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ORIGINAL RESEARCH

Transcatheter Device Closure of Perimembranous and Intracristal Ventricular Septal Defects in Children: Medium- and Long-Term Results

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BACKGROUND: In children, the practice of transcatheter closure of intracristal ventricular septal defect (icVSD) has been limited. Currently, there is a lack of comparison between device closure of perimembranous ventricular septal defect (pmVSD) and icVSD, and long-term clinical outcomes are rare.

METHODS AND RESULTS: This study included a total of 633 children (39 with icVSD and 594 with pmVSD), aged 18 months to 16 years, who underwent transcatheter closure of ventricular septal defect between January 2014 and December 2018. All patients were followed up until September 2020, with a median follow-up of 46 months in the pmVSD group and 52 months in the icVSD group. The procedural success rate was 96.3% and 84.6% in pmVSD and icVSD groups, respectively (P=0.002). The median of age, weight, procedure time, fluoroscopic time, and radiation dose were greater in the icVSD group compared with the pmVSD group. More eccentric ventricular septal defect occluders were used in the icVSD group. Most adverse events were minor without any intervention, with cardiac rhythm/conduction abnormalities being the most common. In the pmVSD group, 2 patients experienced complete atrioventricular block, with one implanting a permanent pacemaker and the other dying of cardiac arrest secondary to reversible complete atrioventricular block 40 days postprocedure. Complete left bundle-branch block occurred in 14 patients, and 12 cases were transient. In the icVSD group, no complete atrioventricular block or death occurred, and one patient developed transient complete left bundle-branch block.

CONCLUSIONS: In selected patients, transcatheter device closure of pmVSD and icVSD can be performed safely and successfully, with excellent medium- and long-term results in children.

Key Words: intracristal ■ perimembranous ■ transcatheter closure ■ ventricular septal defect

Ventricular septal defect (VSD) is the most common congenital heart defect and can be categorized as perimembranous, inlet, muscular, and infundibular types, according to location of defect within the septum.[1] Perimembranous VSD (pmVSD) accounts for around 70% of VSD. Transcatheter device closure of pmVSD has been widely performed, especially in developing countries, with acceptable mortality and morbidity.[2–5] There have been growing concerns about the long-term safety and efficacy of the transcatheter approach. Infundibular VSD can be classified as intracristal VSD (icVSD) or subpulmonary VSD. The latter is considered a contraindication for device closure.[6,7] Transcatheter closure of icVSD has recently been studied and reported in a few of the large experienced heart centers of China,[6–8] although experience in transcatheter closure of icVSD remains limited. There has been no comparison of clinical outcome for transcatheter device closure of pmVSD and icVSD in children, and rare long-term follow-up results

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CLINICAL PERSPECTIVE

What Is New?

- This is the first study of transcatheter closure of intracristal ventricular septal defect (VSD) and a comparison between device closure of intracristal VSD and perimembranous VSD exclusively in children; both procedures can be performed safely and successfully, with excellent medium- and long-term results.

What Are the Clinical Implications?

- Compared with perimembranous VSD, transcatheter closure of intracristal VSD was more technically difficult, and more eccentric VSD occluders were used.
- Most adverse events associated with transcatheter closure of perimembranous VSD and intracristal VSD were minor without any intervention; the transcatheter approach offers an effective alternative for selected patients.

Nonstandard Abbreviations and Acronyms

AR	aortic regurgitation
ADO II	Amplatzer Duct Occluder II
cAVB	complete atrioventricular block
CLBBB	complete left bundle-branch block
CRBBB	complete right bundle-branch block
icVSD	intracristal ventricular septal defect
pmVSD	perimembranous ventricular septal defect
TR	tricuspid regurgitation
TTE	transthoracic echocardiography

for icVSD closure. Therefore, this retrospective study compared the safety and efficacy of transcatheter closure of pmVSD and icVSD in children, and evaluated the medium- and long-term clinical outcomes in these patients.

METHODS

The data that support the findings of this study are available from the corresponding author on reasonable request.

