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Right Ventricular Pump Efficiency in Secundum-Type Atrial Septal Defect

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Background: A well-functioning cardiopulmonary system, which works as a pump, should generate adequate stroke volume with as little stroke work as possible. We propose a new composite parameter, right ventricular (RV) pump efficiency (η) = left ventricular stroke volume / right ventricular stroke work, to describe this idea in a volume overload population with secundum-type atrial septal defect (ASD).

Methods: We consecutively enrolled 50 patients with secundum-type ASD to investigate the relationship between right-sided volume overload and RV pump efficiency. Sixteen patients with a pulmonary to systemic flow ratio (Qp/Qs) > 1.5 underwent implantation of an occluder. The paired t test was used to compare RV pump efficiency before and after ASD closure.

Results: RV pump efficiency was inversely correlated with Qp/Qs and was $60 \pm 20‰ \cdot mmHg^{-1}$ at Qp/Qs = 1. After ASD closure, RV volume, ejection fraction and free wall strain all significantly decreased, while RV pump efficiency significantly increased from 27.4 ± 13.6 to $63.9 \pm 20.4‰ \cdot mmHg^{-1}$.

Conclusions: RV pump efficiency can superiorly reflect the chronicity and severity of secundum-type ASD.

Key Words: Right ventricular pump efficiency • Three-dimensional echocardiography • Volumetric analysis

INTRODUCTION

Extraordinary role of the right ventricle

Homeotherms need a higher blood pressure to maintain a higher basal metabolic rate than ectotherms. Higher blood pressure also helps maintain adequate brain perfusion against gravity but impairs gas exchange in the alveoli.[1] As a result of independent evolution, homeotherms, including both birds and mammals, have low pressure pulmonary circulation which is separate from high pressure systemic circulation. The former is powered by the right ventricle (RV), the volume pump, and the latter by the left ventricle (LV), the pressure pump.[2-4]

In the past decades, assessments and management of cardiac diseases have been heavily depended on the morphology and performance of the LV. Due to deformation imaging,[5] non-invasive estimation of right-sided ventricular arterial coupling,[6,7] and dedicated software for RV three-dimensional (3D) volumetric analysis,[8,9] the RV is no longer a forgotten chamber in contemporary cardiology. Nevertheless, although conditions of right-sided volume overload are common in adult cardiology, these disease models have been less studied during the renaissance of RV assessments. Instead, the chosen disease models are mostly of right-sided pressure overload with either normal or severely reduced LV function. This not only overemphasizes the contractile function of the RV, but also underemphasizes its nature as a volume

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pump to supply the preload of the LV.

Congenital atrial septal defect (ASD) is a useful model of RV adaptation to a long-standing volume overload condition.[10] Due to the advantage of fewer perioperative confounding factors than traditional surgery,[11,12] many studies have used transcatheter ASD closure devices as the intervention to observe post-operative changes of RV volume and function. Although the size of the RV has rapidly reduced as expected after ASD closure in these studies, there are both reports of improved and reduced RV pumping function.[13-24] Such discrepancies limit the clinical prognostic value of RV functional analysis, not to mention the difficulty in estimating its complex geometry.

Numerous parameters have been proposed to assess RV performance, such as the RV ejection fraction (RVEF), fractional area change and myocardial performance index for systolic function as well as the E/A velocity ratio or E deceleration time for diastolic function, respectively. An ideal index of pumping function should be independent of preload or afterload and be safe to apply in the clinical setting. The gold standard to assess RV function is the pressure volume loop, which describes the whole cardiac cycle irrespective of systolic or diastolic function, where the elastance is derived and independent of load.[3] In this study, we tried to introduce a parameter by revisiting the physics and physiology of the RV with the integration of pressure volume loops.

