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CONGENITAL

A novel parameter for pulmonary blood flow during palliative procedures: velocity time integral of the pulmonary vein†

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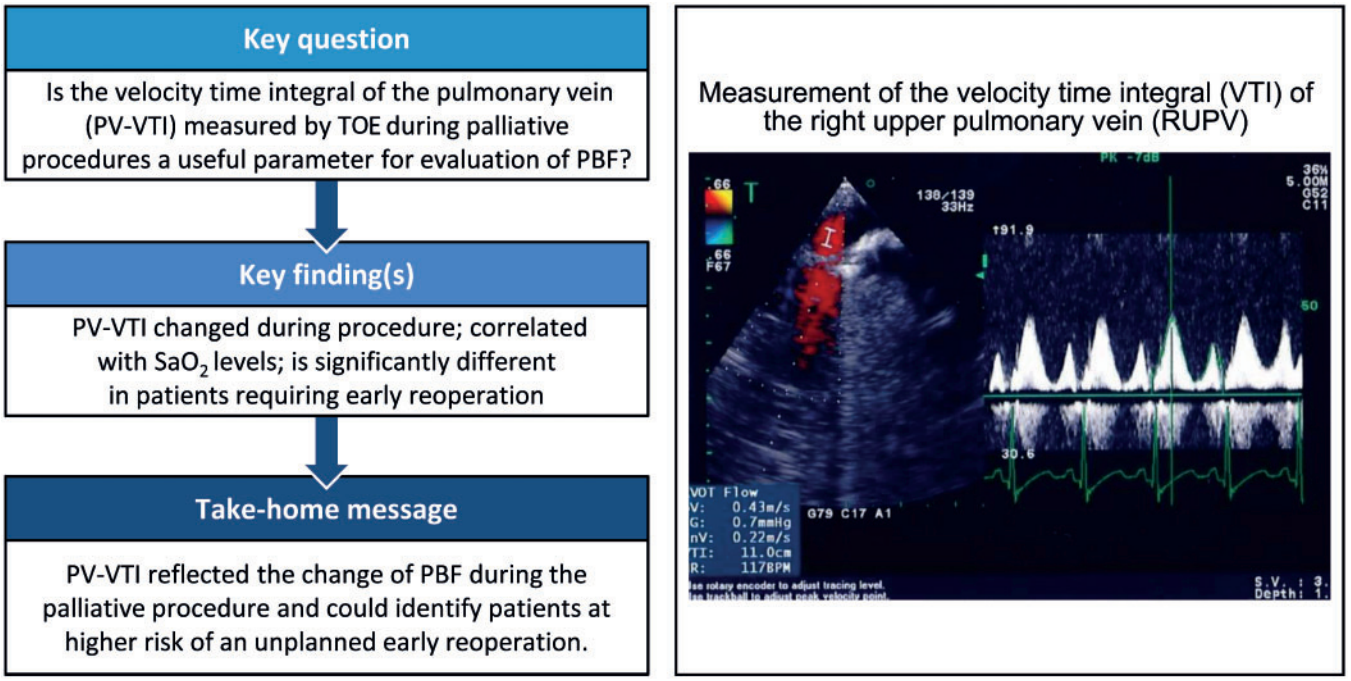

Abstract

OBJECTIVES: The main goal of palliative procedures for congenital heart defects is adequate pulmonary blood flow (PBF), but precise intraoperative PBF evaluation is sometimes difficult. The purpose of this preliminary study was to investigate the usefulness of velocity time integral of the pulmonary vein (PV-VTI) measured by transoesophageal echocardiography (TOE) at the time of palliative procedure as a parameter for PBF.

METHODS: Case histories of 63 patients who underwent palliative procedures (bilateral pulmonary artery banding in 18 patients, main pulmonary artery banding in 22 patients and systemic-to-pulmonary artery shunt in 23 patients) and whose intraoperative PV-VTI was measured by TOE from 2011 to 2017 at our centre were retrospectively reviewed. Low-body-weight infants, cases in which cardiopulmonary bypass was used and cases that were anatomically difficult to measure were excluded.

