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ORIGINAL ARTICLE

Can intraoperative TEE correctly measure residual shunt after surgical repair of ventricular septal defects?

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Abstract

Purpose No groups have yet succeeded in identifying the need for re-repair of residual shunt after surgical repair of ventricular septal defect (VSD) based on quantitative evaluation of the ratio of the pulmonary blood flow to the systemic blood flow (Qp/Qs) by transesophageal echocardiography (TEE). Hence, we studied the accuracy of Qp/Qs as estimated by intraoperative TEE.

Methods Twenty-six patients undergoing VSD closure were studied. After separation from the cardiopulmonary bypass, the presence and severity of residual leakage was evaluated by color Doppler image, and the Qp/Qs (TEE-derived Qp/Qs) was calculated by measuring the vessel diameter and the velocity–time integral of the flow profiles in the main pulmonary artery and left ventricular outflow tract. Transthoracic echocardiography (TTE) was performed at pre-discharge and at 6–12 months after the correction to confirm the presence and severity of residual leakage.

Results TEE detected only minor leakage, with no indication for re-repair, in 8 of the 26 patients. Nevertheless, TEE-derived Qp/Qs varied from 0.57 to 2.07 and were incorrect in 17 patients (65.4%). This meant that when TEE-derived Qp/Qs was outside the acceptable range, the patient was judged not to be in need of re-repair. TTE at pre-discharge confirmed trivial leakage in 3 patients in whom TEE had also identified similar leakages. These leakages were not observed at the follow-up TTE.

Conclusion TEE-derived Qp/Qs lacks the accuracy required to play a crucial role in quantitatively measuring the severity of residual shunt, while two-dimensional TEE can reliably detect residual leakage after VSD closure and lead to optimal judgment on the need for re-repair.

Keywords Ventricular septal defect (VSD) · Transesophageal echocardiography (TEE) · Ratio of pulmonary blood flow to systemic blood flow (Qp/Qs) · VSD closure · Residual leakage

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Introduction

Transesophageal echocardiography (TEE) is very useful and efficient for evaluating repairs after surgery for congenital cardiac diseases [1–5] and detecting the residual leaks that frequently occur after the repair of ventricular septal defects (VSDs) [2–5]. Yet criteria identifying the need for re-repair of residual defects have not been clearly outlined by quantitative shunt measurements by TEE.

Doppler echocardiography techniques have been used to accurately estimate the ratio of pulmonary blood flow to systemic blood flow (Qp/Qs) in various cardiac shunt lesions in non-operating room settings [6–11]. One conventional method applicable either before or after the repair of a shunt lesion is to calculate the relative amounts of flow passing through the pulmonary artery (PA) and left ventricular outflow tract (LVOT) by measuring the velocity–time integrals and luminal areas of the PA and LVOT. The aims of this study were twofold: first, to evaluate the accuracy of Qp/Qs estimated by the conventional method based on TEE after correction of VSD; second, to assess the reliability of color Doppler imaging (CDI) as a method for grading the severity of leakage and predicting the absence of persistent residual leakage during the follow-up period.

Methods

Patients

Twenty-six patients diagnosed with VSD were prospectively enrolled in this study. This study was approved by the institutional ethics committee with a waiver of the requirement to obtain written informed consent from patients older than 20 years old and the parents of the younger patients. All cardiac surgeries (VSD closure with Gore-Tex patch) were performed at the Niigata University Hospital. All patients had undergone preoperative examinations, including cardiac catheterization and transthoracic echocardiography (TTE).

