Comparing Clinical Efficacy and Quality of Life Between Transesophageal Echocardiography-Guided and X-Ray Guided Percutaneous Occlusion in Adults With Secundum Atrial Septal Defect

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AIM: This study aims to compare the clinical efficacy and quality of life between transesophageal echocardiography (TEE)-guided and X-ray-guided percutaneous closure in adults with secundum atrial septal defect (ASD).

METHODS: A retrospective cohort study was conducted on 130 adults with secundum ASD who underwent percutaneous closure in our hospital between January 2022 and January 2024. The patients were divided into an observation group (TEE-guided, n = 58) and a control group (X-ray-guided, n = 72). The patients were followed up for 12 months, and their baseline characteristics, operation success rate, ventricular function parameters, postoperative complications and the 36-Item Short Form Health Survey (SF-36) quality of life scores were comparatively analyzed.

RESULTS: Compared to the control group, the observation group had shorter procedure times, higher rates of successful primary closure, shorter hospital stays, and lower early residual postoperative diversion rates ($p < 0.05$). There were no significant differences in baseline right ventricular end-diastolic volume index (RVEDVi), right ventricular end-systolic volume index (RVESVi), right ventricular ejection fraction (RVEF), left ventricular end-diastolic volume index (LVEDVi), left ventricular end-systolic volume index (LVESVi), and left ventricular ejection fraction (LVEF) between the two groups ($p > 0.05$). However, 3 months after surgery, both groups showed improvement in biventricular function, with the observation group exhibiting better right ventricular functional parameters (RVEDVi, RVESVi, RVEF) than the control group ($p < 0.05$). Furthermore, the overall complication rate was significantly lower in the observation group than in the control group ($p < 0.05$). There was no significant difference in pre-procedure SF-36 scores between the two groups ($p > 0.05$); however, 12 months after surgery, SF-36 scores in all domains increased in both groups, with the observation group scoring higher ($p < 0.05$).

CONCLUSIONS: In treating adult secundum ASD, TEE-guided percutaneous ASD closure yields superior clinical outcomes compared to the X-ray-guided method regarding procedural efficiency, reduction of early residual shunts, recovery of right ventricular function, relief of complication, and improvement in quality of life.

Keywords: percutaneous closure; transesophageal echocardiography; atrial septal defect; clinical efficacy; quality of life

Introduction

Atrial septal defect (ASD) is among the most common congenital heart diseases observed in adults. It results from improper development of the atrial septum during embryogenesis, creating an abnormal passage between the right and left atria [1,2]. Hemodynamically, ASD is characterized by a left-to-right shunt, and over time, this shunting can lead to right atrial and ventricular enlargement, pulmonary arterial hypertension, and atrial arrhythmias [3]. ASD can be classified into four types based on its anatomical location and embryologic origin: (1) Secundum type (75%–80%): Located in the fossa ovalis, this condition often reflects excessive absorption of the primary septum or hypoplasia of the secondary septum. (2) Primum type (15%–20%): A form of atrioventricular septal defect commonly coexists with a cleft in the anterior leaflet of the mitral valve. (3) Sinus venosus type (5%–10%): Found near the junction of the superior vena cava and right atrium, this form is frequently accompanied by anomalous pulmonary venous drainage. (4) Coronary sinus type (rare): Results from a defect in the roof of the coronary sinus, forming a direct communication between the left atrium and the coronary sinus [4].

ASD often presents without symptoms during childhood and early adulthood, particularly in cases of small defects. In infants, higher pulmonary vascular resistance limits left-to-right shunting, frequently rendering characteristic heart murmurs inaudible or absent, and affected individuals typically remain asymptomatic. Symptoms usually manifest when defects are larger (with diameters often exceeding 10 mm). Common clinical manifestations in adult patients in-

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clude decreased exercise tolerance, progressive exertional dyspnea, and rapid atrial arrhythmias such as atrial fibrillation and atrial flutter, diagnosed through echocardiography, cardiac Magnetic resonance imaging (MRI), and other imaging approaches [5,6]. In recent years, the management paradigm for ASD has shifted from invasive surgical repair to minimally invasive percutaneous closure; while open surgical intervention was once the standard, advancements in catheter-based technology and occlusion devices have emerged with percutaneous closure as the preferred approach for secundum ASD [7]. Compared to thoracotomy, percutaneous closure offers the advantages of lower perioperative morbidity and mortality, shorter hospital stays, and rapid recovery [8].

Precise imaging guidance is crucial for achieving technical success in percutaneous ASD closure. Traditionally, fluoroscopy or echocardiography has been predominantly utilized for this purpose [9–11]. Fluoroscopically guided percutaneous ASD closure has become a standard procedure, with studies demonstrating high success rates and low complication rates in both pediatric and adult populations [12,13]. It is critical to note that percutaneous intervention has strict anatomical indications: international guidelines explicitly restrict percutaneous closure to secundum-type ASD, where the condition presents with regular morphology and intact marginal tissues, facilitating precise device positioning and deployment under fluoroscopic or ultrasound guidance, while primum-type, sinus venosus-type, and unroofed coronary sinus-type ASD still require surgical repair [14]. However, radiation exposure during fluoroscopy poses risks to patients and healthcare providers, and iodinated contrast agent administration carries potential risks of allergic reactions and contrast-induced nephropathy [15,16]. Furthermore, fluoroscopy's limited soft-tissue resolution can hinder real-time assessment of device-tissue interactions, making it more challenging to confirm accurate occluder positioning and stability, thereby increasing procedural risks [17,18]. In contrast, transesophageal echocardiography (TEE)-guided closure has gained traction due to its multiplanar imaging capabilities, enabling precise assessment of defect morphology and device placement while eliminating ionizing radiation [19,20]. Nevertheless, TEE-guided interventions demand substantial echocardiographic expertise and may extend anesthesia time, potentially amplifying anesthesia-related risk [20].