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RESULTS: PV-VTIs measured at 4 orifices of the pulmonary veins were all significantly decreased in both the bilateral pulmonary artery banding and main pulmonary artery banding groups and increased in the systemic-to-pulmonary artery shunt group immediately after the procedure. There were significant correlations between the velocity time integrals of both right and left pulmonary veins and arterial oxygen saturation ($r = 0.564$ and 0.703). Nine patients (6 bilateral pulmonary artery banding and 3 systemic-to-pulmonary artery shunt) required unplanned early reoperation due to inadequate PBF; their PV-VTIs were significantly different from those of patients not requiring reoperation. No major complications related to TOE occurred postoperatively.

CONCLUSIONS: The PV-VTI measured by TOE during palliative procedures reflected the change of PBF and could help identify patients at higher risk of early reoperation due to inadequate PBF. This parameter may be a useful additional tool for evaluating intraoperative PBF.

Keywords: Velocity time integral of the pulmonary vein • Transoesophageal echocardiography • Pulmonary artery banding • Systemic-to-pulmonary artery shunt

INTRODUCTION

In the field of congenital heart surgery, palliative procedures remain necessary in several situations. There are 2 main palliative procedures: systemic-to-pulmonary artery shunt (SPS) and pulmonary artery banding (PAB). The main purpose of these palliative procedures is to balance the systemic and pulmonary circulation. SPS provides adequate pulmonary blood flow (PBF) and PAB limits excessive PBF. Although palliative procedures attempt to provide adequate pulmonary circulation, precise evaluation of PBF is sometimes difficult during palliative procedures; thus, unplanned early reoperation for readjustment of PAB or revision of SPS is occasionally required [1–5]. During the palliative procedure, surgeons determine the degree of banding and confirm SPS flow with reference to systemic and pulmonary blood pressures, arterial oxygen saturation (SaO_2) levels and the velocity of blood flow at the banding site by intraoperative epicardial echocardiography, but these parameters are not completely reliable at all times [1, 2].

The velocity time integral of the pulmonary vein (PV-VTI) measured by transoesophageal echocardiography (TOE) has recently been reported as a reliable parameter for quantifying PBF [6–13]. Intraoperative TOE during paediatric cardiac surgery has been widely used since the 1980s to evaluate surgical results and to monitor cardiac function immediately [14–16]. To the best of our knowledge, however, no study has investigated the usefulness of the PV-VTI measured by intraoperative TOE during paediatric palliative surgery as a novel and additional index of PBF.

The purpose of this preliminary study was to investigate the relationship between PBF and the PV-VTI measured by intraoperative TOE during palliative procedures, and to investigate whether this index could predict which patients would require unplanned early reoperation for readjustment of PBF.

MATERIALS AND METHODS

Study group

This study was approved by the Institutional Review Board of the Niigata University Hospital. Because of the retrospective nature of this study, individual patient consent was waived. The case histories of 63 paediatric patients who had undergone palliative cardiac procedures [main pulmonary artery banding (mPAB) in 22 patients, bilateral pulmonary artery banding (BPAB) in 18 patients, and SPS in 23 patients] and whose PV-VTI was measured by intraoperative TOE from 2011 to 2017 in our institution were retrospectively reviewed. To eliminate the effects of cardiopulmonary bypass (CPB), concomitant CPB cases were excluded from this study. In the SPS group, patients who simultaneously underwent ligation of the arterial duct were also excluded from this study to simply observe the change of PBF with additional SPS flow. Low-body-weight infants <2.5 kg, early reoperation (within 30 days after a prior palliative operation) cases, patients whose anatomy was difficult to assess for PV-VTI and patients whose PV-VTI was not measured because of haemodynamic instability or another reason were also excluded from this study. Figure 1 shows the CONSORT flow diagram of this study with inclusion information.