Derivation of RV pump efficiency (η)

In fluid mechanics, a pump is defined as a machine to do work on a fluid, that is, an energy-absorbing machine. A pump works to add mechanical energy to a fluid, and makes energy transformation from this mechanical input power into hydraulic power, that is, output power. The ratio of the pump output power to the input power is defined as the "pump efficiency (η)". To assess the performance of a pump is directly to describe the relationship between the input power needed to drive the pump and the hydraulic power generated by the pump, and pump efficiency can be defined as:

$$\eta = \frac{\rho \cdot g \cdot Q \cdot H}{P}$$

(η, pump efficiency; ρ, density of a fluid; g, gravitational constant; Q, flow of a pump; H, pressure rise; P, mechanical input power)

where the numerator represents the hydraulic power, or output power, and is the integrity of ρ, g, Q and H, and the denominator indicates the mechanical input power.[25,26]

As the very first of the in-series double pumps, the RV generates cardiac output to accept oxygenation at the alveoli and then to replenish the preload of the left heart. The mechanical input power, or the work done by the RV, is the RV stroke work (RVSW). As for the output power of RV, rather than providing kinetic energy to deliver the blood flow, the RV is more likely to provide potential energy for the blood to overcome pulmonary vascular resistance and the slightly higher left atrium (LA) pressure compared to the right atrium. This makes sure that blood can be delivered to the reservoir for the LV to drain, pressurize and then deliver to the whole body. The idea and relationship of energy transformation by a pump from the mechanical energy of the RV into the potential energy reserved for the LV coincide with the fluid mechanics concept of "pump efficiency" mentioned above, in which the output power generated by the RV is considered as a kind of potential energy. However, in human circulation, it is difficult to evaluate the realistic gravitational potential energy since the blood is disseminated in the pulmonary circulation. According to the pump efficiency equation, the output power is correlated with the flow or stroke volume of a pump. Because of a possible conduit phase of the RV and the presence of tricuspid regurgitant volume, LV stroke volume (LVSV) is used as effective right-sided blood flow, which is true output volume reserved for the LV, rather than RV stroke volume (RVSV). Therefore, the numerator of the equation can be simplified and the potential energy reserved for the LV can be defined as $\kappa \cdot$ LVSV, where κ is our hypothesized coefficient for the potential energy of 1 ml blood at the level of the alveoli, with the assumption that the baseline potential energy of the blood is around zero before being drained into the RV. If we hypothesize that κ is constant, the ratio of LVSV and RVSW will stand for the efficiency of the cardiopulmonary system in transporting the systemic venous return into the potential energy bank for systemic cardiac output.

Considering both ventricles as a whole, a well-functioning cardiopulmonary system should generate adequate LVSV with as low RVSW as possible. Furthermore, severe RV failure could also lead to a reduction in LVSV due to ventricular interdependence. As a result, we proposed a composite parameter as follows:

RV pump efficiency (η) = LVSV / RVSW

to describe this idea, and then validated it in a retrospectively collected ASD population.

The aim of this study was to identify the normal range of RV pump efficiency and its relationship with the severity of RV volume overload.

MATERIALS AND METHODS

Study population

From May 2017 to July 2018, 71 patients were diagnosed with secundum-type ASD at our echocardiographic laboratory. Eleven patients had atrial fibrillation and 10 patients had concomitant structural heart diseases (ventricular septal defect, pulmonic stenosis and more than moderate mitral regurgitation), and these 21 patients were excluded. We enrolled the remained 50 sinus rhythm patients with the diagnosis of pure secundum-type ASD, and 16 patients accepted transcatheter closure with an occluder. The institutional review board approved the collection protocol and waived the requirement to obtain informed consent because of the retrospective and non-invasive study design (CHGH-IRB No: (523)104-59).

Echocardiography

All echocardiograms were performed with the EPIQ 7C system equipped with an X5-1 transducer (Philips Medical Systems, Andover, MA, USA). Two-dimensional and 3D echocardiograms were acquired according to suggested guidelines.[27-29] The 3D echocardiographic datasets were analyzed offline with modules for LV and RV volumetric analyses (Modules of 4D LV-Analysis 3.1 and 4D RV-Function 2.0, TTA 2.3, TomTec Imaging Systems, Unterschleissheim, Germany) to report left ventricular end-diastolic volume index (LVEDVi), left ventricular end-systolic volume index (LVESVi), left ventricular stroke volume index (LVSVi), left ventricular ejection fraction (LVEF), left ventricular global longitudinal strain (LVGLS), left ventricular global circumferential strain (LVGCS), right ventricular end-diastolic volume index (RVEDVi), right ventricular end-systolic volume index (RVESVi), RVEF, peak systolic longitudinal right ventricular free wall strain (RVLSfw) and peak systolic longitudinal right ventricular septal wall strain (RVLSsep).

