Value of transesophageal echocardiography in device closure of perimembranous ventricular septal defects in children via ultraminimal intercostal incision

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Research

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Abstract

Background

Investigate the value of transesophageal echocardiography (TEE) in pediatric perimembranous ventricular septal defect (PmVSD) closure which via a left parasternal ultra-minimal intercostal incision.

Methods

190 children with PmVSD were performed device occlusion via ultraminimal intercostal incision. TEE is used throughout the perioperative period, including preoperative accurate TEE assessment, TEE-guided localization of the puncture site, intraoperative TEE guidance, and postoperative immediate TEE assessment.

Results

186 children with PmVSD underwent successfully device closure and operation success rate is 97. 89%. The average size of PmVSDs was 3.98 ± 1.14 mm, and the average device size was 5 ± 1 mm. Preoperative TEE revealed 127 patients had single-orifice PmVSDs and 59 patients had multiple orifices shunts PmVSDs. During the operation, the surgeon readjusted the device or replaced the larger device in 17 cases due to TEE displayed abnormal indications, and all other children went smoothly. After operation, there are 17 cases of slight residual shunts, 13 cases of pericardial effusion and 4 cases of pleural effusion, and all were back to normal during the 4- month follow-up period. Mild mitral regurgitation was reported in 1 patient and remained the same during the follow-up period. Right ventricular outflow tract obstruction in a patient significantly improved. No other complications were found.

Conclusions

Under the guidance of TEE, PmVSDs can be successfully closed via ultraminimal intercostal incision in children. TEE can effectively guide the device occlusion of PmVSD. The role of TEE is very important and it act as the surgeon’s eyes.

Introduction

The transesophageal echocardiography (TEE) has developed rapidly[1−8]due to clearer image[9, 10]. TEE-guided transthoracic minimally invasive perimembranous ventricular septal defect (PmVSD) closure has wide indications and many advantages[10−13] in children. On the basis of the simple and feasible surgical method, it is a trend that the surgical incision is continuously minimized. Our team performed PmVSDs closure in children via a left parasternal ultra-minimal intercostal (LPUMI) incision (the 4th or 5th intercostal spaces) [10]. The incisional length was ≤ 1 cm(minimum 0.6 cm). The surgical incision without cutting the sternum is smaller, more cosmetic, and fewer complications. However, the ultra-minimal incision limits the range of motion of the guide wire and the sheath, which leads to more difficult to operate. Therefore, a successful procedure relies on accurate evaluation and guidance by TEE doctor[10]. This study aimed to investigate the value of TEE in pediatric PmVSD closure via a left parasternal ultra-minimal intercostal LPUMI incision.

Materials And Methods

1. General data

From January 2015 and December 2019, under the guidance of TEE, 186 children with PmVSDs successfully underwent device closure via a LPUMI incision in 190 children. This is a retrospective study. Informed consent was obtained from all of the guardians of the patients.

All of the patients were free of oropharyngeal abnormalities, esophageal abnormalities, recent upper gastrointestinal surgeries and hemorrhages, respiratory dysfunction, aortic arch and branch abnormalities, and cervical spine injuries and abnormalities[14].

2. Surgical inclusion criteria and exclusion criteria

The patients were diagnosed with PmVSDs suitable for closure surgery based on the TEE examination results. The inclusion criteria included patients with restrictive PmVSDs, the upper edge of which was ≥ 2 mm from the aortic valve, and without obvious organic lesions in the tricuspid valve. The exclusion criteria applied to patients with malalignment-type ventricular septal defects (VSDs), or atrioventricularseptal defects, or severe pulmonary hypertension or other surgical contraindications, or combinations with other cardiac malformation or tricuspid valve organic lesions that require surgical treatment under direct visualization with cardiopulmonary bypass (CPB).

3. Ultrasound machine and application of TEE

A Philips IE33 echocardiography machine with a S7-3t probe (Philips Ultrasound, Inc., 22100 Bothell Everett Highway, Bothell WA. 98021 – 8431 USA) was used in this study. TEE was used throughout the ultra-minimally invasive perioperative period. The position and angle (from 0° to 180°) of the TEE probe could be adjusted according to different surgical procedures. The clearest views were selected according to the actual situation. Usually, the four-chamber view, the short-axis view and the long-axis view of the left ventricle were used.

