Effect of 3D-Printed Hearts Used in Left Ventricular Outflow Tract Obstruction: A Multicenter Study

Xianzhi Wang

The First People's Hospital of Guangyuan

Jixiang Liang

Xi'an Jiaotong University

Cunfu Mu

The First People's Hospital of Guangyuan

Wenlin Zhang

The First People's Hospital of Guangyuan

Chunzhu Xue

The First People's Hospital of Guangyuan

Yang He

The First People's Hospital of Guangyuan

Gen Zhang

The Affiliated Traditional Chinese Medicine Hospital of Southwest Medical University

Dianyuan Li (✉ Dianyuanli@yahoo.com)

The Affiliated Suzhou Hospital of Nanjing Medical University, Nanjing Medical University

Research Article

Keywords: Three-dimensional printing, Left ventricular outflow tract obstruction, Cardiac surgery, Cardiac imaging

Posted Date: January 7th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1206928/v1>

License: (cc) (i) This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

Objective: The purpose of this research was to explore the application value of a three-dimensional (3D)-printed heart in the operation for left ventricular outflow tract (LVOT) obstruction.

Methods: From August 2019 to October 2021, 46 patients with LVOT obstruction underwent surgical treatment at Peking University International Hospital, Southwest Medical University Affiliated Hospital of Traditional Chinese Medicine and Guangyuan First People's Hospital. According to the treatment method, 22 cases were allocated to the experimental group and 24 cases to the control group. The operation time, cardiopulmonary bypass time, intraoperative blood loss, hospitalization time, postoperative ejection fraction (EF), left ventricular flow velocity (LVFV), LVOT pressure difference (LVP), postoperative interventricular septal thickness (IST), inner diameter of the left ventricular outflow tract (IDLV), systolic anterior motion (SAM), atrioventricular block rate, aortic regurgitation (AR) rate and surgical complication rate of the two groups were compared.

Results: The operation time, cardiopulmonary bypass time, intraoperative blood loss, hospitalization time, LVP, postoperative IST, AR, SAM, and postoperative LVFV of the experimental group were significantly lower than those of the control group ($P < 0.05$). The IDLV was larger than that of the control group ($P < 0.05$). There was no significant difference in the postoperative EF, atrioventricular block rate or complication rate between the two groups ($P > 0.05$).

Conclusion: A 3D-printed heart model for in vitro simulation surgery is conducive to formulating a more reasonable surgical plan and reducing surgical trauma and operation time, thereby promoting the recovery and maintenance of the heart.

Introduction

According to the hemodynamic characteristics of the left ventricular outflow tract (LVOT), hypertrophic cardiomyopathy (HCM) can be divided into hypertrophic obstructive cardiomyopathy (HOCM) and hypertrophic nonobstructive cardiomyopathy^[1]. Nearly 50% of HCM patients have different degrees of LVOT obstruction due to the site and degree of myocardial hypertrophy^[2-3]. The Morrow operation is an important method for the treatment of HCM. However, due to the complex anatomical relationship of HCM, the operation is relatively difficult. With the application of three-dimensional (3D) digital reconstruction technology in clinical disease treatment, it has been possible to provide a reference for the formulation of surgical plans by obtaining individual patient data^[4]. This study explored the application value of a 3D-printed model of LVOT obstruction in Morrow operations.

Materials And Methods

Case sample selection

From August 2019 to October 2021, 46 patients with HCM underwent surgery at Peking University International Hospital, Southwest Medical University Affiliated Hospital of Traditional Chinese Medicine and Guangyuan First People's Hospital. Inclusive criteria were as follows: LVOT pressure difference (rest or excitation) ≥ 50 mmHg; interventricular septal thickness (IST) > 18 mm; a pressure difference in asymptomatic patients at rest of more than 75–100 mmHg; severe clinical symptoms, such as exertional dyspnea, that were not improved by medical treatment; and complete data regarding the operation and follow-up. Exclusion criteria were as follows: severe organic valvular (mitral or aortic) changes found before the operation; presence of atrioventricular block before the operation; severe cardiopulmonary dysfunction; and major diseases associated with other systems. According to the treatment methods, the subjects were divided into the experimental group (22 cases) and the control group (24 cases). There were no significant differences in the general data between the two groups ($P > 0.05$), which were comparable (Table 1). The study was approved by the hospital ethics committee, and all patients signed informed consent forms.