Patients

From January 2014 to December 2018, a total of 633 consecutive children, aged 18 months to 16 years, with pmVSD or icVSD and undergoing attempted transcatheter device closure at our center were enrolled in our study. Before the procedure, all subjects received transthoracic echocardiography (TTE) and were evaluated by standard echocardiographic protocol. The inclusion criteria were as follows: (1) age ≥2 years or weight ≥10 kg; (2) clinical symptoms, such as growth retardation, recurrent respiratory infections, and heart failure, without improvement on medications; (3) hemodynamically significant VSD (left atrial enlargement and left ventricular volume overload); (4) maximum diameter of VSD ≤16 mm by TTE; (5) defect located at 9- to 12-o'clock (pmVSD) or 12- to 1:30-o'clock (icVSD) positions in the short-axis parasternal view of TTE; (6) pulmonary artery systolic pressure <70 mm Hg by TTE; and (7) absence of cardiac lesions needing open heart surgery. According to the anatomical position of VSD in TTE, patients were divided into pmVSD group (594 cases, defect located at 9- to 12-o'clock position in the short-axis parasternal view of TTE) and icVSD group (39 cases, defect located at 12- to 1:30-o'clock position in the short-axis parasternal view of TTE). Written informed consent was acquired from each child's guardian before the procedure. The Ethics Committee of Shandong Provincial Hospital Affiliated to Shandong First Medical University approved the study protocol. The study complied with the Declaration of Helsinki.

Devices Used

The devices used in this study were the modified double-disk VSD occluders (Shanghai Shape Memory Alloy, Shanghai, China; Lifetech Scientific, Shenzhen, China; Starway Medical, Beijing, China) and the Amplatzer Duct Occluder II (ADO II) device (St. Jude Medical, St. Paul, MN) (Figure). The modified double-disk VSD occluder has 3 subtypes: symmetric occluder, eccentric occluder, and thin-waist occluder. In the symmetric occluder, the diameter of both disks is 4 mm larger than that of the waist. In the eccentric occluder, the aortic flange of the left disk is 0 mm larger than the waist, whereas the opposite flange is 6 mm larger than the waist. In the thin-waist occluder, the diameter of the left disk is 8 mm larger than that of the waist. The right disk of both eccentric and thin-waist occluders is the same as that of the symmetric occluder. The ADO II device has a center disk 6 mm smaller than either of the 2 peripheral disks. The length of the center disk is either 4 or 6 mm.

If the distance from the defect to the aortic valve was <2 mm, eccentric occluder was usually selected. Otherwise, other occluders were used. However, if the left disk of device can be placed within the aneurysmal tissue, a noneccentric occluder may be used even if the distance from the defect to the aortic valve

