International Journal of Cardiology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Cardiology

journal homepage: www.elsevier.com/locate/ijcard

Patient-specific three-dimensional printing for Kommerell's diverticulum

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ARTICLE INFO

Article history:
Received 4 November 2017
Received in revised form 26 November 2017
Accepted 16 December 2017
Available online xxxx

Keywords:
Kommerell's diverticulum
Three-dimensional printing
Cardiac surgery
Preoperative planning
Intraoperative guidance

ABSTRACT

Background: Kommerell's diverticulum is a complex congenital malformation of aorta. Three-dimensional (3D) printing is an innovative manufacturing process that allows computer-assisted conversion of 3D imaging data into physical "printouts." The aim of this study was to explore the feasibility and impact of using patient-specific 3D-printed cardiac prototypes derived from computed tomography data on surgical decision-making and preoperative planning for Kommerell's diverticulum.
Methods: From April to August 2017, five patients with Kommerell's diverticulum were diagnosed and chosen for study. Cardiac computed tomography was done for all patients. One case was diagnosed with left aortic arch, and another four cases presented right-sided aortic arch and aberrant left subclavian artery. In addition, one patient complicated with aortic dissection. Data were used to generate patient-specific 3D models. All cases were reviewed along with their models, and the impact on surgical decision-making and preoperative planning was assessed.
Results: Accurate life-sized 3D models were successfully printed for all patients. These models enabled improved understanding of aortic malformation and preoperative planning. 3D models also allowed real-time intraoperative guidance for surgeons.
Conclusions: 3D printed models can improve the understanding of anatomy and allow anticipation of surgical technique challenges, which could radically assist surgical planning, and safe execution of surgery for Kommerell's diverticulum. The combination of 3D printing technique and surgical procedure is a promising perspective for treatment of complex aortic malformation.

1. Introduction

Kommerell's diverticulum is an extremely rare congenital malformation of aortic arch system even in large heart centers. It occurs in either left or right aortic arch, from which an aberrant subclavian artery rises to the contralateral side. Patients usually present with airway symptoms, such as dysphagia and tracheal compression [1]. Kommerell diverticulum may also suffer from rupture and dissection, which could be lethal to patients. Computed tomography (CT) or magnetic resonance imaging (MRI) can provide two-dimensional (2D) anatomical information of Kommerell diverticulum, aortic branch malformation and the adjacent structures [2]. Clinical management for patients with Kommerell diverticulum includes surgery, hybrid procedure, and conservative treatment with drugs. Due to the complex and diverse anatomical structures, the surgical procedure of repairing Kommerell's diverticulum is somehow unfamiliar to surgeons, to some extent, may be difficult [3,4]. Challenges lie in interpreting 2D slices or arrays of imaging information and mentally reconstructing them into their three-dimensional (3D) perspective. Moreover, lack of understanding of spatial anatomy may lead to poor preoperative planning, conversion to surgical accidents, unexpected intraoperative technical challenges, and long surgical or cardiopulmonary bypass time. These can potentially impact both short- and long-term clinical outcomes. A more intuitive imaging dimension on aortic malformation is necessary for excellent preoperative planning and safe repair.

3D printing is an emerging technology in medicine to transform digital information into physical models [5,6]. In cardiac surgery, 3D printing has been mostly used in congenital heart diseases to assist the understanding of complex anatomic malformation, determine preoperative planning, and enable feasibility of reconstruction [7,8]. Compared with the digital reconstruction, 3D printed physical model could present a preferable vision of the anatomical details, which also provides an intuitional understanding of aortic malformation. In the present study, we have shown, as a proof of concept, how 3D printing technology can allow patient-specific planning and surgical decision making for patients

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https://doi.org/10.1016/j.ijcard.2017.12.065
0167-5273/

with Kommerell's diverticulum. To the best of our knowledge, this is the first report of using 3D printing for complicated aortic disease.

2. Materials and methods

2.1. Research design

From April to August 2017, five patients, who were diagnosed as Kommerell's diverticulum by computed tomography angiography (CTA). They have unresolved clinical management decisions and were chosen for comprehensive cardiac assessment and 3D prototyping. These included one patient with right-sided aortic arch and aberrant left subclavian artery and one patient with aortic dissection. All patients had previously received extensive clinical and cardiovascular imaging, followed by discussion and review at department surgical sessions. This study was approved by the ethics committee of Zhongshan Hospital, Fudan University. All procedures were performed in accordance with the relevant guidelines.

2.2. Cardiac imaging segmentation and digital modeling

DICOM formatted raw image data was reviewed with a surgeon to identify key anatomic features and regions of interest and subsequently imported into dedicated postprocessing software Medraw (Image Medraw Technology Co., Ltd., China) for regions of interest segmentation and 3D surface reconstruction. The data were processed to reduce imaging noise and isolate the anatomy of interest.