A recent comparative pediatric study revealed no significant differences in procedural success rates between TEE- and fluoroscopy-guided approaches. However, TEE guidance reduced radiation exposure, obviated the need for contrast agents, shortened procedural time, and improved ASD sizing accuracy [21]. Notably, in adult congenital heart disease populations, unique anatomical challenges, including frequent atrial dilation and thinner septal tissues, may significantly alter the effects of different imaging approaches [6].

Despite these considerations, current evidence infers from pediatric cohorts, and there is a lack of direct comparison between TEE-guided and X-ray-guided percutaneous interventional occlusion in the adult with secundum ASD. Therefore, this retrospective cohort study compared perioperative outcomes, mid-term efficacy, and quality-of-life indicators in adult patients undergoing percutaneous ASD closure guided by either TEE or fluoroscopy. By analyzing the advantages and limitations of these two imaging-guided approaches, this study aims to identify a minimally invasive and safer imaging-guided surgical strategy.

Materials and Methods

Research Subjects

This retrospective analysis included 130 adult patients with secundum ASD who underwent percutaneous interventional closure at Taizhou Hospital of Zhejiang Province Affiliated to Wenzhou Medical University between January 2022 and January 2024. Out of these patients, 72 underwent X-ray-guided percutaneous closure, and 58 received TEE-guided intervention. This study was approved by the Taizhou Hospital of Zhejiang Province Affiliated to Wenzhou Medical University Ethics Review Board and strictly adhered to the principles outlined in the Declaration of Helsinki. Informed consent was obtained from all patients participating in the study.

Inclusion and Exclusion Criteria

The inclusion criteria for patient selection were defined as follows: (1) Echocardiographically confirmed secundum-type ASD, with a defect measuring between 5 mm and 36 mm. (2) Patient aged $\geq$18 years. (3) Hemodynamically significant left-to-right shunting at the atrial level, accompanied by evidence of right heart volume overload. (4) Adequate tissue around the defect; $\geq$5 mm from the defect margin to the coronary sinus, superior/inferior vena cava, and pulmonary veins; $\geq$7 mm from the defect margin to the atrioventricular valves. (5) An interatrial septum diameter exceeding the left atrial disc diameter of the selected occlusion device.

Exclusion criteria were defined as follows (1) Diagnosis of other congenital cardiac malformations (e.g., ventricular septal defect, patent ductus arteriosus). (2) Comorbid valvulopathy or cardiomyopathy. (3) Active infective endocarditis or hemorrhagic disorders. (4) Intracardiac thrombus at the intended device implantation site or venous thrombosis at catheter access sites. (5) Severe cardiac comorbidities (e.g., decompensated heart failure, refractory arrhythmias, pericardial disease). (6) Significant dysfunction of major organ systems (pulmonary, hepatic, or renal insufficiency). (7) Active malignancy or acute systemic infections. (8) Incomplete clinical data due to study withdrawal, inter-hospital transfer, or loss to follow-up.

Therapeutic Methods

All procedures in both groups were performed by physicians from the same interventional cardiology team, each having received standardized training to ensure homogeneity in surgical treatments. All operators were certified in cardiovascular interventional therapy and congenital heart disease intervention, as granted by the National Health Commission of China.

Observation (TEE-guided) group: Patients were positioned supine, and a Philips IE33 ultrasound system (Philips Medical Systems, Andover, MA, USA) was employed for TEE imaging. Following general anesthesia, a multiplane TEE probe was inserted to obtain precise preoperative measurements, including the maximum ASD diameter, superior/inferior vena cava rim length, aortic rim length, total interatrial septal length, and minimal distances from the defect margins to critical structures. The right femoral vein was accessed using the Seldinger technique, and a 5F venous sheath was placed; systemic anticoagulation was initiated with intravenous heparin (100 U/kg). Under real-time TEE guidance, a 0.035-inch hydrophilic guidewire was advanced to the junction of the superior vena cava and right atrium. A multipurpose catheter was then navigated across the ASD into the left atrium, with positional confirmation in standardized TEE views (four-chamber and aortic short-axis). A stiff guidewire was subsequently positioned, and an appropriately sized delivery sheath (8–12F, selected based on occluder dimensions) was advanced into the left atrium. The Amplatzer duct occluder (ADO-I; St Jude Medical, St Paul, MN, USA) was deployed under multiplanar TEE monitoring, first expanding the left atrial disc to ensure parallel alignment with the septum, followed by deployment of the right atrial disc after sheath retraction. Device stability was rigorously assessed using the "push-pull test" and Doppler evaluation to exclude any residual shunting (>2 mm). After confirming that the atrioventricular valve function was uncompromised, the device was detached by rotating the delivery cable counterclockwise. Finally, the sheath was withdrawn, the femoral vein puncture site was compressed and bandaged, and the femoral artery pulsation and bleeding at the puncture site were monitored.

Control group: Under local infiltrative anesthesia or conscious sedation, patients underwent continuous electrocardiographic monitoring and were imaged under fluoroscopic guidance (Siemens Artis Zee system, Siemens Healthineers, Erlangen, Germany). The right femoral vein was accessed using an identical Seldinger technique, and a pigtail catheter was positioned in the right atrium for contrast-enhanced angiography (iohexol 350 mgI/mL, 15 mL/s) to delineate ASD morphology and dimensions. A 0.035-inch hydrophilic guidewire was advanced across the ASD under fluoroscopic guidance (left anterior oblique 45° with cranial tilt 20°), followed by placement of a delivery sheath. The Amplatzer occluder (Abbott, St. Paul, MN, USA) was deployed by first releasing the left atrial disc confirmed in anteroposterior projection and right atrial disc positioning in lateral projection. After deployment, the contrast was reinjected into the right atrium to exclude significant residual shunting (>2 mm) and coronary artery compression. Sheath removal and hemostasis were conducted identically to the TEE-guided group, with manual compression applied to the femoral puncture site.