Intraoperative transoesophageal echocardiography

TOE examinations (Aloka UST-52110; Hitachi-Aloka single-plain echo probe, 5 MHz, 5.3 mm), incorporating colour flow, pulsed and continuous wave Doppler ultrasonography, were performed during palliative procedures by 4 experienced anaesthesiologists. The pulsed-wave sample volume of the pulmonary venous flow was obtained at 4 points: at the orifices of the right upper pulmonary vein (RUPV), right lower pulmonary vein, left upper pulmonary vein and left lower pulmonary vein individually. PV-VTI was measured before and after banding of the pulmonary artery or reconstruction of the SPS during the operation. The PV-VTI was defined as the area under the curve of the pulse Doppler profile of the pulmonary vein in 1 cardiac cycle (Fig. 2).

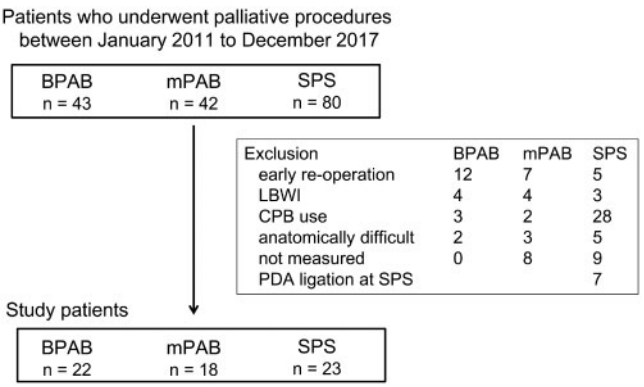

Figure 1: Patient selection flow. BPAB: bilateral pulmonary artery banding; CPB: cardiopulmonary bypass; LBWI: low-body-weight infant; mPAB: main pulmonary artery banding; PDA: patent ductus arteriosus; SPS: systemic-to-pulmonary artery shunt.

Figure 2: Example of intraoperative velocity time integral of the pulmonary vein measurement of right upper pulmonary vein. Doppler flow profile obtained at 4 orifices of the pulmonary vein; the velocity time integral of the pulmonary vein was calculated as the area under the curve of the pulmonary vein Doppler flow in one cardiac cycle.

Palliative procedures

BPAB was done through a median sternotomy in all cases; banding tapes of 1.5 mm width were encircled around the bilateral pulmonary artery branches. The degree of banding was determined according to the blood pressure and oxygen saturation level of the arterial blood, which ranged from 70% to 80% on room air. mPAB was carried out with 4-mm-wide Teflon tape through a median sternotomy in 14 cases and through a left thoracotomy in 8 cases. SPS was reconstructed using an extended polytetrafluoroethylene tube graft (Gore-Tex vascular graft, W.L Gore & Associates, Inc., Azusa, CA, USA) through a median sternotomy in 17 cases and through a thoracotomy in 6 cases. CPB was not used during these procedures in this study group. Details of the study patients are shown in Table 1.

Statistical analysis

Data are expressed as means ± standard deviation for normally distributed continuous variables or as medians for skewed continuous variables, according to the Shapiro–Wilk test. Testing for differences in PV-VTI was performed using the unpaired Student's *t*-test for comparison between reoperation cases and no reoperation cases, and the paired *t*-test for change before and after palliative procedure. Correlations were tested with Pearson's coefficients. No correction for multiple testing was performed. All the statistical tests were 2-sided, and *P*-values of 0.05 or less were considered statistically significant. A statistical analysis was performed using the SPSS statistical software (Version 16.0, SPSS, Inc., Chicago, IL, USA).