Figure 1 illustrates the non-invasive calculation of single-beat RV pump efficiency. Detailed methods for the non-invasive estimation of RVSW from a pressure gradient-volume diagram have been described in our previous work.[30] One month after the percutaneous ASD closure procedure, follow-up echocardiography was arranged to monitor the remodeling process of ventricular size and function.

Transcatheter ASD closure

Clinical indication for ASD closure was hemodynamically significant left-to-right shunt [pulmonary to systemic flow ratio (Qp/Qs) > 1.5] with echocardiographic signs of right heart dilation. Pre-procedural transthoracic or transesophageal echocardiograms were used to decide the size of the closure device.

Statistical analysis

Categorical variables were presented as numbers and percentages. Continuous variables were expressed as the mean $\pm$ standard deviation, and were compared using the paired Student's t test. All statistical analyses were performed using SPSS Statistics for Windows (Version 17.0, IBM SPSS Inc., Chicago, IL, USA). All reported p-values were 2-tailed, and p values < 0.05 were considered to be statistically significant.

RESULTS

Baseline characteristics and volumetric data of the 50 patients with ASD

The baseline characteristics of the study population are summarized in Table 1. The average Qp/Qs of the 50 patients was 2.2 $\pm$ 0.9, and the baseline echocardiographic parameters (Table 2) were compatible with right-sided volume overload (RVEDVi: 80.9 $\pm$ 27.5 ml/m^2, LVEDVi: 62.0 $\pm$ 12.9 ml/m^2) with preserved RV and LV systolic function (RVEF: 59.0 $\pm$ 5.8%, RVLSfw: -28.8 $\pm$ 4.9%, RVLSsep: -21.1 $\pm$ 6.2%, LVEF: 68.2 $\pm$ 7.6%, LVGLS: -22.0 $\pm$ 4.8%, LVGCS: -32.7 $\pm$ 6.3%). The tricuspid regurgitation pressure gradient (TRPG) was 31.6 $\pm$ 11.3 mmHg, and the RVSW was 1703.3 $\pm$ 926.4 ml · mmHg.