Observation Indicators and Data Collection Procedures

Trained researchers collected patient data using a standardized process, which included:

(1) Baseline clinical data: It included demographics and anthropometrics (age, gender, body mass index (BMI)), ASD characteristics (defect diameter and anatomical features), employment status, ASD classification, comorbidities, and New York Heart Association (NYHA) functional class defined as follows [22]: Class I: Patients with heart disease experience no limitations in physical activity; ordinary physical activities do not cause undue fatigue, palpitation, dyspnea, or angina pectoris. Class II: Patients with slight limitations during physical activity; comfortable at rest, but ordinary physical activity results in fatigue, palpitation, dyspnea, or angina pectoris. Class III: Patients with marked limitations in physical activity; comfortable at rest, but less than ordinary physical activity provokes symptoms. Class IV: Patients unable to perform any physical activity without discomfort.

(2) Operation success rate: Total operative duration, length of hospital stay [23], initial closure success rate (defined as the ability of the occluder to successfully seal the defect immediately after deployment, as confirmed by intraoperative imaging examination, closure success rate (evaluated by imaging 24 hours post-procedure, indicating whether the occluder effectively sealed the cardiac defect) [24], immediate post-operative residual shunt rate, at 24-hour and at 1-month post-operative device deployment [25].

(3) Ventricular function assessment: Cardiac magnetic resonance imaging parameters were obtained 3 months before and after the procedure. These measures included right ventricular end-diastolic volume index (RVEDVi), right ventricular end-systolic volume index (RVESVi), right ventricular ejection fraction (RVEF), left ventricular end-diastolic volume index (LVEDVi), left ventricular end-systolic volume index (LVESVi), and left ventricular ejection fraction (LVEF) [26].

(4) Postoperative complications: Adverse events monitored within 12 months after the procedure included, pericardial effusion [27], infective endocarditis [28], valvular regurgitation [29], and subcutaneous emphysema [30].

(5) Quality of life evaluation: The 36-Item Short Form Health Survey (SF-36) score [31] was performed before surgery and at 12 months after surgery. The SF-36 assesses health-related quality of life, including physical component score (SF-36 PCS) and mental component score (SF-36 MCS). Specifically, it comprises eight dimensions: phys-

Table 1. Comparison of general information between the two groups [$\bar{x} \pm$ s, n (%)].

Variable	Observation group (n = 58)	Control group (n = 72)	t/χ^2 value	p-value
Gender			0.077	0.781
Male	28 (48.28)	33 (45.83)		
Female	30 (51.72)	39 (54.17)		
Age (years)	39.24 ± 8.87	39.78 ± 8.54	0.352	0.725
BMI (kg/m^2)	22.55 ± 2.36	22.87 ± 2.60	0.727	0.469
ASD diameter (mm)	18.75 ± 4.19	17.93 ± 4.21	1.106	0.271
Employment			0.030	0.985
Unemployment	9 (15.52)	11 (15.28)		
Part time	16 (27.59)	19 (26.39)		
Full time	33 (56.90)	42 (58.33)		
ASD classification			0.368	0.947
Central type	42 (72.41)	51 (70.83)		
Superior vena cava type	4 (6.90)	5 (6.94)		
Inferior vena cava type	7 (12.07)	11 (15.28)		
Mixed type	5 (8.62)	5 (6.94)		
Hypertension	7 (12.07)	10 (13.89)	0.094	0.760
Diabetes	6 (10.34)	8 (11.11)	0.020	0.889
Pulmonary arterial hypertension	12 (20.69)	16 (22.22)	0.045	0.833
Atrial fibrillation	9 (15.52)	10 (13.89)	0.068	0.794
NYHA functional class			0.410	0.522
NYHA functional class I/II	47 (81.03)	55 (76.39)		
NYHA functional class III/IV	11 (18.97)	17 (23.61)		

BMI, body mass index; ASD, atrial septal defect; NYHA, New York Heart Association.

Table 2. Comparison of operation success rate between the two groups [$\bar{x} \pm$ s, n (%)].

Variable	Observation group (n = 58)	Control group (n = 72)	t/χ^2 value	p-value
Operation duration (min)	30.69 ± 6.17	34.35 ± 7.49	2.992	0.003
Initial successful closure	56 (96.55)	62 (86.11)	4.179	0.041
Length of hospital stay (day)	3.24 ± 0.68	3.83 ± 0.73	4.722	<0.001
Immediate postoperative residual shunt	2 (3.45)	10 (13.89)	4.179	0.041
Residual shunt 24 hours after surgery	0 (0)	7 (9.72)	4.204	0.040
Residual shunt 1 month after surgery	0 (0)	3 (4.17)	0.971	0.324

ical functioning (PF), role physical (RP), body pain (BP), general health (GH), vitality (VT), social functioning (SF), role emotional (RE), and mental health (MH), each scored from 0 to 100, with higher scores indicating better quality of life. The minimum clinically significant difference (MCID) for components of the SF-36 PCS and the SF-36 MCS ranges from 3 to 5 points [32].

Statistical Analysis

Data analysis was performed using SPSS (V.21.0, IBM, Armonk, NY, USA). The normality of continuous variables was assessed using the Kolmogorov-Smirnov test, with data expressed as mean ± standard deviation ($\bar{x} \pm$ s). For continuous variables following normal distribution, comparisons between groups were performed using independent samples t-tests. However, within-group comparisons before and after treatment were conducted using paired samples t-tests. Categorical data were presented as frequencies and percentages [n (%)], and differences between categorical data were analyzed using chi-square tests. For categorical comparisons, the Pearson chi-square test was applied when all expected frequencies (T) were ≥5 and the total sample size (n) was ≥40. If the expected count was between 1 and 5 (1 ≤ T < 5) with n ≥40, the chi-square test with Yates' correction was used. However, in cases where T <1 or the total sample size was n <40, Fisher's exact test was utilized. A p-value < 0.05 was considered statistically significant.

Results

Comparison of Baseline Information Between the Two Groups

There were no significant differences between the observation and control groups in terms of gender, age, BMI, ASD diameter, employment status, ASD classification, comorbidities, and NYHA functional class, indicating comparability between the two groups ($p > 0.05$) (Table 1).