4. Application of TEE in pediatric PmVSDs closure via LPUMI incision

4.1 Preoperative TEE assessment and device selection

After the patients were anesthetized, TEE doctor evaluated carefully the following conditions on the basis of TEE images. First, whether there were other intracardiac malformations that could not be occluded were confirmed. Second, location of the PmVSD and the distance from the upper edge of the defect to the aortic valve. Third, the evaluations of the defect morphology, including the shape, tricuspid valve adhesion, fibrous tissue hyperplasia, formation of an aneurysm of the membranous septum (AMS), PmVSD of left ventricular to right atrial shunt (LV-to-RA) [15] (Fig. 1), the number of shunt orifice, and the direction of the shunt. Fourth, the sizes of PmVSDs at left ventricular side and the right ventricular side of or (and) the sizes of multiple shunt orifices were measured separately. The size of the defect was measured on multiple sonographic views, and the maximum diameter was recorded.

Then, according to the discussion between TEE doctor and surgeon based on the examination results, the appropriate minimally invasive approach and proper occluder were chosen. In this study, the LPUMI incision and concentric occluder were selected. The right and left disks are both 2 mm larger than the waist in all parts of the device. The size of the device was generally 0.5–1.5 mm larger than the maximum diameter of the defect.

4.2 Intraoperative localization via TEE

After pericardium hanging, the TEE doctor used TEE and guided the surgeon to select the appropriate puncture site on the right ventricle surface according to the location of the VSD and the direction of blood flow. The surgeon gently pulled the heart and moved the tweezers tip to the anterior wall of the right ventricle for localization. TEE images can clearly show the high echo of the tweezers tip and the inward convex right ventricular wall. If the defect and the tweezers tip cannot be displayed in the same view, the TEE doctor should adjust TEE view properly to guide the surgeon to adjust. In general, the site where the tweezers tip’s high echo was aligned with the defect was the puncture site, also the site for placing the purse-string suture. However, in special cases, such as the PmVSD blood flow into the right atrium through the tricuspid valve (LV-to-RA)[15], two shunt orifices of the PmVSD forming a 180° angle(Fig. 2), or an irregular and tunnel-like VSD, etc., the site for right ventricular puncture should be selected according to the specific situations to ensure a smooth operation.

4.3 Intraoperative TEE guidance

When the puncture needle was inserted into the right ventricle, TEE could display its weak echo (Fig. 3A). The stylet of the puncture needle was withdrawn, and the guidewire was inserted into the right ventricle. TEE could clearly show the strip-shaped high echo of the guidewire. It is important for the TEE doctor to identify the echo of the guidewire tip (not only the cross section of the middle portion of the guidewire) in the right ventricle using multiple different views (Fig. 3B). Under TEE guidance, the guidewire tip was advanced toward the VSD, passed through the defect, and smoothly entered the left heart.

After withdrawal of the puncture needle, the TEE view displaying the entire wire was selected. The guidewire was always displayed as a soft curve and usually displayed flaky blurred shadow behind the guidewire, which resembled a waterfall (known as the “waterfall” sign). when the delivery sheath (including a dilator) was inserted into the ventricle along the guidewire, the echo of guidewire appeared thicker and lost the soft curvature and became stiff, and the “waterfall” sign became lighter or disappears (Fig. 3C). The TEE doctor must pay attention to the position of the sheath tip and guide the surgeon. When the sheath tip passed completely through the defect, the TEE doctor must remind the surgeon to push the sheath slowly forward 1-2cm more and located the tip at the left ventricular outflow tract. If doctors can’t confirm whether the delivery sheath has entered the left ventricle and safely reached the left ventricular outflow tract, a part of the dilator could be withdrawn so that the delivery sheath could showed as a double tube shadow. Thus, the position of its tip could be easily identified. When the TEE image ensured its tip suspended in the left ventricular outflow tract (Fig. 3D), the dilator and the guide wire were both withdrawn completely.