The VSD was located in the perimembranous region in 17 of the 26 patients. Among these 17 patients, 8 had an outlet extension, 1 had an inlet extension, 1 had a right coronary cusp prolapse (RCCP), 2 had a non-coronary cusp prolapse (NCCP), and 4 had a pouched formation of the septal leaflet (PSL). The VSDs in the other 9 patients were of the outlet type, and RCCP was present in 7 of those 9. Patent ductus arteriosus (PDA) and patent foramen ovale (PFO) were concomitantly present in 2 of the 26 patients. When pulmonary hypertension (PH) was defined simply as a ratio of pulmonary pressure to systemic pressure (Pp/Ps) that exceeds 0.5, PH was present in 17 patients, including 8 with a Pp/Ps greater than 0.8, and 2 with a pulmonary vascular resistance greater than 5 Wood's Unit m^{-2}. The VSD sizes were recorded in 14 patients preoperatively. By indexing the VSD size to the body surface area, the method reported by Sabry et al. [6], 13 of the defects were classified as large and 1 was classified as moderate.

In the surgeries to close the 26 VSDs, 14 of the defects were approached for closure via the tricuspid valve (TV) and 12 were approached via a main pulmonary arteriotomy (PA-tomy).

TEE

A pediatric biplane probe (UST-52111S; Aloka, Tokyo, Japan) was used for patients with body weights of less than 15 kg and an adult multiplane probe (UST-5293S-5; Aloka, Tokyo, Japan) was used for larger patients. After separation from the cardiopulmonary bypass (CPB), two-dimensional TEE with CDI was used to identify residual leakage in the VSD repair. If residual leakage was detected, its severity was qualitatively graded based solely on a subjective visual assessment of the size of the jet on CDI. A tiny jet clearly shorter than 3 mm in length was assessed as a suspected leakage through the suture hole and graded as trivial. A jet reaching approximately 3–5 mm in length was graded as mild, and a greater jet accompanied by an easily detectable suction flow in the left ventricle opposite to the jet was graded as moderate. While trivial leakages were considered acceptable, cases with residual shunts of mild or greater severity underwent blood sampling from the right atrium and pulmonary artery (PA) to calculate blood gas analysis (BGA)-derived Qp/Qs. The following formula was used to calculate the BGA-derived Qp/Qs under conditions where blood oxygen saturation (SO_2) of pulmonary veins ($S_{PV}O_2$) was assumed to be 99% and systemic arterial SO_2 (SaO_2) was substituted for SpO_2:

$$\text{BGA-derived Qp/Qs} = (SaO_2 - S_{RA}O_2)/(S_{PV}O_2 - S_{PA}O_2).$$

In cases where the BGA-derived Qp/Qs was greater than 1.3, revision of the surgical repair was considered based on the institutional policy. The diameter of the PA (PAD) and the velocity–time integral of the systolic flow in the PA (PA-VTI) were measured in the mid-esophageal ascending aorta short-axis view (ME-aAo-SAX). Similarly, the diameters of the left ventricular outflow tract (LVOTD) and the VTI in the LVOT (LVOT-VTI) were measured in the transgastric LV long-axis view (TG-LV-LAX), when feasible. The PAD and LVOTD were measured at the main PA trunk and just below the aortic valve at greatest expansion during systole, respectively. Angle correction was applied whenever the ultrasound was not completely aligned with the blood flow in the VTI measurement. The TEE-derived Qp/Qs was calculated by the following formula:

$$\text{TEE-derived Qp/Qs} = \{(\text{PAD})^2 \times \text{PA-VTI}\}/\{(\text{LVOTD})^2 \times \text{LVOT-VTI}\}.$$

These measurements were completed during periods of stable cardiovascular conditions, and no surgical procedures were allowed during this time in order to avoid influencing Qp or Qs.

In the absence of significant leakage—more specifically, in the absence of mild or greater leakage on CDI or a BGA-derived Qp/Qs of greater than 1.3—we assumed that the TEE-derived Qp/Qs had to be within the range from 1.0 to 1.3. Based on this assumption, a TEE-derived Qp/Qs falling outside of this range without significant leakage had to be incorrect.

All of the TEE examinations were performed and evaluated by anesthesiologists who had passed the Examination of Special Competence in Perioperative Transesophageal

Echocardiography (PTEeXAM) and had been approved by the Japanese Board of Perioperative Transesophageal Echocardiography (JB-POT).