Table 1
Comparison of basic data between the experimental group and the control group

Variable	Experimental group (n=22)	Control group (n=24)	t-value/ χ^2 -value	P-value
Age (years, $x \pm s$)	49.2 $\pm$ 12.2	51.6 $\pm$ 11.1	-1.321	0.129
Male (n, %)	9 (40.9)	10 (41.6)	-1.121	0.215
BMI	21.2 $\pm$ 2.1	20.8 $\pm$ 2.5	1.790	0.106
Preoperative EF (%)	61.0 $\pm$ 4.2	59.0 $\pm$ 4.1	1.308	0.115
LVP (mmHg)	71.5 $\pm$ 30.5	69.5 $\pm$ 42.5	2.864	0.095
IST (mm)	22.7 $\pm$ 5.3	21.9 $\pm$ 4.2	3.252	0.089
SAM (n, %)	7(31.8)	6(25.0)	1.581	0.125
IDLV (mm)	15.8 $\pm$ 4.7	16.5 $\pm$ 4.3	-3.693	0.082
LVFV (m/s)	2.4 $\pm$ 0.5	2.7 $\pm$ 0.6	-3.991	0.078

Note: BMI, body mass index. EF, ejection fraction. LVP, left ventricular outflow tract pressure difference. IST, interventricular septal thickness. SAM, systolic anterior motion. IDLV, inner diameter of the LVOT. LVFV, left ventricular flow velocity.

Data collection

The median follow-up time was 17.23 ± 10.58 months (range: from 6 to 26 months), and there were no deaths. The operation time, cardiopulmonary bypass time, intraoperative blood loss, hospitalization time, ejection fraction (EF), left ventricular flow velocity (LVFV), LVOT pressure difference (LVP), postoperative IST, inner diameter of the left ventricular outflow tract (IDLV), atrioventricular block rate, aortic

regurgitation (AR) rate, SAM, and operation complication rate were compared between the two groups, and the operation complication rate was recorded.

Treatment

In the control group, the operation plan was made according to the conventional method, and the patients in the conventional group were treated with hypertrophic interventricular septal muscle resection and LVOT dredging through the thoracic median incision. According to the preoperative imaging examination, the location of the lesion was determined, the ascending aorta and superior and inferior vena cava were intubated, cardiopulmonary bypass was established. After cardiac arrest, the right aortic coronary valve was pulled through the aortic root transverse incision approach, and the hypertrophic ventricular septum and anterior leaflet of the mitral valve were fully exposed and explored. The upper end was 5 mm below the aortic ring of the right coronary valve. The right side was 2–3 mm to the right of the midpoint of the right coronary sinus and to the left coronary sinus near the anterior mitral junction. The length of the longitudinal resection is usually 50–60 mm near the apex of the left ventricle. The abnormal chordae tendineae and papillary muscle involved in the anterior lobe of the mitral valve are removed at the same time. The abnormal connection between the body of the anterior papillary muscle and the lateral wall and interventricular septum of the left ventricle was removed to completely release the body of the anterior papillary muscle. The aortic incision was sutured and rewarmed, the ascending aorta was opened, the heartbeat was restored, and the blood was stopped. In the experimental group, CT scanning was performed before the operation, 3D reconstruction was performed with Mimics software attached to CT, and the data were input into a 3D printer to print the physical model of HOCM [5]. The virtual operation of myocardial resection was carried out by a computer, and the individualized operation scheme was designed according to the severity of obstruction. The operation was simulated on the physical model, and the best operation scheme was selected according to the resection effect (Figure 1). The patients' resection site, depth, length and direction were recorded. After the LVOT was exposed during the operation, the site of severe stenosis was found according to the 3D-printed model, and the other operations were the same as those in the conventional group. Mitral valve replacement was performed in patients with mitral valve leaflet organic changes or severe calcification. Transesophageal or transthoracic echocardiography was used to evaluate the systolic anterior motion (SAM) sign, mitral and tricuspid valve function and surgical effects. For patients with coronary heart disease, coronary artery bypass grafting (CABG) was performed with the left internal mammary artery and/or great saphenous vein after the Morrow operation.