The loading sheath, including an occluder, was connected to the delivery sheath, and the device was pushed inward within the sheath. When the device was push into the right ventricle, TEE displayed its high echo. TEE can observe the device that through the defect and into the left ventricle in real time. The left disk of the device was released from the sheath, and the sheath was withdrawn further back toward the right ventricle. Then, the waist and the right disk were completely released, and the device disks were clamped on the edge of the defect.

During surgery, TEE doctor payed constant attention to other all kinds of unusual changes of ultrasound images. For example, if TEE shows arrhythmia, the TEE doctor should promptly inform the anesthesiologist ask the surgeon to pause the operation if necessary.

4.4 Immediate TEE evaluation after surgery

After the deployment of device disks being completed, TEE was performed immediately to inspect and evaluate the results. The following conditions should be inspected: shape and position of the occluder, residual shunts, device-related valvular injury, and pericardial effusion, and so on. When an abnormality is found, the TEE doctor should assess the severity and inform the surgeon to discuss the treatment plan together. When the right disk of the device appears in the shape of “mushroom pedicle” (Fig. 3E), or the aortic regurgitation (AR) and tricuspid regurgitation (TR) are aggravated, or detachment of the device or a significant residual shunt is observed, the TEE doctor should tell the surgeon to re-adjust the device or to replace a occluder. After 2 failed attempts, it should be suggested the procedure was converted to open surgery under CPB.

If there is no obvious abnormality, the device must be tested repeatedly by the push-pull maneuver under TEE guidance to ensure successful device closure of the VSD. The delivery cable of the device is released under TEE monitoring only when it is in its proper position with no complications. Repeated TEE is performed with multiangle views. If no abnormality is identified, the procedure is completed.

5. Follow-up

The follow-up exams, including transthoracic echocardiography (TTE), Electrocardiogram, X-rays and blood tests, were used to assess heart function, heart rhythm, occluder placement, residual shunt, valve regurgitation, infective endocarditis, thrombus and pericardial effusion.

6. Statistical analysis

The datas of age, weight, PmVSD size, and procedure duration were normally distributed and were expressed as the mean ± standard deviation and range, as appropriate. The data of device size was non-normally distributed and were expressed as the median ± interquartile range and range, as appropriate. All data were analyzed using SPSS 20.0 statistical software.

Results

186 children underwent successfully device closure of PmVSD through a ultraminimal intercostal incision under the guidance of TEE in 190 cases. Operation success rate is (97.89)%. Baseline characteristics of patients who underwent successfully PmVSD closure are listed in Table 1 (Tab.1).

During the perioperative period, all patients with successful surgery had good cardiac function. No blood transfusion, severe arrhythmia, or deaths were reported. And no obvious gastroesophageal damage or respiratory depression was found. After surgery, mild TR or no TR existed, and no aggravation of aortic regurgitationor was found. The results of Preo- , intra- and postoperative TEE of patients who underwent successfully PmVSD closure are listed in Table 2 (Tab.2). By postoperative TTE examination, 17 patient was found to have the pericardial effusion and the pleural effusion within less 7th day after surgery. Right ventricular outflow tract obstruction occurred in 1 case on the 3rd day after surgery. Short-term complications that disappeared within less 4 months are listed in Table 3 (Tab.3).

All of the patients were followed up for a period ranging from 4 months to 5 years after the operation. Follow-up exams showed good placement of the occluder, no residual shunts, good heart function, no complete atrioventricular block, no infective endocarditis and no thrombus. Right ventricular outflow tract obstruction significantly improved and its flow velocity reduced from 3.1m/s to 2.0m/s. The emerging mild mitral regurgitation remained the same. Device-related aortic regurgitation and TR were not found.

In 4 patients, the device closure of PmVSDs was converted to repair surgery under CPB after failure of two attempts at device closure. The reasons were as follows: mild to moderate AR caused by device placement; dislocation of a device during the push-pull maneuver; severe arrhythmia during the operation; and the failure of the guide wire to pass through a small defect.