Postoperative course, pre-discharge TTE, and follow-up TTE

All patients were followed postoperatively for 12 months to watch for unfavorable events, including reoperation. All patients underwent TTEs at pre-discharge and at 6–12 months after the correction to check for the presence of residual leakage. The procedures were conducted by pediatric cardiologists blinded to the intraoperative TEE results.

Statistical analysis

Data were analyzed by Spearman's rank correlation coefficient, unpaired t test, and the Mann–Whitney U test. $P < 0.05$ was considered statistically significant.

Results

The demographics of the patients are summarized in Table 1. The patients ranged from 3.9 to 58.9 kg (median 7.0 kg) in weight and from 3 months to 21 years (median 8.5 months) in age. Angle correction was applied for measurement of the VTI in 16 cases for the PA and in all 26 cases for the LVOT, but the angle was less than 30° in all of the measurements of the PA-VTI and in 16 of the measurements of the LVOT-VTI.

Table 2 summarizes the intraoperative TEE measurements and the presence of residual leakage by the pre-discharge TTE and follow-up TTE.

Assessment by two-dimensional TEE identified the leakage as minor, with no need for re-repair, in 8 of the 26 cases (7 had trivial leakage and 1 had mild leakage). Based on this assessment, we initially presumed that the Qp/Qs would be equal to or slightly greater than 1.0 in all of the cases. Surprisingly, however, we found that the TEE-derived Qp/Qs varied from 0.57 to 2.07, and was incorrect in 17 cases (65.4%).

The TEE-derived Qp/Qs was significantly correlated with the ratio of pulmonary artery pressure to systemic pressure (Pp/Ps) in preoperative cardiac catheterization, the peak velocity of PA flow, and the peak velocity ratio (Fig.1). The TEE-derived Qp/Qs was not correlated with the PAD, LVOTD, diameter ratio (PAD/LVOTD), peak velocity of LVOT flow, or correction angle for measurement of the PA and LVOT flow velocities. Before analyzing the acquired data, the 26 patients were divided into 2 groups based on the criteria set for these variables and for the surgical approach (Table 3). The TEE-derived Qp/Qs was significantly higher in patients with a preoperative Pp/Ps of greater than 0.8 than in patients with a preoperative Pp/Ps of less than 0.8, and significantly higher in patients with a peak velocity ratio of greater than 1.5 than in patients with a peak velocity ratio of less than 1.5 (Table 3). On the other hand, no significant differences were observed between the error rates in the 2 groups (Table 3).

The postoperative course was favorable in all but one patient. The one patient with an unfavorable course required a second operation due to dehiscence of the patch. The pre-discharge TTE confirmed trivial leakage in 3 patients in whom trivial leakages had been detected by intraoperative TEE. No leakage was observed during the follow-up TTE of these 3 patients.

Discussion

In our study on patients undergoing surgery for repair of VSDs, we found that quantitative measurement of Qp/Qs in the immediate post-repair period was inaccurate and could not be reliably used to decide the need for re-repair of residual leakage.

Previous studies have suggested that Doppler echocardiography accurately estimates Qp/Qs in various cardiac shunt lesions [6–11]. To our knowledge, however, this echocardiographic modality has not been used intraoperatively to determine the indications for revision after correction for intracardiac shunt lesions. Several studies have previously indicated that Qp/Qs evaluated by the conventional method (the same method we employed in this study) was excellently correlated with the Qp/Qs in cardiac catheterization, with a correlation coefficient of greater than 0.90 and a standard error of the estimate of about 0.20 [7, 10]. In addition, the method could accurately estimate Qp/Qs even in subjects without shunt lesion [8]. The transesophageal approach has never been applied for the estimation of Qp/Qs in previous studies [6–11]. Several studies, however, have demonstrated that intraoperative TEE can accurately determine cardiac output either at the PA, right ventricular outflow tract, LVOT, or aortic valve by measuring VTI and the luminal area in patients undergoing cardiac or noncardiac surgery [12–17]. On this basis, TEE may be a reliable measure for the estimation of Qp/Qs. In an additional small experiment, we confirmed that TEE-derived Qp/Qs was accurate over a wide range of left-to-right shunt in a small number of patients. This was achieved by comparing TEE-derived Qp/Qs either with BGA-derived Qp/Qs simultaneously measured during the pre-repair period in 3 patients with ASD or VSD, or with 1 in 3 patients without shunt lesion, based on the assumption