Table 3. Comparison of ventricular function parameters between the two groups [$\bar{x} \pm s$].

Groups	Observation group (n = 58)	Control group (n = 72)	t value	p-value
RVEDVi (mL/m^2)				
Before surgery	129.34 ± 20.48	127.83 ± 17.69	0.451	0.653
3 months after surgery	90.43 ± 8.15**	95.24 ± 9.16**	3.125	0.002
RVESVi (mL/m^2)				
Before surgery	68.44 ± 10.36	68.62 ± 11.76	0.091	0.927
3 months after surgery	44.29 ± 5.53**	47.85 ± 6.81**	3.217	0.002
RVEF (%)				
Before surgery	54.60 ± 8.90	53.30 ± 8.20	0.865	0.389
3 months after surgery	64.80 ± 10.10**	60.30 ± 10.50**	2.470	0.015
LVEDVi (mL/m^2)				
Before surgery	63.52 ± 10.75	61.89 ± 11.84	0.813	0.418
3 months after surgery	67.35 ± 7.29*	67.64 ± 7.90*	0.215	0.830
LVESVi (mL/m^2)				
Before surgery	25.85 ± 5.43	26.76 ± 4.96	0.997	0.321
3 months after surgery	28.27 ± 4.12*	28.84 ± 3.86*	0.812	0.418
LVEF (%)				
Before surgery	57.80 ± 7.50	56.40 ± 8.20	1.005	0.317
3 months after surgery	61.30 ± 7.70*	60.80 ± 6.50**	0.401	0.689

RVEDVi, right ventricular end-diastolic volume index; RVESVi, right ventricular end-systolic volume index; RVEF, right ventricular ejection fraction; LVEDVi, left ventricular end-diastolic volume index; LVESVi, left ventricular end-systolic volume index; LVEF, left ventricular ejection fraction. Compared with the same group before surgery, *$p < 0.05$, **$p < 0.001$.

Table 4. Comparison of overall postoperative complications between the two groups [n (%)].

Variable	Observation group (n = 58)	Control group (n = 72)	χ^2 value	p-value
Total	4 (6.90)	14 (19.44)	4.240	0.039
Pericardial effusion	2 (3.45)	4 (5.56)		
Infective endocarditis	0 (0)	5 (6.94)		
Valvular regurgitation	1 (1.73)	3 (4.17)		
Subcutaneous emphysema	1 (1.73)	2 (2.78)		

Comparison of Operation Success Rate Between the Two Groups

As shown in Table 2, the operation duration was significantly shorter in the observation group than in the control group ($p < 0.05$). Although both the observation and control groups achieved a 100% device-deployment rate, the initial closure success rate was significantly higher in the observation group ($p < 0.05$). Furthermore, the length of hospital stay was significantly shorter in the observation group compared to the control group ($p < 0.001$). The incidence of immediate postoperative residual shunting and the 24-hour post-operation detection rate was significantly lower in the observation group than in the control group ($p < 0.05$). Additionally, there was no significant difference in residual shunt between the two groups at 1-month post-operation ($p > 0.05$).

Comparison of Ventricular Function Parameters Between the Two Groups

Before the surgery, there were no statistically significant differences between the two groups in RVEDVi, RVESVi, RVEF, LVEDVi, LVESVi, and LVEF ($p > 0.05$). However, three months after surgery, both groups demonstrated substantial increases in RVEF, LVESVi, LVEDVi, and LVEF compared with before-surgery values ($p < 0.05$), and a significant decline in RVEDVi and RVESVi ($p < 0.05$). At the 3-month follow-up, the observation group exhibited substantially lower RVEDVi and RVESVi and a higher RVEF than the control group ($p < 0.05$). However, there were no significant differences in LVEDVi, LVESVi, and LVEF between the two groups 3 months after surgery ($p > 0.05$, Table 3).

Comparison of Post-Operative Complications Between the Two Groups

During the 12-month follow-up after surgery, the overall complication rate was 6.90% in the observation group, which was significantly lower than 19.44% in the control group ($p < 0.05$, Table 4).

Table 5. Comparison of SF-36 scores between the two groups [$\bar{x} \pm s$].

Groups	PF	RP	BP	GH	VT	SF	RE	MH
Before surgery								
Observation group (n = 58)	64.22 ± 10.71	56.00 ± 8.46	64.19 ± 11.74	65.12 ± 11.74	63.28 ± 13.48	61.67 ± 12.41	61.76 ± 14.21	64.12 ± 11.57
Control group (n = 72)	62.54 ± 11.42	57.18 ± 9.61	62.28 ± 10.30	63.40 ± 12.74	61.40 ± 12.62	60.64 ± 11.44	62.65 ± 12.37	66.71 ± 10.09
t value	0.857	0.734	0.987	0.792	0.819	0.491	0.382	1.362
p-value	0.393	0.464	0.325	0.430	0.414	0.624	0.703	0.175
12 months after surgery								
Observation group (n = 58)	69.34 ± 9.22*	67.59 ± 7.58**	75.28 ± 7.61**	72.43 ± 7.69**	75.36 ± 6.36**	75.57 ± 7.22**	77.26 ± 6.59**	76.26 ± 6.82**
Control group (n = 72)	66.01 ± 7.82*	64.53 ± 7.85**	71.63 ± 8.31**	68.50 ± 7.84*	70.50 ± 7.54**	68.51 ± 8.68**	72.21 ± 7.44**	72.15 ± 7.53**
t value	2.228	2.243	2.584	2.865	3.913	4.963	4.046	3.225
p-value	0.028	0.027	0.011	0.005	<0.001	<0.001	<0.001	0.002

SF-36, 36-Item Short Form Health Survey; PF, physical functioning; RP, role physical; BP, body pain; GH, general health; VT, vitality; SF, social functioning; RE, role emotional; MH, mental health. Compared with the same group before surgery, *$p < 0.05$, **$p < 0.001$.