2.3. 3D printing, preoperative planning and surgery guidance

Using stereo lithography apparatus (SLA) technique on Pangu V4.1 3D printer (Meditool Enterprise Co., Ltd., China), we printed 3D model of the aorta and its branches based on the dense CTA scanning was set at a slice distance of 1 mm and resolution 512 × 512 pixels at a level up to the internal carotid sinus and down to diaphragm. The building layer thickness is 0.1 mm and the laser spot diameter 80 μm. Proprietary materials were used to construct a 3D porous scaffold that matched the digital mesh to 1 mm globally. The porous scaffold was then infused with silicone and a blend of two types of hydrogels. Silicone provided a flexible protective layer intended to extend the life of the model and facilitate handling and manipulation. We opted for hard, inflexible models in multiple colors for easy anatomic understanding. All printed models were reviewed and evaluated by a team of cardiac surgeon, perfusionist and anesthesiologist at one day before operation. The 3D printed model was positioned in an anatomic position in hands. By carefully observing the 3D printed models, the surgeons could identify the complicated anomaly, confirm the vessel locations and plan the surgical repair. In addition, the 3D printed model was also shown to surgeons for the guidance of surgical anatomy during the operation process.

3. Results

3.1. 3D printing

Each case had different variations in its anatomy and clinical characteristics (Table 1). The workflow of case management was shown in Fig. 1. The 3D printed model was a customized model for each patient. All 3D printing had a good correlation with the anatomy of the original DICOM data set. The measurements of the physical model, the dimension of the original data and the virtual 3D model, were almost identical to the multi-planar reconstructions of raw data and the virtual 3D models (Fig. 2). Spatial anatomy was true to CTA reconstructed anatomy. The relationship between large arteries and the surrounding tissues of the blood vessels for each case were well-depicted.

3.2. Pre-operation planning and surgical guidance

There was universal agreement among team members that the models provided a radical and novel 3D perspective into patient-specific aortic anatomy. Tactile experience of handling the prototypes provided valuable information similar to that obtained during direct intraoperative inspection. It allowed greater ease of understanding specific technical challenges and enabled detailed and accurate surgical planning for each patient. Surgeons were able to anticipate and precisely plan the vascular repair and location. Intraoperative cardiac anatomy was found to be identical to the respective 3D models for all cases. All surgeries were accomplished in accordance with the preoperative plans.

The incision and operation practice were summarized in Table 1. An impregnated woven polyester tube graft measuring 16 to 30 mm with a 10-mm sidearm was used to replace the resected aorta. Deep hypothermic circulatory arrest (DHCA) was used in four cases; mean bypass time was 128.0 ± 30.1 min, and mean circulatory arrest time was 23.0 ± 6.2 min. During the operation, the mean blood loss was 660 ± 89.4 mL. All patients went back to cardiac surgery intensive care unit (CSICU) after surgery. The mean length of stay in CSICU was 4.2 ± 1.3 days. No surgical procedure-related complications or recurrence of symptoms occurred. Four patients discharged successfully. One patient died of infection at 90 days after he returned to the ward.

4. Discussion

3D printing models derived from the imaging modalities has been recently used for assisting cardiac surgery [9]. 3D printing technology allows the possibility of converting imaging datasets into physical models, providing unique, easily accessible, tactile tools to understand aortic malformation and plan management. Open surgery is the traditional and preferred technique for Kommerell's diverticulum. The core of open surgical treatment for patients with Kommerell's diverticulum is appropriate incision approach, resection of the diverticulum and reconstruction the aortic branches. Herein, we developed patient-specific 3D printed model of Kommerell's diverticulum to figure out the complex aortic abnormality and guide safe surgery (Fig. 1).

Patients with Kommerell's diverticulum usually present variable malformation in aortic arch and always confuse experienced surgeons in clinic practice. An aberrant right subclavian artery with a left aortic arch occurs in 0.4% to 2.0%; however, an aberrant left subclavian artery with a right aortic arch has been less common, occurring in approximately 0.1% [2,3]. In patients with an aberrant subclavian artery with a left aortic arch, the diverticulum of the aorta is an embryologic remnant of the dorsal right fourth aortic arch, but in patients with aberrant left subclavian artery and a right aortic arch, the diverticulum is an embryologic remnant of the dorsal left fourth aortic arch. It has been reported that 80% of aberrant subclavian artery were located behind the esophagus, 15% were between the esophagus and the trachea, and 5% were in front of the trachea [3]. In our cases, four patients (Fig. 2, Cases i, iii, iv and v) were diagnosed as diverticulum in right aortic

Table 1
Clinical summary of five cases of Kommerell's diverticulum.

Cases	Age(years)/Gender	Anatomical characteristics	Clinical issues (NYHA class)	Incision/Operation
i	46/Female	Aortic diverticulum in right aortic arch with aberrant left subclavian artery, complicated with aortic dissection	Sudden chest pain (NYHA Class I)	Left posterolateral incision of chest/half aortic arch replacement and descending aorta stent
ii	72/Male	Aortic diverticulum in left aortic arch with aberrant right subclavian artery	Shortness of breath after activity (NYHA Class I)	Median sternotomy/aortic arch replacement, descending aorta stent
iii	42/Male	Aortic diverticulum in right aortic arch with aberrant left subclavian artery	Chest tightness after activity (NYHA Class I)	Median sternotomy/aortic arch replacement, descending aorta stent
iv	66/Male	Aortic diverticulum in right aortic arch with aberrant left subclavian artery	Shortness of breath after activity and Dysphagia (NYHA Class I)	Median sternotomy/aortic arch replacement, descending aorta stent
v	64/Male	Aortic diverticulum in right aortic arch with aberrant left subclavian artery	None (NYHA Class I)	Median sternotomy/aortic arch replacement, descending aorta stent

Please cite this article as: X. Sun, et al., Patient-specific three-dimensional printing for Kommerell's diverticulum, Int J Cardiol (2017), https://doi.org/10.1016/j.ijcard.2017.12.065