Table 1 The demographics of the studied patients

Case	Age (mo)	BW (kg)	Cardiac catheterization			Location	Size	Complicated lesion	Concomitant disease
			Qp/Qs	Pp/Ps	Rp				
1	29	14.9	1.3	0.25	1.6	Outlet		RCCP	
2	6	3.9	2.0	0.83	5.3	Peri	Large	Outlet ext.	PFO, PDA
3	5	5	4.0	0.83	2.7	Outlet	Large		
4	8	6.9	2.5	0.51	1.9	Peri	Large	Outlet ext.	
5	5	5.3	1.9	0.86	5.1	Peri	Large		Down synd.
6	7	4.5	3.0	0.56	3.0	Peri			
7	48	13	1.2	0.17	1.7	Outlet	Mod.	RCCP	
8	156	50.9	1.1	0.23	1.5	Peri		PSL, NCCP	
9	9	7.8	4.0	0.92	2.9	Outlet	Large		
10	7	6.3	3.5	0.86	4.4	Peri	Large		
11	16	9.7	2.2	0.46	2.4	Peri		Outlet ext.	
12	48	14	1.2	0.28	2.0	Peri		RCCP, NCCP, outlet ext.	
13	13	8.7	1.9	0.38	2.4	Peri	Large	PSL	
14	39	14.1	1.2	0.23	1.7	Outlet		RCCP	
15	3	4	2.0	0.9	3.9	Peri	Large		Down synd.
16	18	11.3	1.7	0.3	1.5	Outlet		RCCP	
17	17	7.1	1.6	0.56	3.8	Peri		PSL	PDA
18	120	25.9	1.2	0.18	1.2	Outlet		RCCP	
19	132	53.4	1.3	0.15	1.7	Outlet		RCCP	
20	4	4.5	2.0	0.89	2.7	Peri	Large		
21	5	5.3	2.7	0.49	1.5	Peri	Large	PSL, inlet ext.	
22	252	58.9	1.1	0.2	1.0	Outlet		RCCP	
23	8	6.3	3.4	0.63	2.3	Peri	Large	Outlet ext.	
24	4	3.9	2.9	0.89	4.2	Peri		Outlet ext.	
25	8	5.3	3.0	0.69	3.0	Peri	Large	Outlet ext.	PFO
26	7	6	3.4	0.41	0.9	Peri	Large	Outlet ext.	

mo months, *BW* body weight, *Qp/Qs* ratio of pulmonary blood flow to systemic blood flow, *Pp/Ps* ratio of pulmonary blood pressure to systemic blood pressure, *Rp* pulmonary vascular resistance, *peri* perimembranous, *ext.* extension, *PDA* patent ductus arteriosus, *PFO* patent foramen ovale, *synd.* syndrome

that Qp is completely equivalent to Qs (data not shown). In the presence of a large VSD such as those seen in the pre-repair state, Qp/Qs can be easily affected by many factors, including inspired fraction of oxygen, arterial tension of carbon dioxide and mechanical ventilation; however, in the presence of small defects these factors have less effect on Qp/Qs. We considered, therefore, that this method could differentiate VSD leakages necessitating re-repair from minor leakages acceptable to be left without re-repair. Though the measurement techniques we employed in our study were similar to those used in the previous studies, the errors in the TEE-derived Qp/Qs in our study can probably be attributed to several factors specific to the post-repair state.