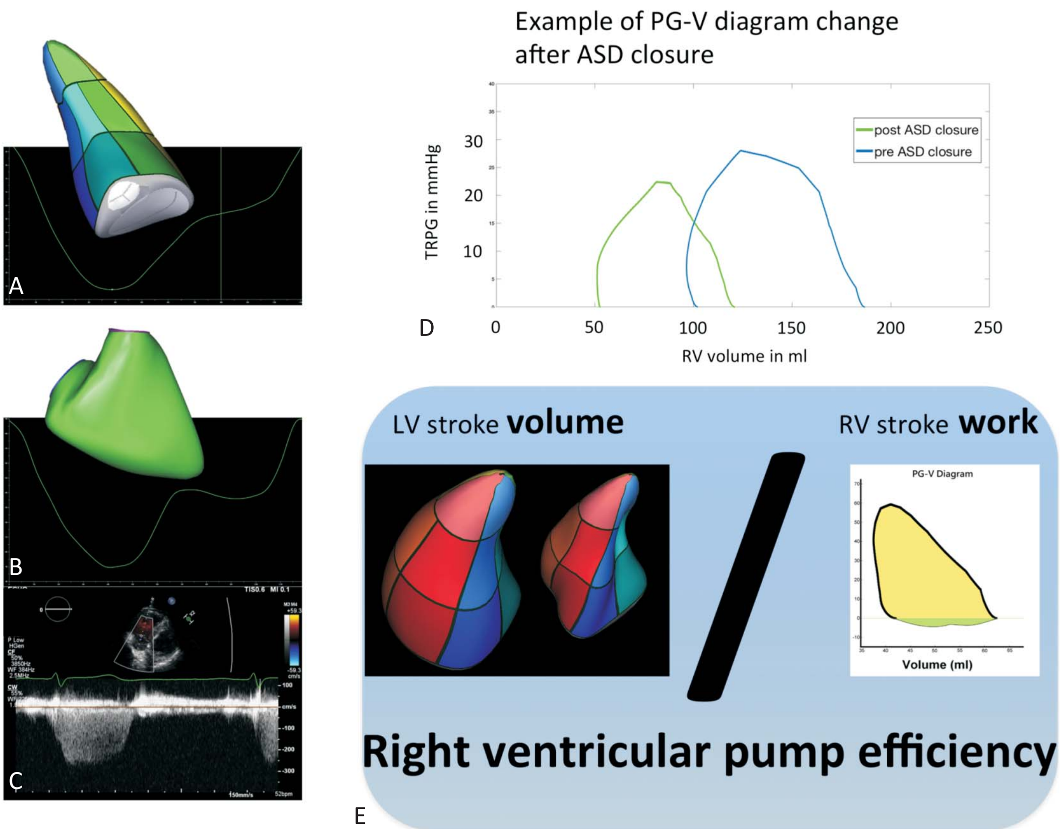

Figure 1. *Calculation of right ventricular pump efficiency. Three-dimensional echocardiography derived volumetric analysis yielded left ventricular stroke volume (A) and right ventricular volume to time curve (B). Conjugation of tricuspid regurgitation pressure gradient envelope (C) and right ventricular volume-to-time curve generates the pressure gradient-volume diagram (D) and the area under the curve is used to calculate the right ventricular stroke work (E). Right ventricular pump efficiency is calculated as left ventricular stroke volume divided by right ventricular stroke work.*

Table 1. Baseline characteristics

	Overall population (n = 50)	ASD closure (n = 16)
Population characteristics		
Age, years	51.0 ± 16.8	48.1 ± 17.7
Male	16 (32%)	6 (37.5%)
Qp/Qs	2.2 ± 0.9	2.4 ± 0.8
Device size, mm	/	26.1 ± 7.0
BSA, m^2	1.6 ± 0.2	1.7 ± 0.2
Diabetes mellitus	10 (20%)	1 (6.3%)
Hypertension	9 (18%)	2 (12.5%)
Coronary artery disease	8 (16%)	0
Prior stroke	1 (2%)	0
Chronic lung disease	0	0
Chronic kidney disease	3 (6%)	0

ASD, atrial septal defect; BSA, body surface area; Qp/Qs, pulmonary to systemic flow ratio.

Before and after ASD closure (Table 2)

Sixteen patients underwent successful transcatheter ASD closure without residual shunt, and the mean device size was 26.1 ± 7.0 mm. After ASD closure, the RVEDVi (88.6 ± 21.4 ml/m^2 vs. 59.9 ± 12.2 ml/m^2, $p < 0.01$), RVESVi (36.0 ± 12.7 ml/m^2 vs. 28.8 ± 8.8 ml/m^2, $p = 0.01$), RVSVi (52.2 ± 10.4 ml/m^2 vs. 31.1 ± 5.4 ml/m^2, $p < 0.01$) and RVEF (59.7 ± 5.9% vs. 52.7 ± 7.5%, $p < 0.01$) were all remarkably reduced. The RVLSfw (30.7 ± 5.0% vs. 27.7 ± 5.6%, $p = 0.03$) and TRPG (32.4 ± 16.3 mmHg vs. 28.5 ± 13.6%, $p = 0.04$) were slightly reduced, but RVLSsep remained unchanged (22.0 ± 5.0% vs. 19.6 ± 7.7%, $p = 0.22$). RVSW was significantly reduced (1930.2 ± 974.8 ml · mmHg vs. 930.6 ± 485.6 ml · mmHg, $p < 0.01$). As to the left heart parameters, LVEDVi (38.4 ± 7.3 ml/m^2 vs. 46.7 ± 8.8 ml/m^2, $p < 0.01$) and LVSVi (25.9 ± 2.9 ml/m^2 vs. 31.6 ± 6.0 ml/m^2, $p < 0.01$) were both significantly increased. LVEF (68.6 ± 8.7% vs. 68.0 ± 6.4%, $p = 0.78$), LVGLS (21.6 ± 4.2% vs. 20.7 ± 3.7%, $p = 0.35$) and LVGCS (32.6 ± 7.1% vs. 36.5 ± 6.4%, $p = 0.10$) remained unchanged.