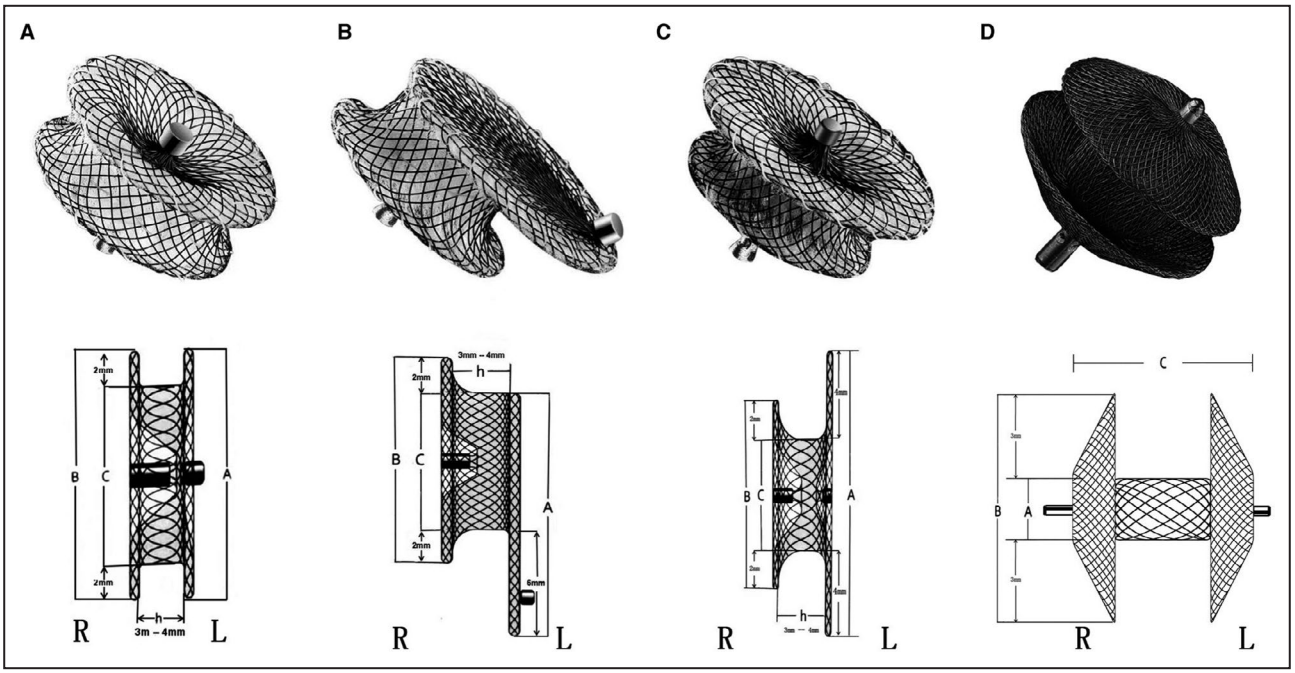

Figure 1. The various occluders and corresponding schematic diagrams.
A, Symmetric occluder. **B**, Eccentric occluder. **C**, Thin-waist occluder. **D**, Amplatzer Duct Occluder II. L indicates left; and R, right.

was <2 mm. The thin-waist occluder was mostly used to close a larger aneurysmal pmVSD with multiple outlets. The use of ADO II generally required a minimum distance of 3 mm from the defect to the aortic valve and a maximum defect diameter of 4 mm.

According to our experience, the selected device size of symmetric and eccentric occluders was usually 2 to 4 mm larger than the defect diameter on angiography, and that of the ADO II device was usually 1 to 2 mm larger than the defect diameter, whereas the diameter of the left disk of the selected thin-waist occluder should generally be at least equal to or greater than the inlet diameter of the membranous aneurysms.

Percutaneous Closure Procedure

The procedure was performed under general anesthesia for patients aged <14 years and under local anaesthesia (lidocaine) for patients aged ≥14 years. The femoral arterial and venous accesses were obtained, and then heparin (100 IU/kg) was administered intravenously. Standard right and left cardiac catheterization was performed to calculate shunting flow and pulmonary vascular resistance. Left ventricular (LV) angiography in long axial oblique view (60° left anterior oblique/20° cranial) was performed to detect the shape, location, size of the defect, and the distance from the defect to aortic valve. A 5 Fr partly cut pigtail or right coronary artery guiding catheter was used to pass through the defect via the femoral artery. In most cases, the establishment of an arteriovenous track was needed. Through a long delivery sheath (4–10 Fr), the selected device was deployed. Angiography was repeated in LV and ascending aorta to confirm appropriate device position, verify complete closure of defect, and screen for any new-onset aortic valve regurgitation. In addition, TTE was performed to ensure that there was no obstruction of tricuspid and aortic valve function by the device before the device was released. The procedure time was defined as the time from puncture of the femoral artery and vein to removal of the sheath at the end of the procedure.

After the procedure, continuous ECG telemetry monitoring was performed for all patients during their hospitalization. All subjects underwent conventional ECG, chest X-ray, and TTE 1 day after the procedure and 24-hour Holter monitoring before discharge. For patients who developed new-onset atrioventricular block, complete left bundle-branch block (CLBBB), or complete right bundle-branch block (CRBBB) after the procedure, intravenous dexamethasone was administered at a dosage of 0.5 to 1.0 mg/kg (maximum, 10 mg) daily for 3 to 5 days and then tapered gradually (intravenous dexamethasone or oral prednisone) over 2 weeks. If there were no adverse events, patients were discharged 5 to 7 days after the procedure. All patients were prescribed aspirin (3–5 mg/kg daily) for 6 months.

Follow-Up Protocol

The follow-up physical examinations, ECG, chest X-ray, and TTE were scheduled at 1, 3, 6, and 12 months after the procedure and yearly thereafter. In addition,

24-hour Holter monitoring was performed for patients who presented with postprocedure atrioventricular block or CLBBB at each outpatient review. Follow-up data were collected up to September 2020.

Statistical Analysis

Statistical analysis was performed using the SPSS software version 25.0 (SPSS Inc, Chicago, IL). Data were expressed as counts and/or percentages for categorical variables and as mean±SD or median with range for continuous variables. Comparisons were performed by χ^2 test, Student *t* test, ANOVA, and Wilcoxon rank-sum test. Univariate analysis using Cox proportional hazard regression analysis was performed to study the role of independent variables on the occurrence of adverse events in the early period and during the follow-up. Proportional hazards assumption test based on Schoenfeld residuals was evaluated. $P<0.05$ was considered statistically significant.