Follow-up

Patients were followed up with a mailed questionnaire or telephone call by contacting the referring cardiologist or general practitioner.

Statistics

SPSS 22.0 software (SPSS Inc., Chicago, Illinois) was used for statistical analysis. The mean $\pm$ standard deviation was determined by t-tests. Count data were expressed as percentages (%). The statistical

analysis was performed by using the χ^2 test, with $P < 0.05$ indicating a significant difference.

Results

Comparison of operation indexes and recovery between the two groups.

The operation time, cardiopulmonary bypass time, intraoperative blood loss and hospitalization time of the experimental group were lower than those of the conventional group, and the difference was significant ($P < 0.05$). There was no significant difference in the postoperative EF or atrioventricular block rate between the experimental group and the control group ($P > 0.05$) (Table 2). Atrioventricular block includes three types, including not only cases requiring pacemaker insertion. At the same time, 2 patients underwent myocardial bridge lysis, 2 patients underwent mitral valve replacement, 2 patients underwent mitral valvuloplasty, 5 patients underwent tricuspid valvuloplasty, and 1 patient underwent a modified maze procedure. There were no intraoperative deaths or deaths within 30 days after the operation in either group. There was 1 case with 1 branch of CABG, 2 cases with 2 branches of CABG and 3 cases with 3 branches of CABG.

Table 2
Comparison of the operation indexes between the two groups

Operation index	Experimental group (n=22)	Control group (n=24)	t-value/ χ^2 - value	P- value
Operation time (min)	262.5± 59.6	281.7± 65.8	2.051	0.012
Cardiopulmonary bypass time (min)	79.5± 21.5	90.8± 26.2	3.894	<0.001
Intraoperative blood loss (ml)	472.5± 60.6	491.6± 73.8	4.981	0.001
Hospitalization time (d)	7.6± 1.8	8.1± 1.6	1.894	0.023
Postoperative EF (%)	61.8± 8.5	59.5± 7.9	-0.582	1.521
Atrioventricular block rate (%)	5.2± 1.8	5.5± 1.6	0.953	0.883
Note: EF, ejection fraction.				

Comparison of left ventricular morphology between the two groups.

There was no significant difference in LVFV, LVP, IST, IDLV, AR rate or rate of a positive SAM sign between the two groups ($P > 0.05$). The measured values of LVFV, LVP, postoperative IST, AR rate and rate of a positive SAM sign in the experimental group were lower than those in the control group, and the IDLV was larger than that in the control group, with significant difference ($P < 0.05$), as shown in Table 3.

Table 3
Comparison of left ventricular morphological indexes

Ultrasonic index	Experimental group (n=22)	Control group (n=24)	t-value/ χ^2 -value	P-value
LVFV (m/s)	1.6± 0.1	2.4± 0.2	6.942	<0.001
LVP (mmHg)	9.3± 0.3	12.3± 0.5	3.933	0.002
IST (mm)	8.8± 0.2	10.5± 0.3	3.912	0.001
SAM (n, %)	2 (9.09)	5 (20.83)	3.861	0.006
IDLV (mm)	30.7± 5.3	24.9± 4.2	3.257	<0.001
AR rate (%)	6.7± 0.5	9.5± 0.5	2.134	0.013
Note: LVFV, left ventricular flow velocity. LVP, left ventricular outflow tract pressure difference. IST, interventricular septal thickness. SAM, systolic anterior motion. IDLV, inner diameter of the left ventricular outflow tract. AR, aortic regurgitation.				