Discussion

The clear images of TEE[9,10] and the ability of displaying the intracardiac structures in real time cause TEE to act as the eyes of the surgeon. Preoperative TEE can be performed to accurately evaluate VSDs and related conditions, and the TEE doctor and surgeon discuss the selection of an appropriate surgical plan and an occluder. Intraoperative TEE can performed precise position and effectively guide device to close the VSDs and can reduce the operative time, increase the success rate of surgery, and reduce the risks. Postoperative TEE can immediately be performed to carefully and comprehensively evaluate and ensure the success and safety of the procedure.

The process of the guide wire advancing into the left ventricle from the right ventricle through the defect is key to the success and the determinant of the procedure duration. If the puncture site in the right ventricular surface is positioned incorrectly, the guide wire is difficult to enter the left ventricle. The puncture site must be relocalized. If the localization is accurate, and the shape of the PmVSD is appropriate, the process of the guide wire advancing into the left ventricle ventricle can be completed within a few seconds. However, the puncture site must be avoid being located near the coronary artery to prevent damaging the coronary artery. The surgeon can see the coronary artery through the ultraminimal incision. Such result cause a certain angle between the puncture site and the VSD inevitably, and can increase the difficulty of the procedure. If the angle is too wide, the intercostal incision can be appropriately extended.

PmVSDs have a variety of shapes due to hyperplasia of the right ventricular fibrous tissue and the adhesion of tricuspid valve. The defects can have an irregular tunnel-like shape, multiple shunts orifices in the right ventricular side, and various directions of blood flow. In this situation, it is more difficult to perform the PmVSD closure via the LPUMI incision under the guidance of TEE. When selecting a puncture site, it is necessary to consider that the site can facilitate the guide wire to entering the left ventricle through the defect. Completion of the closure is fully dependent on the monitoring and guidance of TEE and the experience of the TEE doctor and surgeon. Skillful cooperation is critical to the success. Sometimes, the two orifices in the AMS are far apart and even form a flat angle. In this condition, both the orifices and the VSD presented at a 90° angle. If the guide wire is completely aligned with a orifice, it is not difficult to insert the guide wire into AMS, but it is very difficult to enter the left ventricle by 90° rotation. Under the guidance of TEE, a puncture site and direction is selected with a certain angle with both the VSD and the shunt orifice to make easier of inserting the guide wire into the left ventricle (Fig. 2A). In “S-shaped” or “semiannular” tunnel-like membrane defects, it is necessary to frequently adjust the direction of the guide wire tip to pass the defect. During the procedure, the TEE doctor guides the surgeon according to the TEE images to change the directions of the guide wire in real time and to advance the guide wire smoothly to pass these unusual defects. With patience and tacit collaboration, experienced TEE doctor and surgeon can complete some challenging PmVSD’s device closure.

When the delivery sheath was advanced into the left ventricle, TEE was used to guide the sheath to reach the left ventricular outflow tract but not to contact the aortic valve or the anterior mitral leaflet during the cardiac cycle to prevent valve damage. It must be noted that the device can only be released if the delivery sheath is located in the left ventricular outflow tract. If the device is released in the left atrium, mitral orifice, or aorta, it is likely to cause damage to the valves and/or the chordae tendineaes, resulting in mitral or aortic regurgitation. one child undergoing the procedure in the early stage of this study had a small amount of mitral regurgitation after surgery, beceace the delivery sheath was inserted too deeply and deployment of the left disk of the device caused the rupture of chordae tendineae.

According to the TEE results, the appropriate occluder is selected to avoid device displacement or residual shunts caused by an undersized device and to avoid aortic regurgitation and TR caused by an oversized device. If the upper edge of the PmVSD is less than 2 mm from the aortic valve, it is recommended to use an eccentric device to close the VSD. However, it is difficult for TEE to assess defects and measure distances occasionally due to irregular shapes caused by adhesion of the right ventricular fibrous tissue and tricuspid valve. And it may lead to unsuccessful closure. In our study, a patient with a PmVSD size of 6 mm by TTE measurement underwent finally VSD repair under CPB because mild to moderate AR was present after the VSD was closed with a #7 concentric occluder or a #7 eccentric occlude in turn. Another patient with a PmVSD size of 5.5 mm by TTE measurement underwent finally VSD repair under CPB because the #6 or #8 concentric occluder was detached or migrated respectively, during the push-pull maneuver, and an obvious residual shunt was present.