First, flow turbulence in the PA is thought to a major cause of measurement errors. In our study, nearly two-thirds of the subjects (17/26) had an outlet-type defect or an outlet extension of a perimembranous defect. The patch attached to the right ventricular outflow tract (RVOT) below the pulmonary valve disrupts the laminar blood flow in these types of patients. PA-tomy, the surgical approach selected in 12 patients in our study, might also cause turbulence at suture lines and lead to pulmonary regurgitation. Incidentally, relatively high peak velocities (>1.5 m/s) were observed in the PA profiles of 6 of the patients. None of these patients, however, showed clear signs of flow acceleration at the suture level or mild or greater pulmonary regurgitation. In other studies conducted using the same method for VTI measurement, the measurements were based on Doppler flow velocities in which the spectral widths at the peaks of the curves were less than 25% of the peak velocities overall [6, 7]. Although we did not consider the spectral width in measuring VTI, the velocities in some of the patients probably satisfied the exclusion criteria applied in those other studies. In animal studies, three-dimensional visualization of pulmonary blood flow (PBF)

Table 2 The intraoperative measurements and the results of TTE at discharge and follow-up in all of the patients

Case	Residual leakage	TEE-Qp/Qs	pV_{PA} (m/s)	pV_{LVOT} (m/s)	pV ratio	PAD (mm)	LVOTD (mm)	*D* ratio	Discharge TTE	F/U TTE
1	None	1.02	0.90	0.65	1.38	13.2	13.6	0.97	None	None
2	Mild	1.09	1.00	0.60	1.67	8.9	13.2	0.67	Trivial	None
3	None	1.89	1.15	0.80	1.44	7.9	6.8	1.16	None	None
4	Trivial	0.93	1.00	0.75	1.33	10.7	11.1	0.96	Trivial	None
5	Trivial	2.05	1.40	0.80	1.75	11.7	10.8	1.08	None	None
6	Trivial	1.96	1.60	0.70	2.29	10.8	12.2	0.89	None	None
7	None	1.14	1.80	0.80	2.25	10.9	13.7	0.80	None	None
8	None	0.57	0.70	1.00	0.70	19.4	19.4	1.00	None	None
9	None	1.73	0.90	0.45	2.00	14.7	14.2	1.04	None	None
10	Trivial	1.22	0.65	0.80	0.81	15.7	9.0	1.74	Trivial	None
11	None	1.34	1.10	1.20	0.92	12.6	10.5	1.20	None	None
12	None	1.21	1.60	0.80	2.00	11.2	15.2	0.74	None	None
13	None	1.24	0.70	0.80	0.88	14.3	11.4	1.25	None	None
14	None	0.86	0.75	0.70	1.07	11.7	13.4	0.87	None	None
15	Trivial	1.42	1.10	1.00	1.10	8.3	9.0	0.92	None	None
16	None	1.30	1.80	1.00	1.80	10.6	13.4	0.79	None	None
17	None	1.36	0.80	0.50	1.60	12.2	11.2	1.09	None	None
18	None	1.54	1.80	1.00	1.80	15.9	18.4	0.86	None	None
19	Trivial	1.38	1.45	1.00	1.45	16.9	20.7	0.82	None	None
20	None	1.50	1.00	0.50	2.00	8.3	9.6	0.86	None	None
21	None	1.26	2.00	0.80	2.50	6.1	9.4	0.65	None	None
22	None	0.94	0.65	0.80	0.81	18.9	17.6	1.07	None	None
23	Trivial	1.13	0.75	0.85	0.88	13.5	11.7	1.15	None	None
24	None	2.07	1.15	0.50	2.30	11.1	10.9	1.02	None	None
25	None	0.79	0.75	0.90	0.83	14.4	12.1	1.19	None	None
26	None	1.48	0.60	0.60	1.00	12.9	10.6	1.22	None	None