RESULTS

Procedural Data

In pmVSD and icVSD groups, the procedure was successfully performed in 572 patients (96.3%) and 33 patients (84.6%), respectively. The successful closure rate was notably different between the 2 groups ($P=0.002$). In the pmVSD group, the finally used occluder size was 83.1% consistent with the planned size, whereas that was 72.7% in the icVSD group. The general characteristics of both groups are listed in Table 1. The age, weight, procedure time, fluoroscopic time, and radiation dose were greater in the icVSD group than the pmVSD group. The median distance from the defect to the aortic valve was 0 mm in icVSD group, which was notably closer than the pmVSD group (2 mm; $P=0.000$). Therefore, more eccentric occluders were used in the icVSD group. In the pmVSD group, membranous aneurysms were observed in 433 patients (72.9%), of which 312 (72.1%) had aneurysmal tissue involving the tricuspid valve. Among the 424 successful pmVSD patients with membranous aneurysms, the left disk of device was placed within the aneurysmal tissue in 113 cases (26.7%). In both groups, both LV end-diastolic diameter and left atrial diameter decreased significantly 1 day after procedure (Table 2). We also found that in both groups, there was no significant difference in the cardiothoracic ratio 1 day after procedure compared with that before procedure ($P>0.05$), whereas there was significant difference at the last follow-up

Table 1. General Characteristics

Characteristics	icVSD	pmVSD	*P* Value
Women, n (%)	18 (46.2)	285 (48)	0.825
Age, y	4.3 (3.1–7.5)	3.1 (2.8–4.9)	0.001
Weight, kg	18.0 (15.0–24.5)	15.0 (13.5–19.0)	0.001
Defect diameter by TTE, mm	3.9 (3.0–4.6)	3.8 (3.0–5.0)	0.517
Defect diameter on angiography, mm	3.3 (2.5–4.1)	3.5 (2.5–5.0)	0.178
Distance from defect to aortic valve, mm	0 (0–1)	2 (1–3)	0.000
Procedure time, min	100 (70–130)	70 (60–90)	0.001
Fluoroscopic time, min	16.4 (11.3–25.3)	10.5 (6.5–17.0)	0.000
Radiation dose, mGy	154.0 (79.0–315.0)	91.5 (57.8–146.9)	0.000
Dosage of contrast medium/weight, mL/kg	4.5 (3.7–4.6)	4.3 (3.4–4.8)	0.900
Procedural success rate, n/total (%)	33/39 (84.6)	572/594 (96.3)	0.002
Devices used in successful procedures, n	33	572	
Device diameter used in successful procedures, mm	6 (6–8)	6 (5–8)	0.336
Device type used in successful procedures, n (%)			0.000
Symmetric	4 (12.1)	404 (70.6)	
Eccentric	29 (87.9)	56 (9.8)	
Thin waist	0	49 (8.6)	
ADO II	0	63 (11.0)	
Known aortic valve prolapse before procedure, n (%)	15 (38.5)	19 (3.2)	0.000
Known aortic regurgitation before procedure, n (%)	9 (23.1)	11 (1.9)	0.000

Data are given as median (25^{th} percentile–75^{th} percentile), unless otherwise indicated. ADO II indicates Amplatzer Duct Occluder II; icVSD, intracristal ventricular septal defect; pmVSD, perimembranous ventricular septal defect; and TTE, transthoracic echocardiography.

Table 2. LVEDD and LAD Before and 1 Day After Procedure

Variable	icVSD			pmVSD		
	Before Procedure	1 d After Procedure	*P* Value	Before Procedure	1 d After Procedure	*P* Value
LVEDD, mm	3.74±0.50	3.47±0.43	0.021	3.66±0.39	3.41±0.38	0.000
LAD, mm	2.41±0.39	2.24±0.34	0.040	2.34±0.33	2.16±0.3	0.000

Data are given as mean±SD. icVSD indicates intracristal ventricular septal defect; LAD, left atrial diameter; LVEDD, left ventricular end-diastolic diameter; and pmVSD, perimembranous ventricular septal defect.

compared with that before procedure and 1 day after procedure ($P<0.05$).

In the pmVSD group, 22 patients' procedure failed because of the following: significant device-related aortic regurgitation (AR)[9]; significant residual shunts, despite use of a larger occluder[6]; easy dislodgment of the device even using a larger device,[3] one of which also presented a partial tear of the right aortic valve; complete atrioventricular block (cAVB) after closure[2]; severe tricuspid regurgitation (TR) after device deployment[1]; and obvious tricuspid stenosis after occluder placement.[1]

In the icVSD group, the procedure failed in 6 patients. Four patients had significant device-related AR (with a partial tear of the right aortic valve in one case), and 2 had easy dislodgment of the device even when using a larger device.