During device closure of a tunnel-like defect, TEE showed that the occluder resembles a “mushroom pedicle”, indicating that the right disk was still located in the tunnel and has not been fully deployed. The surgeon necessarily retracted the right disk and pulled tensely the sheath to fully deploy the right disk. After the deployment of the device disks was completed, the device was tested by the push-pull maneuver under TEE guidance to ensure successful closure of the VSD.

When the interventricular septum at the edge of the VSD is thin, a residual shunt can be present within the device. When the device disks can not cover all of the shunt holes in the right ventricular septum, a residual shunt can be present at the its edge. At this moment, the residual shunt condition should be carefully evaluated, and the appropriate treatment method should be selected according to the size and the flow rate of the residual shunt. If the residual shunt at the edge of the device is > 2 mm with high-speed flow, a larger device should be selected, or repair surgery should be performed under CPB. A small residual shunt (≤ 2 mm [16] with a flow rate < 2.5 m/s) can all be cured spontaneously. In this study, it is found that in children with multiple shunts orifices in AMS, even a small residual shunt with flow velocity > 2.5 m/s exists after occluder, the device can be released if the device is stable. And the residual shunt tends to heal gradually. The right ventricular outflow tract obstruction significantly decrease during the 4th month’s follow-up. It may be related to the shape of the device getting better with heart beats and right ventricular outflow tract widening with growing .

Limitations

This study was limited by being a single-center study. Our hospital is a children’s hospital and the age of the research subjects was between 10 months and 127 months old. This study is not a prospective randomized study, we just reviewed the previous results and draw the conclusion about the important value of TEE.

Conclusions

In conclusion, under the guidance of TEE, children with PmVSDs successfully underwent device closure via LPUMI incision. TEE is used throughout the perioperative period for preoperative assessment, intraoperative localization, intraoperative guidance, and immediate postoperative evaluation. The TEE doctor participates in the complete process of the procedure and collaborates closely with the surgeon as a team for completion of the procedure.

Abbreviations

TEE
transesophageal echocardiography
PmVSD
perimembranous ventricular septal defect
LPUMI
left parasternal ultra-minimal intercostal
VSD
ventricular septal defects
CPB
cardiopulmonary bypass
TTE
transthoracic echocardiography
AMS
aneurysm of the membranous septum
LV-to-RA shunt
left ventricular to right atrial shunt
AR
aortic regurgitation
TR
tricuspid regurgitation

Declarations

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Authors' contributions

Jin Yu, Jingjing Ye: Conception and design, performed echocardiography, analysis and interpretation of data, drafting and final approval of manuscript. Zewei Zhang, Lianglong Ma: Conception and design, performed Surgery, analysis and interpretation of data, final approval of manuscript. Xiuzhen Yang, Jingjing Qian, Lei Zhao：Collection and interpretation of data, performed echocardiography, final approval of manuscript. Jie Jin：performed Surgery, manuscript revision, final approval of manuscript.

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Availability of data and materials The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Our study was approved by the ethics committee of the Children's Hospital, Zhejiang University School of Medicine. Informed consent was obtained from all of the guardians of the patients.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Tables

Tab. 1: Baseline characteristics of patients who underwent successfully PmVSD closure.