Qp/Qs ratio of pulmonary blood flow to systemic blood flow, pV_{PA} peak velocity of pulmonary artery flow, pV_{LVOT} peak velocity of left ventricular outflow tract flow, *pV ratio* ratio of pV_{PA} to pV_{LVOT}, *PAD* pulmonary artery diameter, *LVOTD* left ventricular outflow tract diameter, *D ratio* ratio of PAD to LVOTD, *TTE* transthoracic echocardiography, *F/U* follow-up

velocity profiles revealed spatial heterogeneity in the main PA among normal subjects and subjects with PH, but several characteristics of the spatial flow profiles were also found to differ between the 2 groups [18]. In another study yielding similar results, the spatial flow profiles varied markedly between subjects and were altered by increases in PAP or PBF [19]. Hence, the position of the sample volume and the presence of PH might influence the measured VTI. These clinical findings in our patients are inconsistent with the basic assumption of a flat profile PA flow in the Doppler-based calculation.

Second, inaccurately measured PAD can be a cause of error in calculation of flow. Given that the PAD is squared in the formula for the Qp/Qs calculation, the errors in PAD measurements may have magnified the errors of the measured Qp/Qs. In our study, PAD was measured as the distance between inner borders of the PA wall in ME-aAo-SAX during the greatest systolic expansion of the vessel. Yet, in doing so, the parallel alignment of the walls to the ultrasound often made it difficult to visualize the walls. When this difficulty was encountered, the width of the color signal of the PA flow on CDI was substituted for the distance on the two-dimensional image. The accuracy of the PAD measurements may be compromised by a fuzzy definition of inner borders due to either suboptimal resolution or the "bleed-through" phenomenon specific to CDI [20]. Moreover, the dimension of the PA changes throughout the cardiac cycle [21]. Automated cardiac flow measurement, a method in which the color Doppler velocity profiles are automatically spatially and temporally integrated, requires fewer assumptions about the PA flow profile or the PA dimensional change mentioned above. This method correlates outstandingly with oximetry in determining Qp/Qs, with an accuracy comparable to that of the conventional pulsed Doppler method [22]. Nearly two-thirds of the patients (17/26) in our study had PH, and the PH was severe in 8 cases. This suggests that several patients with markedly dilated PA were included in the