RESULTS

Bilateral pulmonary artery banding

Eighteen patients underwent BPAB. Dominant primary diagnoses of these patients were hypoplastic left heart syndrome and its variant in 10 patients. Details of patient characteristics are shown in Table 1. There were no cases of mortality or morbidity related to intraoperative TOE. After the banding procedure, the SaO_2 was significantly decreased. PV-VTIs measured at 4 pulmonary veins were significantly decreased immediately after the banding procedure (Table 2). There were significant correlations between both right and left PV-VTIs and SaO_2 at the time of PV-VTI measurement (Fig. 3). Of these patients, 6 required unplanned early reoperation (<30 days) due to inappropriate degree of banding: 5 patients had low PBF and 1 patient had excess PBF. The low-flow patient had significantly lower RUPV-VTI compared to patients not requiring reoperation (6.6 ± 1.5 vs 10.9 ± 3.8 cm, $P = 0.029$); the high-flow patient also had a significantly higher PV-VTI of 27.9 cm (Fig. 4).

Table 1: Baseline patient characteristics

BPAB patients	
Age at procedure	3–12 days
Primary diagnosis	
HLHS/variant	10
TAC	3
Other	5
mPAB patients	
Age at procedure	5 days to 4 months
Primary diagnosis	
CAVSD	6
DORV	6
VSD/AAO	4
Other	6
SPS patients	
Age at procedure	4 days to 10 months
Primary diagnosis	
TOF/DORV	17
PA/IVS	6
SV	5
Other	2

AAO: aortic arch obstruction; BPAB: bilateral pulmonary artery banding; CAVSD: complete atrioventricular septal defect; DORV: double outlet right ventricle; HLHS: hypoplastic left heart syndrome; IVS: intact ventricular septum; mPAB: main pulmonary artery banding; PA: pulmonary atresia; SPS: systemic-to-pulmonary artery shunt; SV: single ventricle; TAC: truncus arteriosus communis; TOF: tetralogy of Fallot; VSD: ventricular septal defect.

Main pulmonary artery banding

Twenty-two patients underwent mPAB. Dominant primary diagnoses of these patients were complete atrioventricular septal defect in 6 and double outlet right ventricle in 6. Details of patient characteristics are shown in Table 1. There were no cases of mortality or morbidity related to intraoperative TOE. After the banding procedure, SaO_2 was significantly decreased. PV-VTIs measured at 4 pulmonary veins were significantly decreased immediately after the banding procedure (Table 2). There was no unplanned early reoperation (<30 days) due to inadequate PBF in this study group.

Systemic-to-pulmonary artery shunt

Thirty patients underwent SPS. Dominant primary diagnoses of these patients were tetralogy of Fallot or double outlet right

ventricle in 11. Details of patient characteristics are shown in Table 1. There were no cases of mortality or morbidity related to intraoperative TOE. After SPS reconstruction, SaO_2 was significantly increased. PV-VTIs measured at 4 pulmonary veins were significantly increased in 23 patients who did not undergo simultaneous ligation of the arterial duct (Table 2). Of these patients, 3 required unplanned early reoperation (<30 days) due to shortage of shunt flow. The low-flow patient had a significantly lower PV-VTI than patients not requiring reoperation (8.5 ± 4.0 vs 18.1 ± 5.3 cm, $P = 0.020$).

DISCUSSION

To the best of our knowledge, this is the first report to evaluate the PV-VTI as a parameter for PBF measured by intraoperative TOE during palliative procedures for paediatric cardiac defects. This study demonstrated that the PV-VTI measured by intraoperative TOE decreased after the banding procedure, whereas it increased after SPS reconstruction immediately. Both right and left PV-VTIs were correlated with SaO_2 before and after BPAB. Furthermore, the PV-VTI of patients who required unplanned early reoperation was significantly different from that of patients not requiring early reoperation.