Variables	Values
Sex (F/M)	90/86
Age (months)	36.68±24.15 (range: 10-127)
Weight (kg)	13.89±4.90 (range: 7.7-36)
PmVSD size (mm)	3.98±1.14 (range: 2-8)
Device size (mm)	5 ± 1 (range: 4–9)
Procedure duration (min)	58.56±27.65 (range: 26–170)

PmVSD: Perimembranous ventricular septal defect

Tab. 2: The results of Preo- , intra- and postoperative TEE of patients who underwent successfully PmVSD closure

Item	Number of patients
Preoperative TEE	
Single-orifice PmVSDs (common defects, AMS with single-orifice, tunnel-like defects, etc.)	127
Irregular tunnel-like PmVSDs (semiannular, S-shaped, etc.)	4
Multiple shunts orifices on the right ventricular side of AMS	59
Two shunts orifices forming a 180° angle	3
PmVSDs with partly or fully LV-to-RA shunt	17
With mild tricuspid regurgitation	6
With mild to moderate tricuspid regurgitation	9
With moderate tricuspid regurgitation	2
Intraoperative TEE	
Readjustment of the device	13
Right disk of "mushroom pedicle"	2
Aggravation of AR or TR	6
Obvious residual shunts	5
Replacement of the larger device	4
Postoperative TEE	
Mild mitral regurgitation	1
Slight residual shunts (diameter < 2 mm)	17
With flow velocity < 2.5 m/s	14
With flow velocity ≥ 2.5 m/s	3

TEE: transesophageal echocardiography; PmVSD: Perimembranous ventricular septal defect; AMS : aneurysm of the membranous septum; LV-to-RA shunt: left ventricular to right atrial shunt

Tab. 3: Short-term complications that disappear within less 4 months.

item	Number of patients
Slight residual shunts	17
Disappear within 7 days	13
Disappear within 4 months	4
Pericardial effusion	13
Disappear within 15 days (mild)	10
Disappear within 10 days (moderate)	1
Disappear within 60 days (severe)	2
Pleural effusion	4
Disappear within 3 months (mild)	3
Disappear within 3 months (moderate)	1

Figures

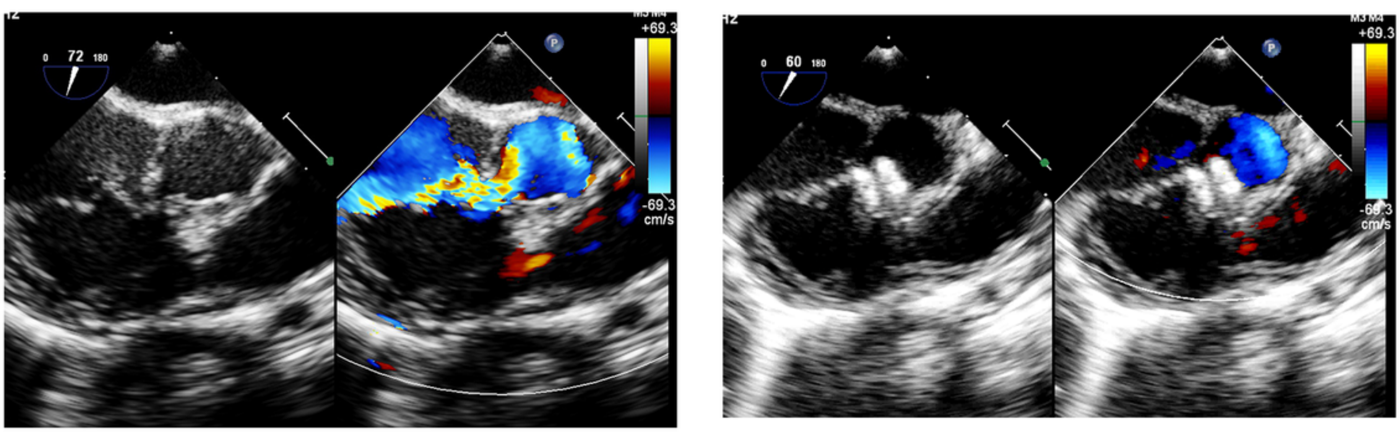

Figure 1

A: Perimembranous ventricular septal defect with LV-to-RA shunt B: Under the guidance of TEE, PmVSD with LV-to-RA shunt was closed successfully via ultraminimal intercostal incision, and there was only a very small amount of TR after the operation