Table 2. Echocardiographic parameters

	Overall population (n = 50)	Before ASD closure (n = 16)	After ASD closure (n = 16)	p value*
RV				
RVEDV, ml	133.9 ± 48.9	147.9 ± 39.0	99.7 ± 21.7	< 0.001
RVEDVi, ml/m^2	80.9 ± 27.5	88.6 ± 21.4	59.9 ± 12.2	< 0.001
RVESV, ml	55.7 ± 24.8	60.3 ± 22.4	48.0 ± 15.4	0.010
RVESVi, ml/m^2	33.5 ± 13.8	36.0 ± 12.7	28.8 ± 8.8	0.012
RVSV, ml	78.0 ± 27.1	87.0 ± 20.0	51.7 ± 9.6	< 0.001
RVSVi, ml/m^2	47.3 ± 15.7	52.2 ± 10.4	31.1 ± 10.4	< 0.001
RVEF, %	59.0 ± 5.8	59.7 ± 5.9	52.7 ± 7.5	0.006
RVLSsep, %	-21.1 ± 6.2	-22.0 ± 5.0	-19.6 ± 7.7	0.224
RVLSfw, %	-28.8 ± 4.9	-30.7 ± 5.0	-27.7 ± 5.6	0.027
TRPG, mmHg	31.6 ± 11.3	32.4 ± 16.3	28.5 ± 13.6	0.039
RVSW, ml · mmHg	1703.3 ± 926.4	1930.2 ± 974.8	930.6 ± 485.6	< 0.001
RV pump efficiency, ‰ · mmHg^{-1}	32.5 ± 22.1	27.4 ± 13.6	63.9 ± 20.4	< 0.001
LV				
LVEDV, ml	62.0 ± 12.9	64.2 ± 14.6	77.4 ± 15.3	0.002
LVEDVi, ml/m^2	37.5 ± 7.5	38.4 ± 7.3	46.7 ± 8.8	0.001
LVESV, ml	41.9 ± 7.9	21.1 ± 9.8	25.2 ± 8.0	0.076
LVESVi, ml/m^2	12.2 ± 4.6	12.5 ± 5.7	15.1 ± 4.7	0.076
LVSV, ml	41.9 ± 7.9	43.1 ± 6.8	52.2 ± 9.9	0.001
LVSVi, ml/m^2	25.5 ± 4.6	25.9 ± 2.9	31.6 ± 6.0	0.001
LVEF, %	68.2 ± 7.6	68.6 ± 8.7	68.0 ± 6.4	0.783
LVGLS, %	-22.0 ± 4.8	-21.6 ± 4.2	-20.6 ± 3.7	0.354
LVGCS, %	-32.7 ± 6.3	-32.6 ± 7.1	-36.5 ± 6.4	0.102

* p value of paired t test of echocardiographic parameters among the 16 patients before and after ASD closure.
ASD, atrial septal defect; EDV, end-diastolic volume; EDVi, end-diastolic volume index; EF, ejection fraction; ESV, end-systolic volume; ESVi, end-systolic volume index; GCS, global circumferential strain; GLS, global longitudinal strain; LV, left ventricular; RV, right ventricular; RVLSfw, peak systolic longitudinal right ventricular free wall strain; RVLSsep, peak systolic longitudinal right ventricular septal wall strain; SV, stroke volume; SVi, stroke volume index; SW, stroke work; TRPG, tricuspid regurgitation pressure gradient.