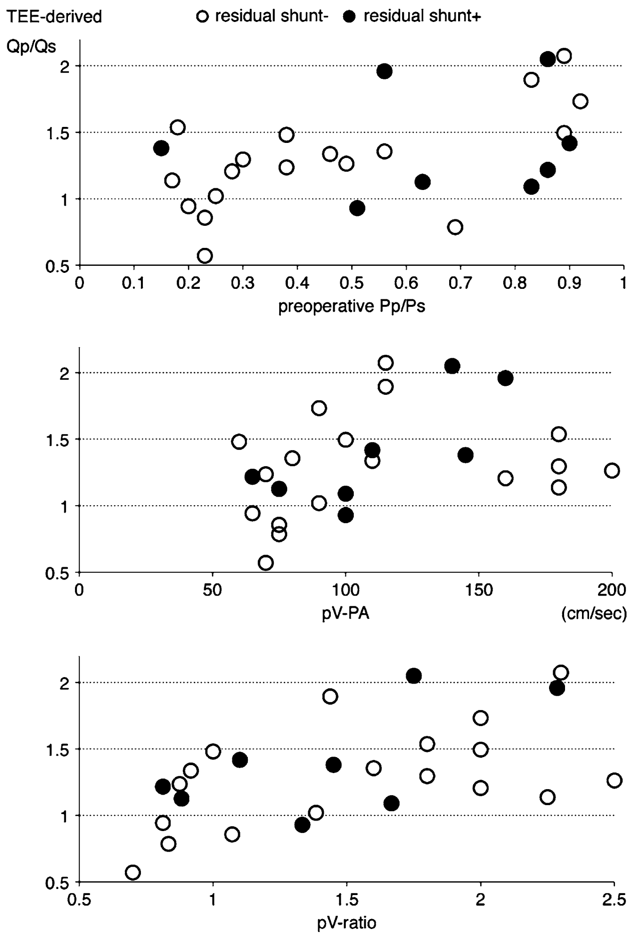

Fig. 1 Correlations of the TEE-related Qp/Qs with the preoperative Pp/Ps, pV_{PA}, and pV ratio. Patients without residual shunt are shown as *white circles* and patients with residual shunt are shown as *black circles*. The TEE-derived Qp/Qs correlated with the preoperative Pp/Ps (*upper panel*), pV_{PA} (*middle panel*), and pV ratio (*lower panel*). *Qp/Qs* ratio of the pulmonary blood flow to the systemic blood flow, *Pp/Ps* ratio of the pulmonary pressure to the systemic pressure, pV_{PA} peak velocity of PA flow, *pV ratio* ratio of pV_{PA} to pV_{LVOT}

population. Dilated PA might cause greater errors in PAD measurement, as larger measurements are involved and the changes in size are greater throughout the cardiac cycle. Incidentally, TEE-derived Qp/Qs correlated with preoperative Pp/Ps, but not with the PAD or PAD/LVOT ratio. Our results suggest that the lack of accuracy in the TEE-derived Qp/Qs in our patients with PH might be chiefly related not to the inaccurate measurements of the PAD, but to the abovementioned heterogeneity of the PA flow profiles. Cloez et al. [7] conclude their paper by emphasizing that high-quality Doppler signals are necessary for accurate and reliable measurements of the Qp/Qs, regardless of the methods used.

Third, inaccurate flow profiles and vessel diameters can also be a source of error in measuring systemic blood flow (Qs). While 10 of our patients had RCCP or NCCP, none of them showed any significant aortic regurgitation. Unlike the peak velocity of the PA flow, the peak velocity of the LVOT was low and had a spectral width which probably accounted for less than 25% of the peak velocity. Yet angle correction was more frequently applied in measuring the LVOT velocities, and the angle in obtaining the LVOT flow was larger than that in obtaining the PA flow. This occurred due to the frequent substitution of the TG-LV-LAX with the mid-esophageal aortic valve long-axis view to obtain the LVOT flow. In the majority of the cases (22/26), the pediatric biplane probe was used in our study. The use of a biplane probe can constitute an important reason for the inability to visualize TG-LV-LAX or align the ultrasound to the blood flow. Yet, in our study, the angle correction applied to the patients with the biplane probe was quite similar to that applied to the patients with the multiplane probe, both in frequency and in size. Darmon et al. [12], meanwhile, used a biplane probe to indicate the accuracy of Doppler echocardiography in the quantification of cardiac output measured at the aortic valve using the TG-LV-LAX view. In other studies, the angle correction was either prohibited or kept to less than 20° [6–8]. Yet, in our study, the accuracy of the TEE-derived Qp/Qs was not improved when patients requiring an angle correction of greater than 30° were excluded. It remains unclear whether the cross-sectional area of the LVOT can be assumed to be circular under conditions where the outlet-type VSD is closed with a patch, and this could also affect the accuracy of the measurements. The aortic dimension also changes throughout the cardiac cycle, but to a lesser degree than the PA dimension [21].

Having failed to improve the accuracy of the TEE-derived Qp/Qs by excluding any of the individual factors, we conclude that the causes of the inaccuracy were multifactorial. The number of patients studied was too small to elucidate the influence of each factor by multivariate analysis.

On the other hand, our study also strongly suggested that qualitative evaluation of residual leakage by two-dimensional TEE with CDI is reliable in determining the need for re-repair of a residual leakage. Every leakage that had been determined by intraoperative TEE to be too minor for re-closure disappeared spontaneously before the follow-up TEE. Furthermore, no significant residual leakage lasting up to the follow-up period ever resulted from detection failures of the TEE.