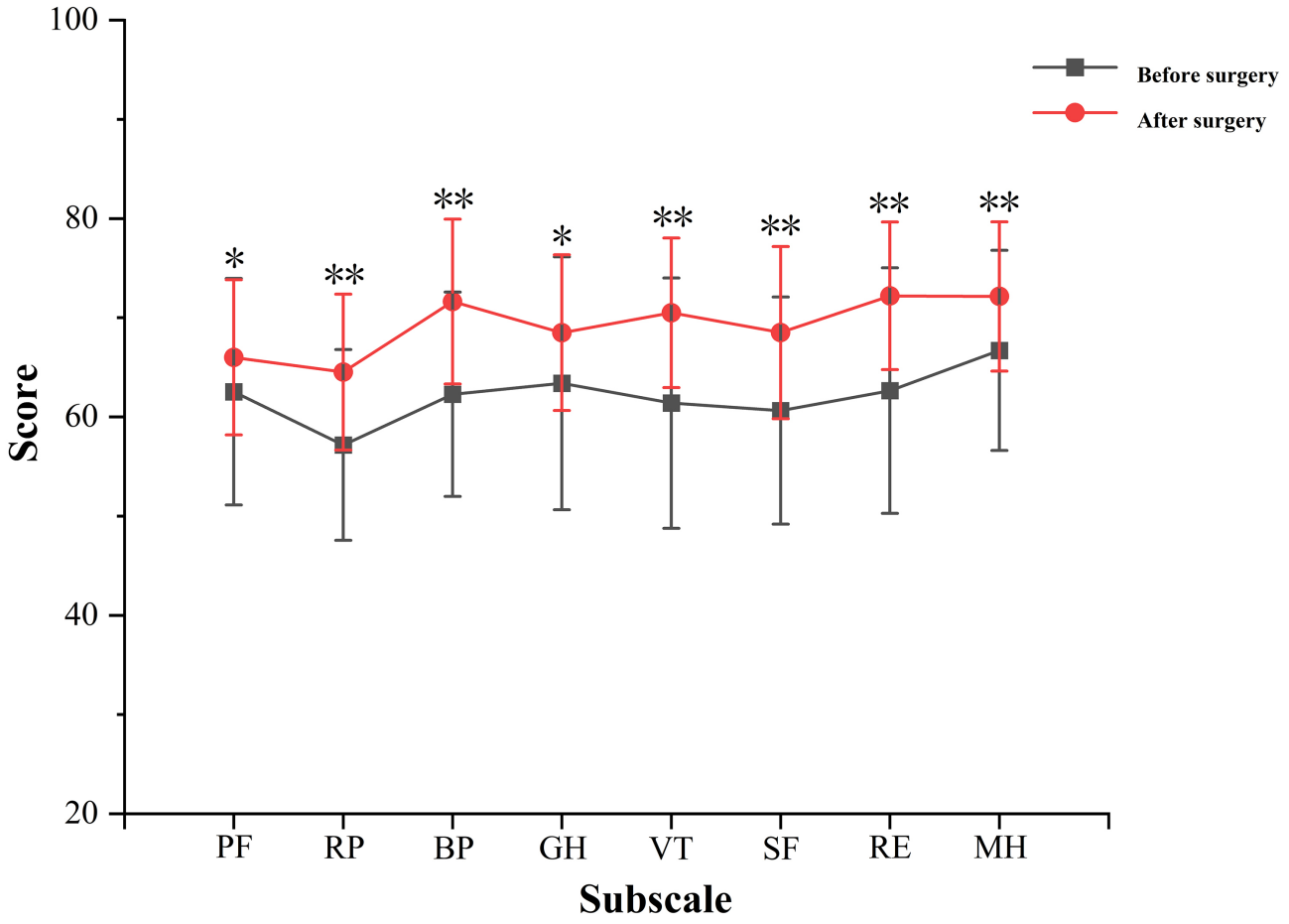

Fig. 1. A line graph comparing SF-36 scores across the eight health domains before and after surgery in the control group. SF-36, 36-Item Short Form Health Survey; PF, physical functioning; RP, role physical; BP, body pain; GH, general health; VT, vitality; SF, social functioning; RE, role emotional; MH, mental health. Compared with the same group before surgery, *$p < 0.05$, **$p < 0.001$.

Assessing the Quality of Life Among Study Participants via SF-36 Scores

Preoperative baseline assessment revealed no significant difference in the two groups across all SF-36 dimensions ($p > 0.05$). However, 12 months after surgery, both groups demonstrated a significant increase in PF, RP, BP, GH, VT, SF, RE, and MH than their preoperative scores ($p < 0.05$; Table 5 and Figs. 1,2). Furthermore, 12 months after surgery, the observation group showed higher outcomes in PF (69.34 ± 9.22 vs. 66.01 ± 7.82, $p = 0.028$), RP (67.59 ± 7.58 vs. 64.53 ± 7.85, $p = 0.027$), BP (75.28 ± 7.61 vs. 71.63 ± 8.31, $p = 0.011$), GH (72.43 ± 7.69 vs. 68.50 ± 7.84, $p = 0.005$), VT (75.36 ± 6.36 vs. 70.50 ± 7.54, $p < 0.001$), SF (75.57 ± 7.22 vs. 68.51 ± 8.68, $p < 0.001$), RE (77.26 ± 6.59 vs.72.21 ± 7.44, $p < 0.001$), and MH (76.26 ± 6.82 vs.72.15 ± 7.53, $p = 0.002$) compared to the control group (Table 5, Fig. 3).