RV pump efficiency (η)

Since the mean LVSV was around 40 ml and mean RVSW was around 1700 ml · mmHg, the LVSV directly divided by RVSW would yield a value far less than 1.0, which would be inconvenient in clinical practice. Therefore, we magnify the scale by one thousand per mille.

Baseline RV pump efficiency of all 50 ASD patients was 32.5 ± 22.1‰ · mmHg^{-1}, ranging from 8.8 to 143.6‰ · mmHg^{-1}. For 11 patients with Qp/Qs < 1.5, RV pump efficiency was 56.8 ± 32.2‰ · mmHg^{-1}; for 16 patients with Qp/Qs 1.5-2.0, RV pump efficiency was 32.6 ± 11.1‰ · mmHg^{-1} and for 23 patients with Qp/Qs > 2.0, RV pump efficiency was 20.8 ± 8.6‰ · mmHg^{-1}. According to regression, RV pump efficiency was 60 ± 20‰ · mmHg^{-1} at Qp/Qs = 1. In the 16 patients who underwent ASD closure, RV pump efficiency increased significantly from 27.4 ± 13.6 to 63.9 ± 20.4‰ · mmHg^{-1} after the procedure (Figure 2C).

Figure 2 demonstrates the scatterplots of Qp/Qs, RVEF, TRPG, RVSWi and RV pump efficiency versus RVEDVi. RVEF was not associated with RVEDVi (r = -0.128, p = 0.289), TRPG was positively correlated with RVEDVi but was of poor linearity (r = 0.375, p = 0.001). Qp/Qs and RVSWi were both positively correlated with RVEDVi and were of good linearity (r = 0.848, p < 0.001 for Qp/Qs; r = 0.842, p < 0.001 for RVSWi). RV pump efficiency was inversely correlated with Qp/Qs and RVEDVi.

DISCUSSION

Assessment of the cardiopulmonary system

This study demonstrated the concept and application of RV pump efficiency defined as LVSV divided by