Follow-Up Evaluation and Adverse Events

In the pmVSD group, because of the loss of follow-up in 33 patients, data were collected from 539 patients (94.2%), with a median follow-up duration of 46 months (range, 20–80 months). In the icVSD group, all 33 patients (100%) completed follow-up, with a median follow-up time of 52 months (range, 24–80 months). In the Cox proportional hazard regression analysis, we included sex, age, weight, and device type. However, no variable was significantly associated with the occurrence of adverse events between the 2 groups (icVSD versus pmVSD; hazard ratio, 0.74; 95% CI, 0.41–1.31; $P=0.297$). During the procedure and follow-up, all adverse events are reported in detail below.

Residual Shunt and Hemolysis

Residual shunts were categorized into 2 size groups: mild (<2 mm) and moderate (2–3 mm). A total of 72 (12.1%) patients had mild shunts and 12 (2.0%) patients had moderate shunts identified via TTE 24 hours postprocedure in the pmVSD group. At the final follow-up, a moderate residual shunt was present in 3 (0.5%) patients and a mild residual shunt was present in 24 (4.0%) patients. Three patients who had mild residual shunts failed to follow up. Hemolysis occurred in 11 (1.8%) patients, with only 1 needing blood transfusion. Ten of the 11 patients had hemolysis within 24 hours, and the eleventh occurred within 48 hours after device implantation. Hemolysis resolved spontaneously within 1 week in all subjects.

Only 3 (7.7%) patients in the icVSD group had a mild residual shunt 24 hours postprocedure. All 3 shunts were resolved by last follow-up. No hemolysis occurred in the icVSD group.

Cardiac Rhythm/Conduction Abnormality

Cardiac rhythm/conduction abnormality after procedure in the 2 groups is shown in Table 3. Incomplete right bundle-branch block was the most common rhythm/conduction abnormality found. In the pmVSD group, 150 patients (25.3%) developed postprocedure rhythm/conduction abnormalities, with cAVB in 2 (0.3%) and CLBBB in 14 (2.3%). The vast majority of the rhythm/conduction abnormalities were transient, leaving persistent abnormalities in only 27 patients (4.5%). One patient with CRBBB and 5 patients with incomplete right bundle-branch block failed to follow up.

A 3-year-old girl developed cAVB 5 days after the placement of a 10-mm eccentric occluder. After 18 days of dexamethasone and isoprenaline administration, the patient returned to sinus rhythm before relapsing back to cAVB a year later. A permanent pacemaker was implanted in this patient 2 years after her transcatheter procedure. Another cAVB occurred in a 4-year-old boy 1 day after the placement of a 6-mm thin-waist occluder. He received temporary pacemaker implantation and corticosteroid therapy for 11 days before his cAVB had transitioned to CRBBB. Unfortunately, he died of cardiac arrest secondary to cAVB 40 days postprocedure. The parents of both patients with cAVB refused surgical occluder removal.

Among the 14 patients with CLBBB, 13 developed CLBBB within 1 week and 1 developed CLBBB 6 months following the procedure. In 2 of these patients, device removal with surgical repair of VSD was performed at 6 and 40 days postprocedure, respectively. Both patients returned to normal cardiac conduction after surgery. Last, 2 patients from this group experienced persistent CLBBB with normal LV end-diastolic diameter and LV ejection fraction.

In the icVSD group, postprocedure rhythm/conduction abnormality occurred in 9 patients (23.1%) without occurrence of cAVB. One patient with CLBBB recovered normal conduction after corticosteroid therapy.

Valve Complications

In the pmVSD group, new-onset AR and TR occurred in 27 (4.5%) and 45 (7.6%) patients, respectively. In the icVSD group, 2 patients (5.1%) presented with new-onset AR and 1 patient (2.6%) had TR. Most of the new-onset regurgitations were resolved by the last follow-up. Remaining regurgitation that persisted was noted to be mild, with no indication for treatment (Table 4).

In the pmVSD group, 6 patients had AR before procedure and 22 patients had TR. AR disappeared in 4 cases and TR relieved or resolved in 21 cases postprocedure. In the icVSD group, 4 of the 5 patients with known AR preprocedure had resolution of their AR after closure of defect. In both groups, valvular regurgitation was not aggravated after procedure (Table 4).