Discussion

This study reports the first comprehensive comparison between TEE-guided and conventional X-ray-guided interventional treatment in adult patients with secundum ASD. Our results showed that TEE-guided technology not only overcomes the dependence on ionizing radiation but also demonstrates multidimensional clinical advantages. Regarding surgical efficiency, TEE guidance significantly shortened the procedure time, improved initial closure success rates, and reduced the incidence of immediate post-operative residual shunts. Hemodynamically, it improved cardiac performance, promoted ventricular function recovery, and enhanced overall cardiac function. In terms of surgical safety, TEE-guided intervention was associated with lower post-operative complications. More importantly, patients receiving TTE-guided treatment reported better quality of life at 12 months after surgery compared to the X-ray-guided closure. These observations highlight the clinical significance of TEE-guided ASD occlusion in adult patients, particularly radiation-sensitive individuals, by optimizing operational efficiency, promoting right ventricular reverse remodeling, reducing post-operative complications, and improving quality of life after surgery.

Our study showed that both TEE-guided and X-ray-guided techniques achieved a 100% occlusion success rate, highlighting the established efficacy of percutaneous occlusion

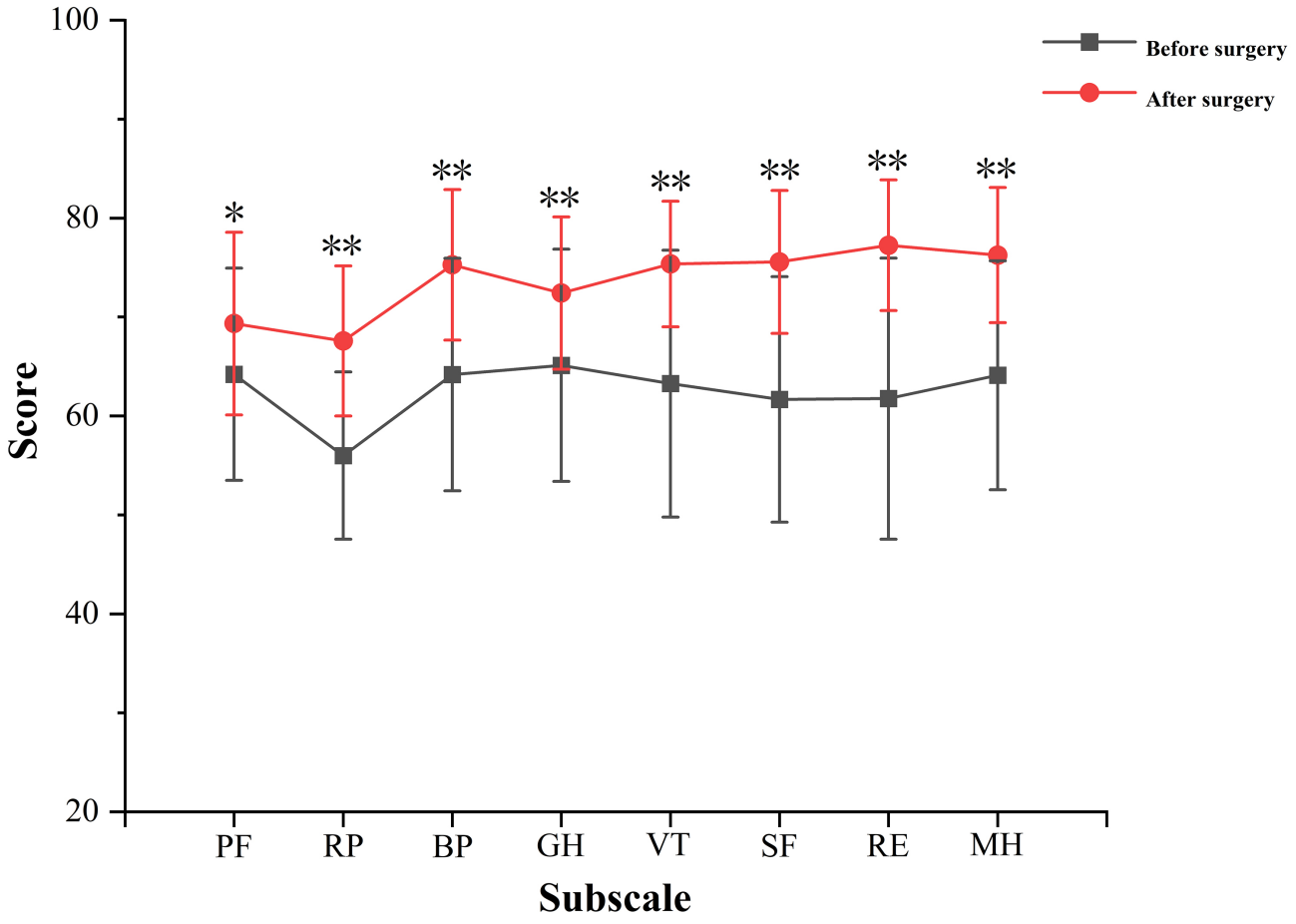

Fig. 2. A line graph comparing SF-36 scores across the eight health domains before and after surgery in the observation group. SF-36, 36-Item Short Form Health Survey; PF, physical functioning; RP, Role physical; BP, Body pain; GH, General health; VT, Vitality; SF, social functioning; RE, Role emotional; MH, Mental health. Compared with the same group before surgery, *$p < 0.05$, **$p < 0.001$.

in treating secundum ASD and aligning with recent literature [21]. Notably, the observation group showed significantly shorter operation times and hospital stays, consistent with Xu *et al.*'s study [33] on TEE-guided percutaneous ASD closure in children. Moreover, this study indicated that the initial occlusion success rate was higher, and the immediate and 24-hour residual shunt rates were lower in the observation group (TEE-guided cohort). This may be due to the following two mechanisms: (1) TEE color Doppler shows greater sensitivity to low-velocity blood than X-ray angiography, enabling earlier identification of cases requiring adjustment [34]. (2) Multiplanar TEE imaging allows real-time visualization of symmetrical deployment and proper apposition of the occluder left and right atrial discs against the atrial septum, avoiding minor shunts from disc tilt or incomplete expansion [20]. At 1-month after surgery, there was no difference in the residual shunt rate between the two groups, reflecting the neoendothelialization process of the Amplatzer occluders, where endothelial cell proliferation typically seals the small residual shunt channels within 4–8 weeks post-implantation [35]. Moreover, the occluder double-disc structure of the Amplatzer promotes tissue proliferation, further reducing residual shunts [36]. Although TEE provides high-resolution anatomical images of the heart and surrounding structures, it typically requires general anesthesia and carries potential risks such as esophageal mucosal injury [37,38]. Therefore, in health-care centers lacking TEE capability or patients who cannot tolerate anesthesia/sedation, X-ray-guidance remains a reliable option, but with the recommendation of accurate post-operative echocardiographic surveillance to monitor early residual shunts.