The incidence of residual leakage after separation from CPB in our study was 31%. This is comparable to the rates observed after VSD closure for isolated simple VSD in 2 other studies with large sample volumes, namely 25 and 33% in the reports by Dodge-Khatami et al. [23] and Yang et al. [24], respectively. Our incidence of 12% at pre-discharge was far more favorable than the incidences of 35 and 34% in those reports, and our 0% incidences at

Table 3 Comparisons of the TEE-derived Qp/Qs and the error rate

Variables	Criteria	TEE-derived Qp/Qs		Criteria	TEE-derived Qp/Qs		Statistical analysis
		Error rate			Error rate		
Minor leakage	−	1.29 ± 0.38		+	1.40 ± 0.41		NS
		66.7%	12/18		62.5%	5/8	NS
Qp/Qs	≤2	1.25 ± 0.35		>2	1.41 ± 0.42		NS
		64.3%	9/14		66.7%	8/12	NS
Pp/Ps	<0.8	1.19 ± 0.32		≥0.8	1.62 ± 0.37		$P < 0.01$
		61.1%	11/18		75.0%	6/8	NS
Rp	<4	1.27 ± 0.35		≥4	1.61 ± 0.53		NS
		68.2%	15/22		50.0%	2/4	NS
Peak PA velocity	<1.5	1.30 ± 0.41		≥1.5	1.40 ± 0.31		NS
		75.0%	15/20		33.3%	2/6	NS
Peak LVOT velocity	<1.0	1.34 ± 0.40		≥1.0	1.26 ± 0.35		NS
		60.0%	12/20		83.3%	5/6	NS
Velocity ratio	<1.5	1.16 ± 0.34		≥1.5	1.52 ± 0.36		$P < 0.05$
		71.4%	10/14		58.3%	7/12	NS
PAD	<15	1.37 ± 0.38		≥15	1.13 ± 0.38		NS
		61.9%	13/21		80.0%	4/5	NS
LVOTD	<15	1.37 ± 0.38		≥15	1.13 ± 0.38		NS
		61.9%	13/21		80.0%	4/5	NS
Diameter ratio	<1	1.30 ± 0.30		≥1	1.34 ± 0.46		NS
		58.3%	7/12		71.4%	10/14	NS
PA angle correction	−	1.31 ± 0.40		+	1.33 ± 0.39		NS
		60.0%	6/10		68.8%	11/16	NS
LVOT angle correction	≤30	1.47 ± 0.33		>30	1.22 ± 0.40		NS
		81.8%	9/11		53.3%	8/15	NS
Surgical approach	TV	1.24 ± 0.35		PA	1.42 ± 0.42		NS
		64.3%	9/14		66.7%	8/12	NS

TEE-derived Qp/Qs are presented as mean ± standard deviation, and the error rates are presented as percentage and number of patients. The unpaired *t* test and Mann–Whitney *U* test were used for comparisons of the TEE-derived Qp/Qs and the error rate between 2 groups, respectively

Qp/Qs ratio of pulmonary blood flow to systemic blood flow, *Pp/Ps* ratio of pulmonary blood pressure to systemic blood pressure, *Rp* pulmonary vascular resistance, *PA* pulmonary artery, *LVOT* left ventricular outflow tract, *PAD* PA diameter, *LVOTD* LVOT diameter, *TV* tricuspid valve

follow-up also compared favorably with the 9% incidence at the median follow-up of 3.1 years in the former report by Dodge-Khatami et al.

Dodge-Khatami et al. [23] reported that defects of less than 2 mm are likely to close spontaneously. Yang et al. concluded that defects on CDI measuring more than 4 mm in diameter predicted the need for immediate reoperation, while 3 mm defects were potentially significant and required additional intraoperative hemodynamic evaluation [24]. Though our measurements of the sizes of the jets were inexact, our method of grading the leakage based on subjective judgment by anesthesiologists experienced with TEE was certainly stricter than the actual measurements in the other two reports. Thus, our method exhibited excellent reliability in predicting the absence of residual leakage in the follow-up period.

In conclusion, two-dimensional TEE can reliably detect residual leakage after corrective surgeries for VSD and lead to optimal judgment on the need for re-closure. However, the TEE-derived Qp/Qs lacks the accuracy required to play a crucial role in quantitatively measuring the severity of residual shunt.

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