Table 2: Changes of the PV-VTI before and after palliative procedures

Variables	Before, mean ± SD	After, mean ± SD	*P*-value
BPAB patients			
SaO_2 (%)	93.2 ± 5.4	80.9 ± 10.7	<0.001
VTI-RUPV (cm)	20.0 ± 6.0	10.6 ± 5.7	0.018
VTI-RLPV (cm)	15.4 ± 6.4	7.7 ± 2.6	0.027
VTI-LUPV (cm)	17.9 ± 5.0	10.7 ± 4.2	0.028
VTI-LLPV (cm)	15.6 ± 5.1	9.7 ± 4.4	<0.001
mPAB patients			
SaO_2 (%)	93.7 ± 6.5	86.4 ± 9.6	<0.001
VTI-RUPV (cm)	20.8 ± 4.5	12.3 ± 3.3	<0.001
VTI-RLPV (cm)	15.8 ± 5.2	10.1 ± 4.2	<0.001
VTI-LUPV (cm)	17.6 ± 3.6	13.3 ± 5.3	<0.001
VTI-LLPV (cm)	17.9 ± 7.1	12.8 ± 5.7	<0.001
SPS patients			
SaO_2 (%)	85.2 ± 8.9	88.6 ± 7.3	0.021
VTI-RUPV (cm)	15.5 ± 4.6	16.7 ± 5.0	0.017
VTI-RLPV (cm)	11.2 ± 3.1	14.8 ± 4.4	0.008
VTI-LUPV (cm)	13.5 ± 5.0	18.0 ± 5.0	0.007
VTI-LLPV (cm)	12.3 ± 3.9	15.2 ± 3.5	0.003

BPAB: bilateral pulmonary artery banding; LLPV: left lower pulmonary vein; LUPV: left upper pulmonary vein; mPAB: main pulmonary artery banding; PV: pulmonary vein; RLPV: right lower pulmonary vein; RUPV: right upper pulmonary vein; SaO_2: arterial oxygen saturation; SD: standard deviation; SPS: systemic-to-pulmonary artery shunt; VTI: velocity time integral.

Velocity time integral of the pulmonary vein as a parameter for pulmonary blood flow

The PV-VTI has been previously reported as a reliable parameter for PBF in several fields. In an experimental animal model, the PV-VTI measured by TOE was significantly correlated with a regional change of PBF [6]. The correlation between the PV-VTI and PBF in patients with congenital heart defects was previously confirmed by some authors [7, 8]. Furthermore, in a study of low-body-weight infants, the lower PV-VTI was a significant predictor for spontaneous closure of the arterial duct [9]. In this analysis, this parameter decreased in the BPAB and mPAB groups and increased in the SPS group and they were correlated with SaO_2; thus, these findings are in agreement with previous literatures that reported the relationship between the PV-VTI and PBF.

In the conventional method for quantification of total PBF by means of echocardiography, both velocity time integral of the pulmonary artery and the cross-sectional area of the pulmonary artery should be measured. However, the diameter of the pulmonary artery is frequently difficult to measure accurately, especially in small infants. Accordingly, a previous report described PV-VTI as a simple and sensitive parameter for the quantification of the ratio of pulmonary to systemic blood flow in patients with secundum atrial septal defect (ASD) [7], and they argued that the measurement of PV-VTI does not require the dimensions of the pulmonary artery or the ventricular outflow tract, hence minimizing the measurement error.

Measurement of velocity time integral of the pulmonary vein by intraoperative transoesophageal echocardiography

Intraoperative TOE had been widely used in the field of paediatric cardiac surgery since the 1980s to confirm cardiac function, the preoperative diagnosis and the results of intracardiac repair [14–17]. Intraoperative epicardial echocardiography has also