Patients with ASD experience significant changes in cardiac hemodynamics due to the chronic left-to-right shunt at the atrial level. Specifically, this causes an excessive volume load on the right ventricle and a relative underload of the left ventricle, reflecting the ventricles' structural and functional interdependence, where changes in one chamber inevitably affect the other [39]. In our study, both treatment groups showed improved left and right ventricular function compared to preoperative levels, consistent with previous research findings [40,41]. Occluding the defect effectively relieved the volume load over the right ventricle, improving its hemodynamics and ultimately enhancing its over-

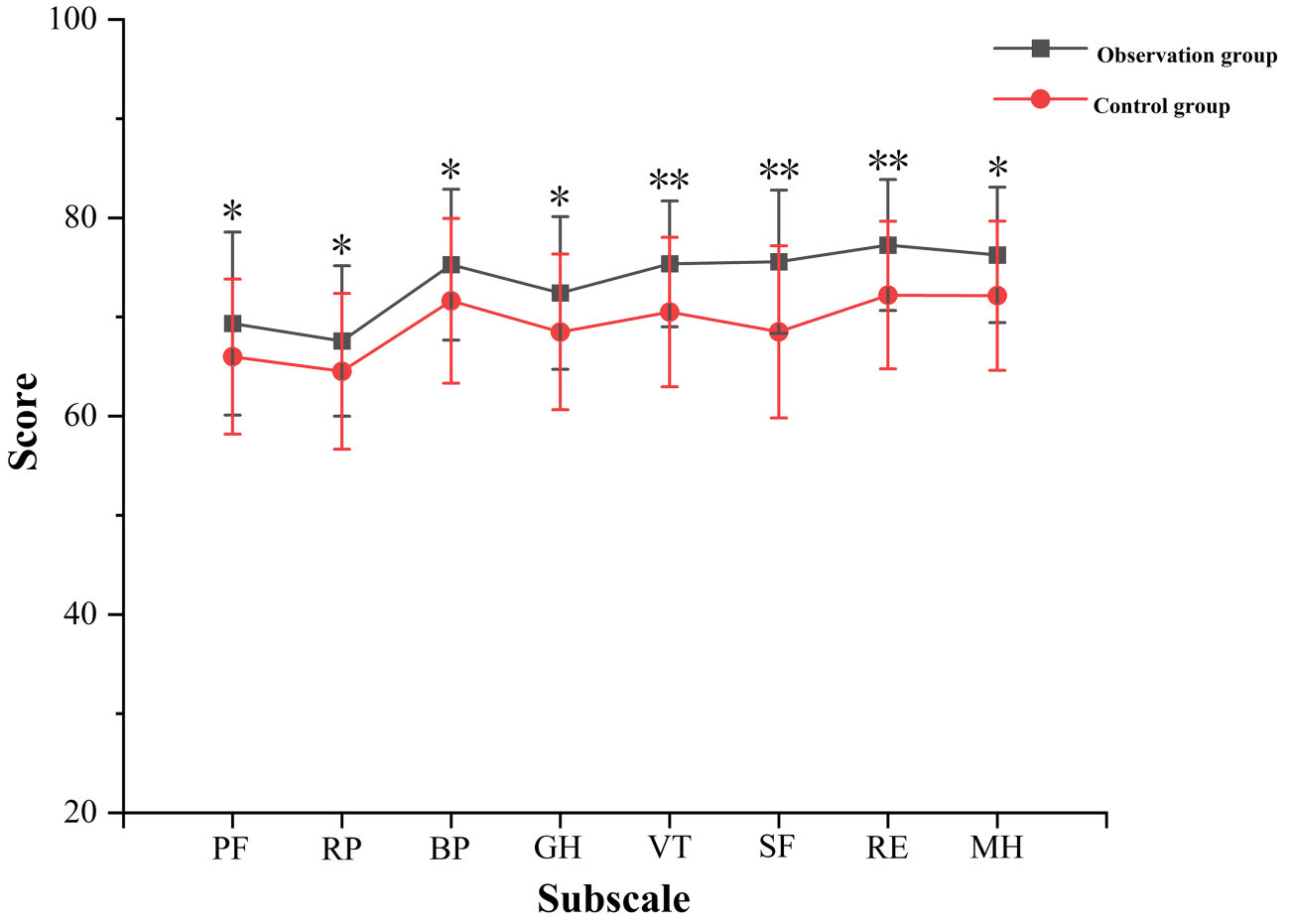

Fig. 3. A line graph comparing the eight dimensions of the SF-36 score between the observation and control groups after the surgery. SF-36, 36-Item Short Form Health Survey; PF, physical functioning; RP, Role physical; BP, Body pain; GH, General health; VT, Vitality; SF, social functioning; RE, Role emotional; MH, Mental health. Compared to the control group, *$p < 0.05$, **$p < 0.001$.

all function. Meanwhile, normalizing intracardiac flow reduced left ventricular load, thereby enhancing its performance [42]. At 3 months postoperatively, the right ventricular functional parameters were substantially better in the observation group than in the control group, indicating that TEE guidance accelerates the right ventricular reverse remodeling. This advantage may be because of TEE's ability to provide detailed, real-time visualization of the defect anatomical structure [43], allowing more accurate device sizing and optimal ventricular load reduction [6,44], which further improves right ventricular function [45].

