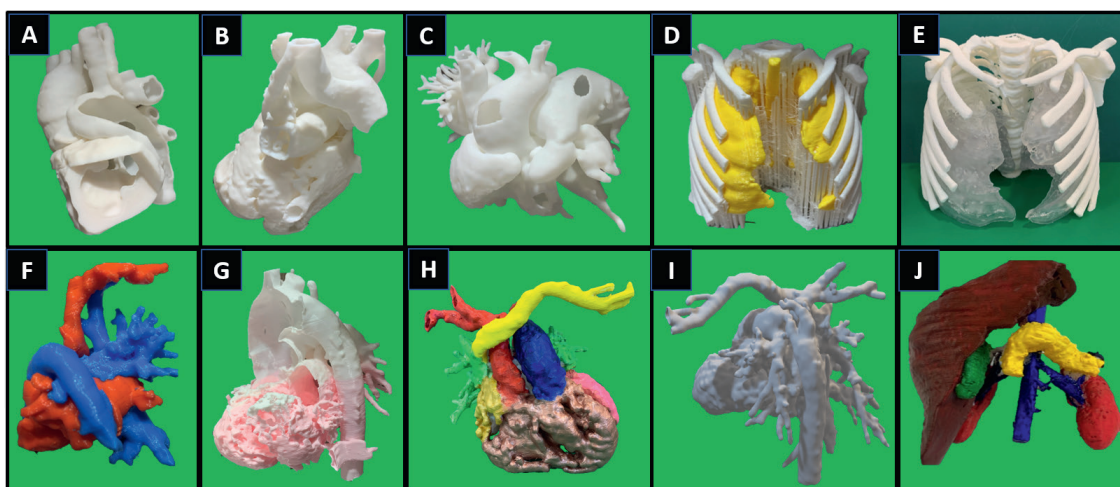
Figure 8.
Surgical planning in medical application; (A) (B) (C) 3D printing for congenital heart, (D) (E) 3D model for surgical planning, (F) (G) 3D printing of heart congenital heart, (H) front side of double outlet right ventricle (DORV), (I) Back side of double outlet right ventricle, (J) 3D printing model.

Employing 3DP for anatomical modeling based on scan data is increasingly valuable in personalized precision medicine. Implantable 3D-printed organs may become available in the future, reducing waiting times and increasing survival rates. The development of implantable living 3D-printed organs is also possible [65].

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Conflict of interest

The authors declare there are no conflict of interests.

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