Each of the 2 failed groups had one patient experiencing moderate AR caused by iatrogenic injury of the right aortic valve. They then underwent aortic valve repair combined with surgical repair of VSD. Both patients had mild right coronary prolapse and regurgitation before procedure, and the distance between their defect and the right coronary valve was 0 mm.

A 3-year-old boy with pmVSD was hypotensive after the release of the 6-mm eccentric occluder during procedure. TTE showed significant tricuspid stenosis, so emergency thoracotomy was performed. During the operation, the occluder was observed to be clamping the tricuspid septal valve and chordae tendineae. The occluder was then removed, and the defect was repaired.

Death

No pericardial tamponade and deaths occurred during procedure. Two patients with pmVSD died after procedure and during follow-up (0.3%). One died from postprocedure cAVB, as mentioned above, whereas another 3-year-old girl developed diffuse subarachnoid hemorrhage an hour after transcatheter closure with 7-mm symmetric occluder and died 11 days later. It was speculated that the cause of death might be possible congenital cerebral vascular malformation, which could have caused intracranial hemorrhage when the patient was emerging from anesthesia.

Results of ADO II Use

A total of 63 patients had successfully transcatheter retrograde closure of pmVSD via the femoral artery with ADO II. Of these patients, 35 had aneurysmal

Table 3. New-Onset Rhythm/Conduction Abnormality After Procedure and Outcome of Follow-Up

Abnormality	icVSD		pmVSD	
	New Onset After Procedure	Last Follow-Up	New Onset After Procedure	Last Follow-Up
First-degree AVB	0	0	1	0
Second-degree AVB	0	0	2	0
Third-degree AVB	0	0	2	2
IRBBB	2	1	79	16
CRBBB	1	0	17	5
LAH	1	1	6	2
CLBBB	1	0	14	2
Nonparoxysmal junctional tachycardia	2	0	12	0
Junctional rhythm	0	0	5	0
IRBBB+nonparoxysmal junctional tachycardia	2	0	8	0
CRBBB+nonparoxysmal junctional tachycardia	0	0	1	0
CRBBB+LAH	0	0	1	0
LAH+nonparoxysmal junctional tachycardia	0	0	1	0
Ventricular escape rhythm	0	0	1	0

AVB indicates atrioventricular block; CLBBB, complete left bundle-branch block; CRBBB, complete right bundle-branch block; icVSD, intracristal ventricular septal defect; IRBBB, incomplete right bundle-branch block; LAH, left anterior hemiblock; and pmVSD, perimembranous ventricular septal defect.

Table 4. Preprocedure and Postprocedure AR and TR and Follow-Up Results

Variable		icVSD			pmVSD			
		New Onset After Procedure	Last Follow-Up	Present Before Procedure	Last Follow-Up	New Onset After Procedure	Last Follow-Up	Present Before Procedure	Last Follow-Up
AR	Trivial	2	1	4	1	22	9	4	2
	Mild	0	0	1	0	4	3	2	0
	Mild to moderate	0	0	0	0	1	1	0	0
TR	Mild	1	0	0	0	39	15	15	1
	Mild to moderate	0	0	0	0	4	1	5	0
	Moderate	0	0	0	0	2	0	2	0

AR indicates aortic regurgitation; icVSD, intracristal ventricular septal defect; pmVSD, perimembranous ventricular septal defect; and TR, tricuspid regurgitation.

tissue over the pmVSD, and the left disk of ADO II was placed within the aneurysmal tissue only in 5 cases. One patient developed intermittent CLBBB on the fourth day after the procedure and recovered sinus rhythm 2 days later. ECG and 24-hour Holter monitoring were normal during the 3-year follow-up. Other rhythm/conduction abnormalities included CRBBB in 1 case, incomplete right bundle-branch block in 6 cases, and nonparoxysmal junctional tachycardia in 2 cases. Except for one case with CRBBB, the other rhythm/conduction abnormalities returned to normal during follow-up. A mild residual shunt was present in 2 patients 24 hours after the procedure and 1 disappeared during follow-up. One patient developed mild AR, and 6 patients developed mild TR, after the procedure. During follow-up, TR in 5 patients disappeared, and TR in 1 patient and AR in 1 patient both relieved. There were no other complications.