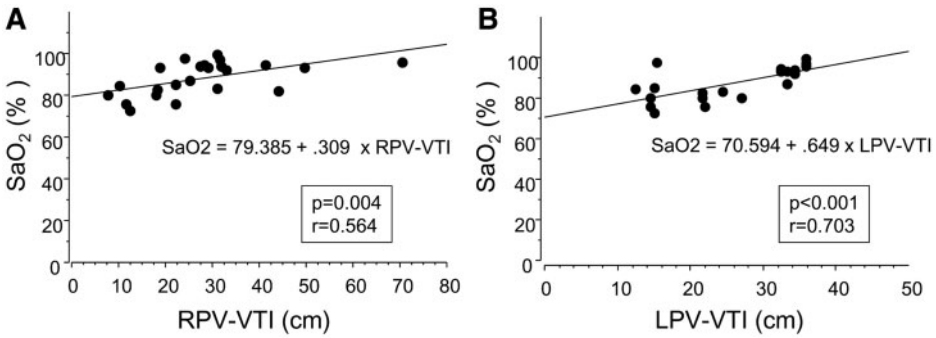

Figure 3: Correlation between the PV-VTI and SaO_2. RPV-VTI = RUPV-VTI + RLPV-VTI; LPV-VTI = LUPV-VTI + LLPV-VTI. LLPV: left lower pulmonary vein; LPV: left pulmonary vein; LUPV: left upper pulmonary vein; RLPV: right lower pulmonary vein; RPV: right pulmonary vein; RUPV: right upper pulmonary vein; SaO_2: arterial oxygen saturation; VTI: velocity time integral.

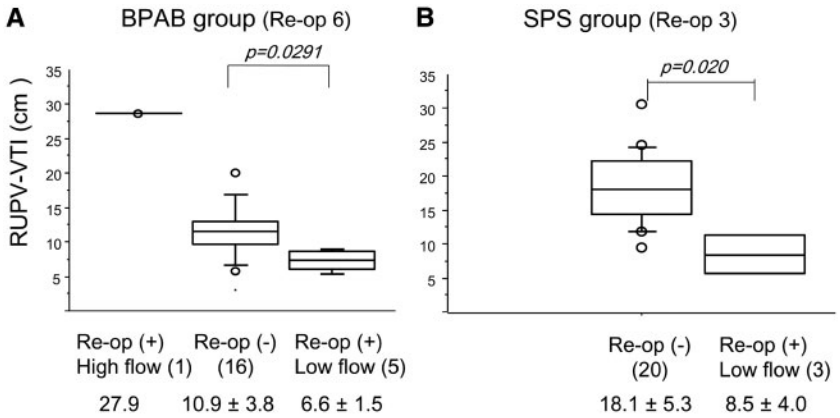

Figure 4: RUPV-VTI of unplanned early reoperation (<30 days) cases. BPAB: bilateral pulmonary artery banding; Re-op: reoperation; RUPV: right upper pulmonary vein; SPS: systemic-to-pulmonary artery shunt; VTI; velocity time integral.

been widely used for paediatric cardiac surgery, though it seems to have several disadvantages: limitation of the echo window, interruption of the surgical procedure during measurement, invasion of the surgical field and the possible risk of hypotension induced by compression of the heart. On the contrary, TOE does not interrupt the procedure during an operation and has a low risk of compression of the heart. Furthermore, PV flow was more easily measured by TOE than by epicardial echocardiography, probably because of the positional relation of PV and oesophagus. Although a multi-plane echo probe would be desired to measure the PV flow, only a single-plane echo probe was used for the TOE measurement in this study because of the size of the small infants. However, we could observe and measure the changes of PV-VTIs of all 4 pulmonary veins intraoperatively.