Comparison of the incidence of complications between the two groups.

In the experimental group, deep venous thrombosis occurred in 1 case. In the control group, 1 case of incision infection and 2 cases of deep venous thrombosis occurred. There was no significant difference between the experimental group (6.25%) and the control group (11.36%) ($\chi^2=0.579$, $P=0.447$).

Discussion

The Morrow operation is the gold standard for the treatment of HCM. Although Lekaditi Dimitra and others believe that medical drug treatment can improve the outcome, the effect is not as clear as that of the operation [6–7]. Havndrup, O et al. believe that compared with other treatments, the Morrow operation is still the best in terms of postoperative effects [8]. In experienced hospitals, the mortality rate with experienced cardiac surgeons is less than 1%. After the operation, they can obtain immediate and permanent improvement of clinical symptoms, a decrease in the LVOT pressure difference and improvement of the exercise stress response. The life span of patients in the operation group was essentially the same as that of normal individuals, which was better than that yielded by any other treatment method for obstruction.

Why 3D printing?

The risk of Morrow surgery is increased due to the relatively poor visualization of the left ventricular cavity and the heterogeneity of the LVOT anatomy. The incidence of postoperative complications of the Morrow operation for doctors who have not yet acquired experience is relatively high; such complications include injury to the conduction tract, damage to the atrioventricular wall, coronary artery injury, valve injury and even the occurrence of new-onset postoperative atrial fibrillation(POAF)[9].

In recent years, 3D printing technology has been increasingly widely used in complex heart disease surgery. Lee, M et al. believed that a 3D-printed heart model can be used to reconstruct the coronary artery anatomy and improve the understanding of coronary artery abnormalities^[10]. It has been proven that 3D printing technology can be widely used in congenital heart disease surgery. In the treatment of coronary heart disease and acquired valve disease, the curative effect is satisfactory^[11]. Jivanji, SGM, et al. studied the repair of aneurysm neck occluders and right ventricular outflow tract Venus P valves using a 3D-printed heart model. The encouraging findings of the simulation enabled them to plan complex surgical procedures effectively and achieve successful results^[12]. 3D printing can visually display the geometric relationship between the hypertrophic myocardium, papillary muscle, ventricular muscle band and mitral annulus with different colors and simulate myocardial resection in a 3D model to better grasp the scope of hypertrophic septum resection, define the position and length of the papillary muscle and abnormal ventricular muscle band, and formulate a better operation plan (Figure 2).

The intraoperative effect of 3D printing.

The results of this study showed that the operation time, cardiopulmonary bypass time, intraoperative blood loss and hospitalization time of the experimental group were significantly lower than those of the control group, suggesting that 3D printing of a heart model for extracorporeal simulation surgery for patients with LVOT obstruction is helpful to shorten the operation time and reduce surgical blood loss. The specific location, depth, direction and the best resection method for the stenosis can be determined before the operation, and the Morrow operation can be simulated on this basis. Surgeons can repeatedly test the resection on the model to determine the best resection range and depth. The simulation results can help to shorten the time of lesion resection in the actual operation and are also helpful for avoiding unnecessary exposure of the surgical field and the excessive anatomical bleeding caused by the formal operation, thus shortening the time necessary to search for the best resection site and depth in the operation (Figure 3).

The postoperative effect of 3D printing.

The results showed that the values of the LVFV, LVP, IST, AR rate and SAM-sign positive rate were lower in the experimental group than in the control group, and the IDLV was larger than that of the control group ($P < 0.05$). It is suggested that 3D printing of a cardiac model for in vitro simulated resection of a hypertrophic myocardium for the Morrow operation is helpful for patients with outflow tract obstruction to recover a better morphology and physiological anatomy and achieve an ideal long-term effect (Figure 4).

The advantage of fat stem cell treatment in patients with coronary heart disease.