Other Complications

In one patient of the pmVSD group, the device migrated to the descending aorta the day after the procedure. It was retrieved percutaneously, and a larger device was implanted successfully. In addition, groin hematomas were shown in 4 patients with pmVSD. In the icVSD group, no other complications were present.

DISCUSSION

Current studies on transcatheter closure of VSD are limited to pmVSD, with few studies on icVSD, especially in children. A pioneering study was reported to close some type of doubly committed subarterial VSDs using Nit Occlud Lê VSD coil.[9] The frequency of AR 24 hours and 6 months postprocedure was both high (39.4% and 33.3%, respectively), and the residual shunt did not appear to have a tendency to decrease with time during the 6-month follow-up. As far as we know, this is the first study of transcatheter closure of icVSD and the comparison for device closure of icVSD and pmVSD exclusively in children. The present study shows evidence that percutaneous device closure of pmVSD is effective and safe, with excellent long-term outcome. In select patients, transcatheter closure of icVSD using modified double-disk VSD occluder is feasible and safe, with favorable long-term results. Severe adverse events associated with transcatheter closure of pmVSD or icVSD were rare.

The success rate of icVSD closure was relatively lower than that of pmVSD. The main cause was the 0-mm distance between the defects and the aortic valve, which was associated with aortic valve prolapse and regurgitation. This was likely to have affected the aortic valve after placement of the occluder. The procedure time, fluoroscopic time, and radiation dose

in the icVSD group were greater compared with the pmVSD group. The probable reason was that the defect position of icVSD was higher and thus it was difficult to press the distal part of the delivery sheath into LV. The eccentric occluders were preferred in these patients, keeping the platinum marker on the left disk toward the apex. Moreover, because the defect was often partially covered by the right aortic valve, it was difficult to confirm the defect size by TTE and angiography, which caused the estimated diameter of the defect to be too small. Therefore, in some cases, it was necessary to repeat with a larger occluder during procedure. Overall, transcatheter closure of icVSD is technically more difficult than pmVSD.

In our study, the vast majority of complications were minor, without needing any intervention. Among all adverse events, cardiac rhythm/conduction abnormalities were the most common, whereas other common events included residual shunt and valve regurgitation.

The incidence of rhythm/conduction abnormality following VSD closure is relatively high, but the outcome remains satisfactory, as most were transient.[10] In our study, the most frequent rhythm/conduction abnormality was incomplete right bundle-branch block. At the last follow-up, the incidence of persistent rhythm/conduction abnormality was 4.5% in the pmVSD group and 5.1% in the icVSD group. cAVB has been considered to be the most serious complication,[2,11] with rate of incidence gradually decreasing to 1% in recent years.[12–14] CLBBB draws more attention because definite proof from clinical and experimental studies has identified that CLBBB might cause abnormal LV contraction and deteriorate LV function, which could induce progressive LV remodeling and heart failure.[15] Special attention was paid to the possibility of recurrence and late onset of cAVB and CLBBB. In our cohort, 2 patients had recurrence of cAVB after initial resolution; 2 patients with CLBBB developed reversible CLBBB, and 1 patient developed CLBBB at 6 months postprocedure. Careful ECG examination may be mandatory throughout follow-up as a result of the recurrence and late onset of cAVB and CLBBB.

The cardiac conduction system is close to the margins of the defect, and the conduction bundle tends to be injured by the pressure of the catheter or device. Therefore, the most likely mechanism of postprocedure rhythm/conduction abnormality may be mechanical compression and inflammatory edema of the conduction bundle.[12] Recent reports have identified occluder size and diameter difference between occluder and defect as independent risk factors for occurrence of postprocedure heart blocks.[10,15] Thus, oversized occluders should be avoided. Late-onset and recurrent heart block seemed to be more difficult to recover from.[12,15] The outcome of our study was consistent with this theory. Studies have proved that steroid therapy has an encouraging effect on the recovery of early heart block after VSD closure, and the conduction system might return to sinus rhythm after surgical occluder removal in cases presenting with early cAVB associated with VSD closure.[16,17] Two of our cases with CLBBB underwent surgical occluder removal together with defect repair 6 and 40 days postprocedure, respectively. Both were restored to normal conduction. However, whether the conduction system recovers after surgical occluder removal is still unclear, particularly for patients with recurrent and late-onset cAVB and CLBBB. When surgical occluder removal should be performed in patients with postprocedure cAVB and CLBBB remains obscure. According to current literature and our experience, surgical occluder removal in patients with early cAVB and CLBBB after device closure of VSD may allow recovery of normal conduction.