Identification of a high-risk patient for unplanned early reoperation by velocity time integral of the pulmonary vein

Another finding of this study is that the PV-VTI of the patients who required unplanned early reoperation was significantly different from that of patients not requiring reoperation. Because RUPV was the easiest site of all 4 pulmonary veins for PV-VTI measurement, we compared the velocity time integral of RUPV. Thus, the PV-VTI seemed to be a useful predictor of inadequate PBF and may help to avoid unplanned early reoperation. The goal of palliative surgery for congenital heart defects is to maintain the balance between the systemic and pulmonary circulations; therefore, adequate control of PBF is essential. Inadequate balance of PBF after palliative procedures may lead to several morbidities and mortality, such as persistent pulmonary hypertension, congestive heart failure, shunt occlusion and unbalanced growth of right to left pulmonary arterial growth [1, 2, 4, 5]. Furthermore, unplanned early reoperation for readjustment of banding degree and revision of SPS is occasionally required. Therefore, precise intraoperative evaluation of PBF and right-to-left balance during palliative procedures is crucial.

The conventional measurement method of PBF is by the indicator dilution technique or oximetry using Fick's principle with a Swan–Ganz catheter, but these methods are invasive, and therefore, difficult intraoperatively, especially in small infants. Other methods for measuring PBF, including cardiac magnetic resonance imaging and radionuclide imaging, are not feasible for the purpose of intraoperative evaluation. In a clinical situation, the degree of pulmonary artery banding is determined by Trusler's rule, the change of systemic arterial blood pressure, SaO_2 and the blood pressure of the distal pulmonary artery. However, this is sometimes difficult to evaluate accurately using these parameters because of hypotension, desaturation of pulmonary venous blood from parenchymal lung disease such as atelectasis and persistent pulmonary artery hypertension of the neonate. In addition, with the conventional method of assessment it is impossible to verify the right-to-left balance. To avoid early reoperation, an adjustable PAB device had been reported [17], though it is expensive and is not feasible for BPAB. Furthermore, for patients with hypoplastic left heart syndrome who are planning the hybrid Norwood–Glenn procedure, right-to-left balance of PBF is ideal because such patients have a longer waiting period of around 3–4 months [3–5] and balanced pulmonary arterial growth is necessary for next-stage cavopulmonary anastomosis. Therefore, a real-time, less invasive and simple parameter that can quantify PBF and evaluate right-to-left balance is desirable during PAB and SPS intraoperatively.

Possible advantages of velocity time integral of the pulmonary vein for palliative procedure

For reasons mentioned above, there are several possible advantages of the PV-VTI measured by intraoperative TOE during palliative procedures. First, the PV-VTI changes immediately after palliative procedures in real time; therefore, surgeons can determine the banding degree and revision of SPS if necessary. Second, this parameter can be easily obtained without any manoeuvres in the operative field during the surgical procedure without interruption. Third, right-to-left balance can be evaluated by means of quantification of PBF and compared with before and after the procedure. Fourth, this parameter may demonstrate the cut-off value for the life-threatening high pulmonary flow shock after SPS. Further investigation regarding this issue is warranted. We believe that this novel index measured by intraoperative TOE could be clinically novel and an additional parameter for evaluating total PBF and assessing the right-to-left balance.

Limitations

One of the main limitations of this study is that the PV-VTI was not measured in all cases during the study period. There were patients in whom the anatomy of all the 4 pulmonary veins was not feasible for measuring the PV-VTI. However, it may not be necessary to measure the PV-VTIs of all 4 veins, because a previous report [7] suggested that PV-VTIs of only the right and left upper pulmonary veins were measured and well reflected the total PBF. Low-body-weight infants cannot be assessed because of echo probe size; therefore, development of a smaller size echo probe is warranted.

Second, the effects of respiratory condition, oxygen partial pressure and pH of arterial blood and heart rate were not evaluated. Previous studies reported that these factors affected the blood flow pattern of the pulmonary veins. Moreover, atelectasis due to lateral thoracotomy apparently influences the lung condition and PBF. Further prospective analyses in which the effects of these conditions are simultaneously evaluated would be desirable.

CONCLUSION

The PV-VTI measured by intraoperative TOE changed during paediatric palliative procedures, was correlated with SaO_2 and may reflect PBF. There was a significant difference in the PV-VTI between patients requiring unplanned early reoperation and those who did not.

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Conflict of interest: none declared.

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