It has been reported that the incidence rate of adult HOCM combined with CAD accounts for approximately 20% of HOCM. Huang, CH, et al. suggested that the risk of coronary heart disease with obstructive heart disease is higher whether interventional therapy or surgical treatment is applied^[13]. The sudden death rate and total mortality of HOCM with severe CAD were significantly higher than those of

HOCM alone. For patients with HOCM, CAD often aggravates the symptoms of angina pectoris and affects the prognosis of surgery. For patients with severe CAD, CABG should be performed at the same time. However, due to the hypertrophic myocardium, it is difficult to check the coronary artery and free blood vessels, so 3D printing technology can be used for preoperative evaluation (Figure 5).

The treatment advantage of fat stem cells in valvular disease.

For patients with HOCM complicated with valvular disease, hypertrophic ventricular muscle leads to valve changes. The common mitral valve problem is due to LVOT obstruction. The SAM of the mitral valve can contact the ventricular septum and produce dynamic subaortic occlusion. This problem can be solved by the Morrow operation. Lefebvre, XP and others studied the mechanism of mitral valve systolic forward motion in HCM under the condition of stable blood flow, which greatly facilitates completion of the Morrow operation^[14]. However, valvular disease (such as valve calcification) requires surgical treatment to correct the valve, which cannot be simply removed as myocardial tissue can^[15]. Therefore, preoperative 3D printing technology can simplify the repair of valvular disease by clarifying the scope and severity of the disease and simulating the operation (Figure 6).

The treatment advantage of fat infarction patients with atrial fibrillation.

We previously described a patient who had atrial fibrillation before surgery and needed modified maze surgery^[16]. For the preoperative evaluation of patients with fat infarction, it is necessary not only to evaluate the extent of resection but also to understand the shape of the nerve tracts in patients with fat infarction. Because fat infarction patients are different from general heart patients, their nerve path is different because of the change in the heart state, such as the wrong ablation position, which may affect the surgical effect. Therefore, 3D printing before surgery poses certain advantages for understanding the overall shape of the heart and the patient's nerve path.

Postoperative cardiac function.

In the past, many experts have said that too much cardiac tissue resection may lead to postoperative cardiac dysfunction^[17]. However, this study found that the LVOT diameter and wall thickness of the two groups were significantly improved compared with those of the control group ($P < 0.05$), but there was no significant difference in cardiac function between the two groups ($P > 0.05$). However, improvement of the LVOT can change the incidence of diseases related to the risk of an insufficient blood supply (e.g., stroke, myocardial insufficiency). Therefore, during the Morrow operation, with the aid of 3D printing technology, more cardiac tissue can be removed as much as possible without affecting the heart function of patients.

The disadvantages of 3D printing.

However, because the current 3D printing technology is caused by vascular perfusion imaging, the nerve conduction bundle cannot be displayed. Lau, IWW and other researchers found that even if 3D printing is perfect, it is still a serious defect to be unable to display the shape of the micro-nerve bundle^[18]. When we

try to remove hypertrophic myocardial tissue, it is difficult to detect the shape of the conduction beam and block conduction after the operation. This is a problem that 3D printing technology cannot solve. Therefore, in the experimental group and the control group, we found that there was no significant difference in the conduction block between the two groups ($P > 0.05$).

Conclusion

3D printing of the heart model can enable the doctor to more instinctively understand the patient's heart condition and make the operation more intuitive. The optimal scheme simulation before the operation can help to reduce the damage to adjacent nerves, blood vessels and other tissues during the operation and can decrease the surgical risk. In conclusion, a 3D-printed heart model for in vitro simulation surgery is conducive to creating a more reasonable surgical plan, which can reduce surgical trauma and operation time and is conducive to the recovery and maintenance of the heart.

Declarations

Availability of data and materials: For data sharing, please contact the corresponding author of this article.

Funding: The project was supported by the Beijing Municipal Science & Technology Commission (Z191100006619005), Peking University International Hospital Research Grant YN2019ZD01, The Affiliated Suzhou Hospital of Nanjing Medical University, Suzhou Municipal Hospital, Gusu School, and Nanjing Medical University Research Grant GSRCKY20210101. The funders had no role in the study design, data collection or analysis, decision to publish, or preparation of the manuscript.