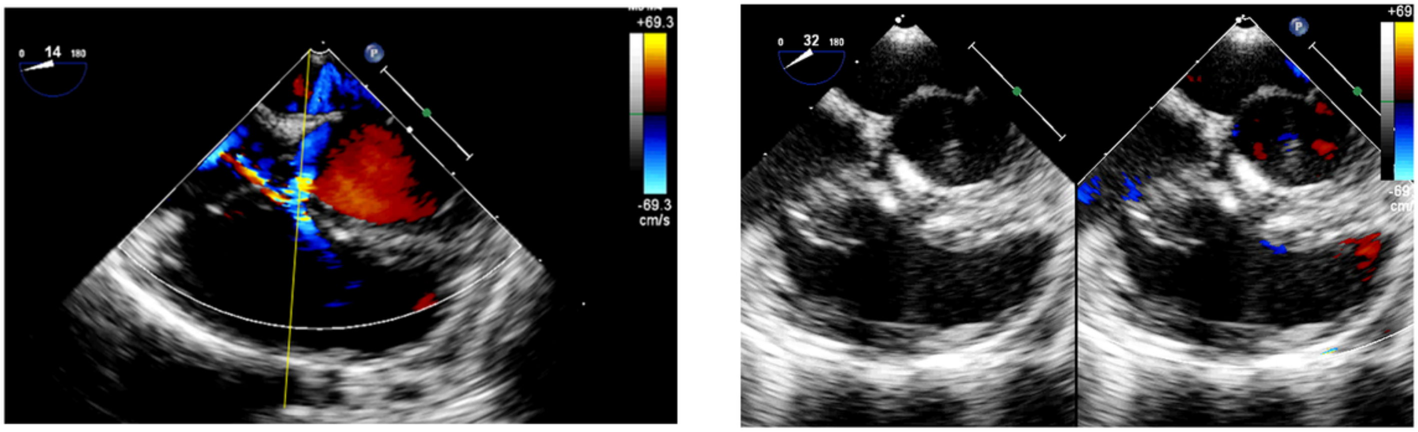

Figure 2

A: Perimembranous ventricular septal defect with two orifice shunts forming a 180° angle. The yellow line represents the direction in which the wire enters. B: Under the guidance of the TEE, PmVSD with two orifice shunts forming a 180° angle was closed successfully via ultraminimal intercostal incision.

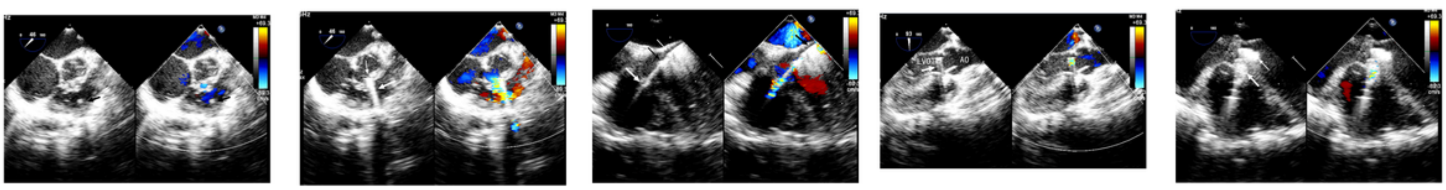

Figure 3

Some of the steps and precautions： A：The TEE image seems to show the echo of the puncture needle(arrow). B： TEE clearly shows the high echo of the guidewire (thick arrow) and the guidewire tip (thin arrow). C：The long guidewire (black thick arrow) presents a soft curve with a waterfall-like shadow behind the guide wire. After insertion of the delivery sheath (including a dilator sheath), TEE displayed that the "guidewire" became thicker, lost its soft curvature, became stiff, and the "waterfall" sign behind it disappeared (white thick arrow). TEE shows the delivery sheath tip (black thin arrow) and the dilator tip (white thin arrow). D：The delivery sheath tip was kept in the left ventricular outflow tract (arrow). E：TEE displayed that the left disk of the device was completely released (thin arrow) and the right disk of the device appears in the shape of “mushroom pedicle” (thick arrow).