Valvular regurgitation, especially AR, was another major concern in VSD closure.[3] Several possible causes of AR are: injury or edema of aortic valve induced by the procedure and contact between the occluder and aortic valve, especially in patients with combined primary aortic valve prolapse. In our failure cases, 66.7% of the icVSD group and 40.9% of the pmVSD group were attributed to significant device-related AR. In this study, both cases of aortic valve tear were in patients with known aortic valve prolapse and regurgitation before procedure. Therefore, special attention should be paid to those with aortic valve prolapse attributable to increased risk of aortic valve injury secondary to repeated pressing of the distal part of the delivery sheath into LV and establishment of an arteriovenous track. In a few patients, the distal part of the delivery sheath was difficult to be pressed into LV. This caused the left disk of the occluder to be released in the ascending aorta, which increased the chance of damage to the aortic valve. Therefore, we recommend such procedures be performed by skilled physicians in experienced centers to avoid technical complications.

No surgery was performed for patients with significant TR in this study. Moderate-to-severe TR was usually caused by the injury of tricuspid chordae tendineae during the establishment of an arteriovenous track or caused by the occluder encroaching on the tricuspid valve. In the current study, 65.2% and 51.7% of new-onset postprocedural TR and AR were found to have reduced or resolved during follow-up, respectively. At the final follow-up, all AR and TR were less than moderate without any intervention. There have been previous reports of late onset of AR and TR requiring surgery, so close follow-up for valve regurgitation was also required after VSD closure.[3] Most of the preprocedure TRs and ARs were also noted to have resolved or improved (TR, 95.4%; AR, 72.7%) after procedure. The outlet of

the membranous aneurysmal VSD often adhered to the tricuspid valve. Therefore, after placement of the occluder, the occluder's right disk may clamp the leaflet or chordae tendineae of the tricuspid valve, which could result in tricuspid stenosis. This usually induced a blood pressure decrease and heart rate increase, which can sometimes be mistaken for the effect of the delivery sheath. Hence, thorough TTE by an experienced sonographer was required before the occluder could be released. In this study, one patient underwent emergency surgery with significant tricuspid stenosis and decreased blood pressure after the release of the occluder.

In our cohort, 65.5% of residual shunts disappeared during follow-up, probably attributable to gradual endothelialization around the occluder. All hemolysis was transient and resolved after medication treatment, with no cases needing surgical retrieval of the occluder or a second interventional procedure to close the residual shunt.

In our center, transesophageal echocardiography guidance was used during the procedure in the early stage of transcatheter pmVSD closure and later it was gradually replaced by TTE. TTE guidance was used during the procedure in this study. Although transesophageal echocardiography can show the location and morphological features of the defect more accurately compared with TTE, it may increase the pain of the patients and complicate the procedure, which may increase the procedure time. With the increasing maturity of TTE monitoring technology, we believe that replacing transesophageal echocardiography with TTE in VSD device closure in children will not increase the incidence of complications.

Compared with pmVSD, transcatheter closure of icVSD was more technically difficult. First, it was difficult to press the distal part of the delivery sheath into LV. If this process failed, the left disk of the eccentric occluder would need to be released in the ascending aorta, which would make the adjustment of the platinum marker on the left disk toward the apex more difficult. Second, conventional LV angiography usually cannot clearly define the size of the defect.[6,8] In our experience, the defect could be visualized relatively clearly after placing the delivery sheath with a combination of TTE and LV angiography. Finally, the device size of our selection of eccentric occluders was 2 to 4 mm larger than the defect diameter in general. If the defect was >5 mm, a device with its size 4 to 6 mm larger than the defect diameter was usually chosen.

Limitations

There are some limitations in our study. First, this is a nonrandomized and retrospective study, including data from a single center. Moreover, the sample size of patients with icVSD was not large enough for the analysis to be convincing, although the results were consistent with clinical practice. Future prospectively designed studies with larger sample size and involvement of multiple centers would be necessary to confirm the results from this study.

CONCLUSIONS

Transcatheter device closure of pmVSD is effective and safe, with excellent results and long-term outcome. In experienced centers and select patients, percutaneous closure of icVSD is feasible and safe, with favorable long-term results. Most adverse events associated with transcatheter closure of pmVSD and icVSD were mild and generally manageable. The transcatheter approach provides a promising alternative to conventional surgical repair for pmVSD and icVSD.

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Disclosures

None.

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