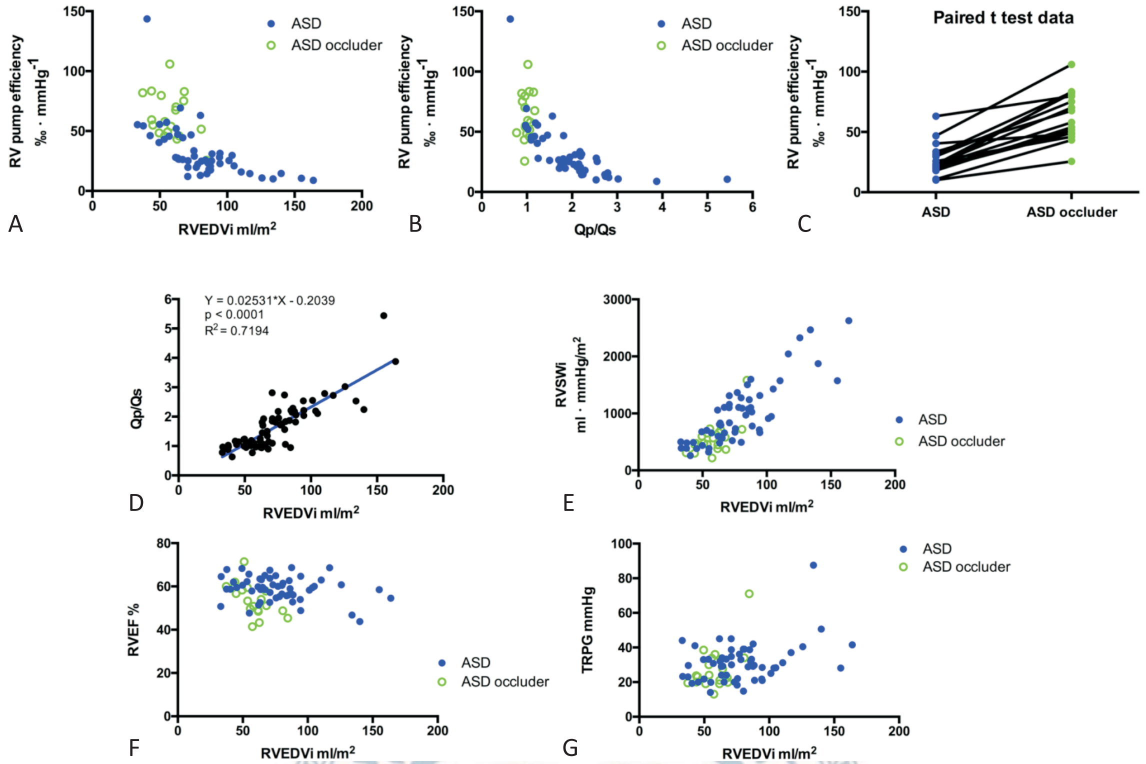

Figure 2. *Relationships between right ventricular pump efficiency and traditional echocardiographic parameters. (A, B) RV pump efficiency is inversely correlated with RVEDVi and Qp/Qs. (C) RV pump efficiency improved after transcatheter closure of ASD. (D, E) Qp/Qs and RVSWi are significantly correlated to RVEDVi with good linearity. (F) RVEF is not significantly correlated with RVEDVi. (G) TRPG is weakly correlated with RVEDVi. ASD, atrial septal defect; EDVi, end-diastolic volume index; EF, ejection fraction; Qp/Qs, pulmonary to systemic flow ratio; RV, right ventricular; SVi, stroke volume index; SWi, stroke work index; TRPG, tricuspid regurgitation pressure gradient.*

RVSW in a volume overload model. 3D volumetric analysis provides the opportunity to use RVEDVi as a surrogate of ASD chronicity and severity. Our ASD population is thus reliable, as both the Qp/Qs and RVSWi were not only significantly correlated but also of good linearity with RVEDVi. Furthermore, the value of RV pump efficiency in the normal population was derived at Qp/Qs = 1 by means of regression. RV pump efficiency was inversely correlated with RVEDVi and Qp/Qs, and reduced RV pump efficiency secondary to ASD with volume overload was improved after transcatheter closure. It is thus reasonable to assess the performance of the whole cardiopulmonary system using RV pump efficiency, as clearly shown in the setting before and after ASD closure, RV pump efficiency improved as RVSW decreased and LVSV increased due to the device therapy.

Considering the pressure pump and volume pump as a whole

In our formula of RV pump efficiency, it is interesting that stroke "volume" of the "pressure" pump and stroke "work" of the "volume" pump were involved alternately, including both pressure and volume parameters. Combining the right and left parameters is not a new idea, and a RVEDV/LVEDV ratio > 1.27 has been reported to be more sensitive than RVEDVi to detect RV enlargement.[31] However, without pressure-related parameters, the RVEDV/LVEDV ratio can only detect but not prevent RV enlargement. In contrast, RV pump efficiency is of higher generalizability because it would be diminished once the increased RV load does not generate comparable LVSV.

Incorporating pressure volume loops

We estimated RVSW from a pressure gradient-volume diagram, and used it to standardize the LVSV for further comparisons, and this could provide several advantages. First, it is not necessary to separate forward RVSV and volume of tricuspid regurgitation (TR), because both volumes should be involved in the RVSW estimation. Second, the pressure volume loop is considered to be the gold standard in assessing RV function, which describes the whole cardiac cycle, irrespective of systolic or diastolic phase, providing an overall estimation. Finally, the body surface area was eliminated when we divide LVSV by RVSW (i.e. the same result with LVSVi/RVSWi).