Ethical statement: This study has been approved by the Hospital Ethics Committee, with the approval No.: ks2585. Patients in this study have signed written informed consent and obtained relevant reports and attached pictures from patients. All methods were performed in accordance with the relevant guidelines and regulations.

Acknowledgement: This work was supported by the Beijing Municipal Science & Technology Commission (Z191100006619005), Peking University International Hospital Research Grant (YN2019ZD01) and The Affiliated Suzhou Hospital of Nanjing Medical University, Suzhou Municipal Hospital, Gusu School, and Nanjing Medical University Research Grant (GSRCKY20210101).

Consent for publication: Not applicable.

Declaration of conflict of interest: None.

References

1. Ten Cate, FJ. Prognosis of hypertrophic cardiomyopathy. *J Insur Med.* 1996 ;28(1):42–5.

2. Mirza, SJ, Radaideh, GA. Pattern of left ventricular hypertrophy seen on transthoracic echo in patients with hypertensive cardiomyopathy when compared with idiopathic hypertrophic cardiomyopathy. *J Pak Med Assoc.*2013 Jan;63(1):16–9.
3. Eidem, BW, Lindor, NM, Driscoll, DJ. Resolution of neonatal hypertrophic cardiomyopathy in an infant with an affected mother. *Pediatr Cardiol.*1999;20(3):208–11.
4. Lee, S; Squelch, A; Sun, Z. Quantitative Assessment of 3D Printed Model Accuracy in Delineating Congenital Heart Disease. *Biomolecules.*2021 02 12;11(2).
5. Frank, DO, Zanation, AM, Dhandha, VH, McKinney, KA, Fleischman, GM, Ebert, CS, et al. Quantification of airflow into the maxillary sinuses before and after functional endoscopic sinus surgery. *Int Forum Allergy Rhinol.*2013 Oct;3(10):834–40.
6. Saltman, AE; Lahey, SJ; Francalancia, NA; Tselentakis, EV. Origin of atrial fibrillation in a patient who had undergone septal myectomy. *J Cardiovasc Electrophysiol.*2003 Jul;14(7):786; author reply 786-7.
7. Lekaditi, D; Sakellaropoulos, S. Myosin Modulators: The New Era of Medical Therapy for Systolic Heart Failure and Hypertrophic Cardiomyopathy. *Cardiology Research* Volume 12, Issue 3. 2021. PP 146–148.
8. Havndrup, O, Bundgaard, H, Hansen, FV, Pietersen, AH, Kelbaek, HS. Treatment of hypertrophic cardiomyopathy. *Ugeskr Laeger.*1998 Sep 14;160(38):5495–500.
9. Maaros, M, Pohjantähti-Maaroos, H, Halonen, J, Vähämetsä, J, Turtiainen, J, Rantonen, J, et al. New onset postoperative atrial fibrillation and early anticoagulation after cardiac surgery. *Scand Cardiovasc J.*2017 Dec;51(6):323–326.
10. Lee, M, Moharem-Elgamal, S, Beckingham, R, Hamilton, M, Manghat, N, Milano, EG, et al. Evaluating 3D-printed models of coronary anomalies: a survey among clinicians and researchers at a university hospital in the UK. *BMJ Open.*2019 03 08;9(3):e025227.
11. Hachulla, AL, Noble, S, Guglielmi, G, Agulleiro, D, Müller, H, Vallée, JP. 3D-printed heart model to guide LAA closure: useful in clinical practice? *Eur Radiol.*2019 Jan;29(1):251–258.
12. Jivanji, SGM, Qureshi, SA, Rosenthal, E. Novel use of a 3D printed heart model to guide simultaneous percutaneous repair of severe pulmonary regurgitation and right ventricular outflow tract aneurysm. *Cardiol Young.*2019 Apr;29(4):534–537.
13. Huang, CH, Chen, IC, Chiou, HC. Coronary stent graft for hypertrophic obstructive cardiomyopathy combined with coronary artery disease. *J Formos Med Assoc.*2003 Aug;102(8):574–7.
14. Lefebvre, XP, Yoganathan, AP, Levine, RA. Insights from in-vitro flow visualization into the mechanism of systolic anterior motion of the mitral valve in hypertrophic cardiomyopathy under steady flow conditions. *J Biomech Eng.*1992 Aug;114(3):406–13.
15. Ohkado, A, Kitamura, M, Hachida, M, Nishinaka, T, Hanayama, N, Sato, W. Hypertrophic obstructive cardiomyopathy with abnormalities of the mitral valve complex. *J Heart Valve Dis.*1997 Jan;6(1):60–2.
16. Sayed, SA, Katewa, A, Srivastava, V, Jana, S, Patwardhan, AM. Modified radial v/s biatrial maze for atrial fibrillation in rheumatic valvular heart surgery. *Indian Heart J.*2014;66(5):510–6.