In contrast, X-ray-guided imaging techniques have certain limitations, which can lead to possible selection bias for complex defects and a higher incidence of residual shunts. Therefore, the postoperative right ventricular function was better in the TEE group than in X-ray-guided group. It is worth noting that there was no significant difference in left ventricular function between the two groups postoperatively, likely due to the left-to-right shunt caused by the atrial septal defect. Conversely, due to the higher compliance of the right ventricle compared to the left ventricle, the right ventricle experiences volume overload, while the left ventricle, with its main pressure load and strong compensatory ability. As a result, improvement in left ventricular functional indices tends to be relatively moderate, yielding minimal difference between the two imaging methods in adjusting left ventricular load [46,47].

Percutaneous ASD adoption has gradually increased in clinical practice and is progressively replacing traditional surgical methods. Despite this procedure offering numerous advantages, including a relative safety profile, close monitoring for possible complications, such as device embolization, cardiac erosion, infective endocarditis, and pericardial effusion, remains crucial [48,49]. In this study, the observation group showed a significantly lower complications rate within 12 months postoperatively than in the control group. TEE's high-resolution imaging allows real-time evaluation of the occluder's spatial relationship with surrounding structures, thereby reducing mechanical complications resulting from malposition or improper device sizing (e.g., valve regurgitation) [50]. Moreover, TEE guidance optimizes puncture-site selection, effectively reducing the risk of vascular injury and air embolism, and consequently decreasing the likelihood of subcutaneous em-

physema [51]. Additionally, the observation group also avoided exposure to iodinated contrast agents during the entire surgical process, eliminating contrast-induced inflammatory reactions [52]. It is worth noting that the risk of infective endocarditis correlates with increased inflammatory response during cardiac surgery [53].

A recent study comparing short-term quality-of-life outcomes between percutaneous closure and median sternotomy for ASD repair in adult patients reported a more significant improvement with the percutaneous approach [54]. Based on these observations, our study further found that the observation group undergoing TEE-guided occlusion achieved significantly higher SF-36 scores at 12 months postoperatively compared to the X-ray-guided control group. This difference indicates both physiological and psychological advantages conferred by the TTE-guided approach. Physiologically, TTE's imaging accuracy allows for precise defect assessment and optimal occluder selection, reducing the need for intraoperative device adjustments [43]. As a result, the risk of post-operative complications is decreased, promoting earlier recovery and mobilization. Psychosocially, TEE guidance avoids the multiple contrast agent injections and radiation exposure required by X-ray guidance, significantly reducing safety-related concerns [55]. Moreover, real-time ultrasound visualization provides continuous intraoperative feedback, potentially enhancing patients' confidence in procedural success and improving emotional role and mental health scores [56]. Finally, the more precise closure achieved under TEE guidance can reduce residual shunting, accelerating cardiopulmonary functional adaptation [46].

With the advancement in imaging technologies, transthoracic echocardiography (TTE) and three-dimensional intracardiac echocardiography (ICE) have gradually been applied in clinical practice [6,57]. Three-dimensional ICE provides a stereoscopic illustration of ASD morphology, enhancing the accuracy of occluder sizing. Although studies have shown that ICE can shorten operative times and lower complication rates compared to traditional X-ray guidance, its broader adoption is currently restricted by stringent equipment requirements and the need for specialized operator expertise [58,59]. Existing research indicates that TTE-guided and TEE-guided ASD occlusion procedures achieve comparable success rates and similar incidences of post-operative residual shunting [60]. However, TTE's imaging quality can be significantly compromised by patient-specific anatomical factors: in adults with obesity or pediatric patients with chest wall deformities or increased thoracic wall thickness, acoustic windows may obscure ASD rim visualization [61,62]. In patients with chest wall thickening (such as obesity or excessive breast tissue), post-surgical anatomical alterations, or other factors compromising acoustic window interferences, TEE via direct esophageal acoustic access provides superior visualization of ASD anatomy and occluder-tissue interface, making it the preferred imaging modality for these complex cases [63].

Despite collecting extensive baseline data and confirming no statistical differences between the two groups regarding demographic and preoperative clinical indicators, the non-randomized study design may still introduce potential selection bias. The retrospective nature of data collection also limits access to certain surgical parameters, such as the precise intraoperative contrast agent dosage, cumulative radiation exposure, and long-term complications like the recurrence of residual shunts, which could impact surgical safety and complication rates. Furthermore, the TEE guidance needs a significant learning curve, and variations in operator expertise; such factors are challenging to standardize retrospectively. As a single-center study, our results may be influenced by the specific surgical procedures and patient demographics of our hospital, which limit their generalizability. To address these limitations, future research should include multicenter, prospective randomized controlled trials with multiple regression models to adjust for confounding factors; extend the follow-up period to 3–5 years to comprehensively assess mid-to-long-term efficacy and safety; and perform stratified analyses in high-risk subgroups to provide more precise bases for clinical decision-making. These improvements will offer a more objective evaluation of clinical performance and broader applicability of TEE guidance in ASD interventions.

Conclusions

In adult patients undergoing percutaneous secundum ASD closure, TEE-guided intervention demonstrates superior clinical efficacy over conventional X-ray fluoroscopy. Specifically, TEE guidance yields a higher primary plugging success rate, reduced operative times and hospital stays, and a lower incidence of early residual shunting. Furthermore, TEE guidance facilitates enhanced right ventricular reverse remodeling and reduces the incidence of complications. Moreover, patients undergoing TEE-guided intervention experienced greater improvements in quality of life at 12 months after surgery.

Availability of Data and Materials

The data analyzed were available on request from the corresponding author.

Author Contributions

WWY and GW designed the research study and wrote the first draft. WWY and YYZ performed the research. YYZ analyzed the data. All authors contributed to important editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

This study was approved by the Taizhou Hospital of Zhejiang Province Affiliated to Wenzhou Medical University Ethics Review Board (No. K20250545) and strictly adhered to the principles outlined in the Declaration of Helsinki. Informed consent was obtained from all patients participating in the study.

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Conflict of Interest

The authors declare no conflict of interest.

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