Volume overload paradox

Regardless of the left or right ventricle, pressure overload conditions eventually lead to impaired ventricular function. Aortic stenosis and pulmonary arterial hypertension can be considered as the prototype of pressure overload diseases of the LV and RV respectively. However, the relationship between ventricular function and disease severity is even more complex in volume overload conditions. Debate over watchful waiting and early surgery for severe degenerative mitral regurgitation[32,33] has shown that it may be too optimistic to use an overestimated LVEF to catch the ideal surgical timing, and that it may lead to post-operative LV dysfunction. Such volume overload paradox also exists in the RV, and as demonstrated in our relatively pure volume overload population, the RVEF could remain > 40% even when the RV was severely dilated (Figure 2F). Furthermore, owing to the better compliance of the right heart,[3] this volume overload paradox may be even more prominent than the left heart. Since the RV is usually under mixed pressure and volume overload conditions, this paradox will limit the prognostic value of current RV evaluation in real-world patients.

Beyond the LVEF

Looking back to the development of echocardiographic parameters, multiple therapeutic trigger points have been defined according to a single index, LVEF. However, for heart failure with preserved ejection fraction (HFpEF), we need several parameters (i.e. LV diastolic function, LA function and RV function) instead of LVEF to gauge disease severity. As a result, we tried to propose a composite parameter with proven feasibility in a pure volume overload disease model to allow for accurate assessments of a spectrum of diseases, including HFpEF, and further studies are warranted to investigate the prognostic value of RV pump efficiency.

Mechanical efficiency, myocardial efficiency or myocardial work efficiency

One parameter with a similar name but different concept, mechanical efficiency (also called myocardial efficiency), which was proposed far from now may be confused with pump efficiency in the present study. Mechanical efficiency is a physics concept, defined as the ratio of mechanical energy of myocardial contraction and consumed chemical energy from metabolism,[34-37] and it is used to investigate energy transformation within the myocardium. In comparison, pump efficiency is defined as the ratio of output energy transmitted from the myocardium to the blood and mechanical energy of myocardial contraction, and it deals with energy transformation between the myocardium and blood. The two parameters, mechanical efficiency and pump efficiency, focus on different stages of energy transformation, and pump efficiency has not been reported before. Another index that might be confused with pump efficiency is myocardial work efficiency, which is a tool used to assess LV function, predominantly in the setting of LV dyssynchrony, and analyze the relationship between constructive work and wasted work due to dyssynchronous contraction. It is used to discuss energy distribution within the myocardium, an irrelevant field beyond our study.[38,39]

Study limitations

There are a number of limitations in this pilot study. First, to estimate RVSW, we conjugated the TR spectral Doppler envelope and RV volume-time curve from different single beats to plot the pressure gradient-volume diagram, and the area under the curve was calculated as RVSW. However, an obscure and ambiguous TR envelope could have compromised the accuracy of RVSW as well as RV pump efficiency. Consequently, the acquisition of high quality TR envelopes may be more time consuming than RV 3D datasets even by well-experienced sonographers. Second, LVSV, RV volume-time curve and TR envelope were actually analyzed from three different heartbeats, and this may also have impeded the accuracy of RV pump efficiency. In addition, the effective LVSV will be overestimated by 3D volumetric analysis in patients with significant aortic or mitral regurgitation. Therefore, the feasibility of applying RV pump efficiency in future longitudinal heart failure studies depends on whether the relatively higher compliance of the RV will make up for this overestimation. Third, the most important limitation of this study is that we hypothesized that the potential energy of 1 ml blood at the level of the alveoli would be equal in every patients (i.e. κ was hypothesized to be constant), and currently we cannot solve the value of κ. Further studies on various etiologies of heart failure are thus warranted to see if it is reasonable to neglect possible differences in κ.

CONCLUSIONS

RV pump efficiency derived from fluid mechanics, circulatory physiology and non-invasive pressure gradient-volume diagram was inversely correlated with Qp/Qs in a volume overload model of secundum-type ASD, and was a superior parameter for the assessment of overall cardiopulmonary performance. In this ASD population, RV volume, RVEF and RV free wall strain were all significantly decreased after transcatheter ASD closure. In contrast to the counterintuitive reduction in RV systolic function, an increase in RV pump efficiency can help to confirm improvements in cardiopulmonary function.

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DECLARATION OF CONFLICT OF INTEREST

All authors declare no conflict of interest to the contents of this paper.

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