17. Obase Kikuko; Maemura Koji; Matsumaru Ichiro; Eishi Kiyoyuki. Left ventricular outflow tract obstruction related to systolic anterior motion of anomalous secondary chords. *Eur J Cardiothorac Surg.* 2021 ;7(12):255.
18. Lau, IWW, Liu, D, Xu, L, Fan, Z, Sun, Z. Clinical value of patient-specific three-dimensional printing of congenital heart disease: Quantitative and qualitative assessments. *PLoS One.*2018;13(3):e0194333.

Figures

Figure 1

The process of resection of hypertrophic myocardium by 3D-printed model. A. 3D-printed model of the hypertrophic myocardium before the operation. B. 3D-printed model of the resection site after the operation. C. Resected myocardial tissue model. D. Myocardial tissue excised according to 3D-printed model.

Figure 2

3D rendering of LVOT obstruction before surgery. A. Different colors can be used to display the heart regions directly, which is helpful to distinguish the tissue components. B. The LVOT is extracted from the 3D reconstruction of the heart, which is convenient for understanding the shape of the LVOT, the location of stenosis and the relationship of the surrounding tissues.

Figure 3

Comparison of the 3D printing thoracoscopic effect of patients with LVOT obstruction before and after the operation. A. 3D printing video-assisted thoracoscopy can show obstruction of the LVOT, which indicates severe stenosis and hypertrophy of the ventricular septum. B. After 3D printing, the LVOT obstruction was significantly improved, the diameter was significantly widened, and more hypertrophic tissue was removed. LVOC, left ventricular outflow channel, VS, ventricular septum.

Figure 4

3D printing of preoperative and postoperative results in LVOT obstruction. A. 3D printing of coronary sections of patients with outflow tract obstruction showed severe stenosis of the outflow tract and hypertrophy of the ventricular septum. B. 3D printing of coronary cross sections of outflow tract obstruction showed that the outflow tract was significantly improved, the diameter was widened, and ventricular septal hypertrophy was reduced. C. 3D reconstruction of the LVOT in patients with outflow tract obstruction before 3D printing indicated severe stenosis. D. 3D reconstruction of the LVOT in patients with outflow tract obstruction after 3D printing indicated that the stenosis was significantly improved. LVOC, left ventricular outflow channel.

Figure 5

3D printing of the heart and coronary artery. A. According to the various parts, different colors were marked to display the 3D structure of the heart, and the RCA was clearly displayed. B. The left and right hearts were dissected as a whole to understand the shape of the coronary artery. PH, pulmonary heart, RCA, right coronary artery, CA, cor arteriosum.

Figure 6

The 3D-printed heart shows the calcified area of the valve. A. The coronary position can be used to determine the area covered by calcification, indicating that there are obvious calcifications in the aortic valve and mitral valve, and the range of involvement is wide. B. The relationship between the calcified valve and pulmonary artery and vein can be identified in the sagittal view, and the depth of calcification invasion, which is not easy to find in the operation field, can be determined. VCA, valve calcification area.