Assessment of proximal isovelocity surface area (PISA) shape using three-dimensional echocardiography in a paediatric population with mitral regurgitation or ventricular shunt

Évaluation de la PISA par échocardiographie 3D dans une population pédiatrique avec fuite mitrale ou shunt ventriculaire

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KEYWORDS
Proximal isovelocity surface area; Ventricular shunt; Mitral regurgitation; Real-time three dimensional echocardiography; Paediatric population; Congenital heart disease

Summary
Background. — The proximal isovelocity surface area (PISA) method is validated to quantify mitral regurgitation (MR) and ventricular shunt (VS). However, the two-dimensional echocardiography (2DE) PISA method assumes a hemispherical distribution of velocity factors proximal to the MR or VS orifice.

Aim. — To assess the PISA shape by three-dimensional echocardiography (3DE) in a paediatric population with MR or VS. According to the true PISA shape, we suggest different models to calculate the MR or VS volume by the 3DE PISA method.

Methods. — Thirty-one paediatric patients (aged 1 month to 20 years, median 69 months) were included: 17 had MR and 14 had VS. The orifice area and volume of MR and VS were evaluated by 2DE. 3DE acquired the entire PISA volume at orifice level. The PISA shape was estimated according to three diameters as being hemispherical, prolate hemispheroid, oblate hemispheroid and hemiellipsoid.
Results. — Data from 28 patients were analysed. The PISA shape was variable: hemispherical, 11%; prolate hemispheroid, 43%; oblate hemispheroid, 32%; hemi-ellipsoid, 14%. Oblate hemispheroids occurred more frequently in the MR group (47%), whereas prolate hemispheroids occurred more frequently in the VS group (62%); hemispheres were scarce in both groups (10%). The mean MR or VS orifices and volumes measured by 2DE and 3DE were significantly different (0.123 cm² versus 0.094 cm² and 13.2 mL versus 10.1 mL, respectively; \( p = 0.019 \)).

Conclusions. — 3DE describes the true surface of the PISA shape. In a paediatric population with MR or VS, the PISA is rarely hemispherical but is more often prolate or oblate hemispheroid.

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Abbreviations

2DE two-dimensional echocardiography
3DE three-dimensional echocardiography
MR mitral regurgitant
PISA proximal isovelocity surface area
VS ventricular shunt

Background

Accurate quantification of MR or VS is an ongoing challenge in the evaluation of children with congenital heart diseases. The PISA method is validated to estimate MR and VS volume in adult and paediatric patients [1—3]. However, the 2DE PISA method assumes a hemispherical distribution of velocity factors proximal to the regurgitant (or shunt) orifice. This method has a conspicuous drawback due to the 2D nature of the conventional imaging system, as the true shape of the isovelocity surface may be not hemispherical.

Real-time 3DE is a new technology that can provide information about the 3D shape of the PISA using a handled ultrasound system. A recent in vitro model study validated 3DE PISA imaging to assess MR volume [4]. In clinics, 3DE has been used to measure the regurgitant orifice area volume [5,6]. However, these studies did not describe the true shape of the PISA according the mechanism of regurgitation or shunt. We report the assessment of the PISA shape using 3DE in a paediatric population with either MR or VS.

According to the true shape of the PISA, we suggest different models to calculate the regurgitant (or shunt) volume by the 3DE PISA method.

Methods

Echocardiographic acquisitions

For each paediatric patient with MR or VS, both 2DE (iE33 or Sonos 7500, Philips, with S3 or S8 transducers) and 3DE (X3-1, X4-2 or X7-2 matrix probes, Philips) were performed. Apical and parasternal windows were used for 2DE and 3DE acquisitions of MR and VS PISA, respectively. We optimized the aspect of the proximal convergence field by reducing the colour Doppler aliasing velocity to a value between 20 and 40 cm/s (mean 34 ± 7 cm/s). For colour Doppler 3DE acquisition of the PISA, six smaller real-time volumes, acquired from consecutive cardiac cycles and during a breath hold when possible, were combined to provide a large pyramidal volume. To optimize the frame rate of acquisition, depth was minimized; care was taken to visualize the entire PISA in the acquired volume.

Echocardiographic measurements

The 2DE PISA method was used to evaluate the orifice area and volume of MR and VS [7]. The off-line dedicated Q-Lab 3D 4.2 system (Philips) was used for 3DE PISA analysis. To measure the region at the flow convergence, we...
used the ‘plane-cropping’ mode and moved the active plane along a line transversal to the longitudinal axis of the PISA. All measurements were performed in mid-systole. The isovelocity radius \( r_1 \) was measured in the longitudinal plane as the maximal radial distance between the first aliasing contour and the centre of the regurgitant (or shunt) orifice. Two diameters (D2 and D3) were measured in the transversal plane at the orifice level.

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The surface of the PISA was calculated by applying mathematic formulae, where \( e \) (the eccentricity index) = \( \sqrt{1 - \left(\frac{b}{a}\right)^2} \), \( a \) is the longest radius and \( b \) is the smallest radius:

- hemisphere = \( 2\pi r_1^2 \);
- prolate hemispheroid = \( \pi b(b + a \arcsin \frac{e}{e}) \);
- oblate hemispheroid = \( \frac{1}{2} \pi \left(2a^2 + \left[b^2 \ln \left(1 + e\right)/\left(1 - e\right)/e\right]\right) \).

The hemiellipsoid surface, which depends on the angle, was not calculated. The regurgitant and shunt orifice area and volume of MR and VS were obtained similarly as in the 2DE method, with \( r \) being the maximal radius of the PISA:

- orifice area = \( (2\pi r^2) \times \text{(the velocity at which the aliasing surface occurred/peak velocity of the MR and VS jet)} \);
- volume = orifice area \times \text{velocity time integral of the MR and VS jet}.

**Statistical analysis**

Continuous variables are expressed as means ± standard deviations (S.D.). The differences between regurgitant and shunt orifice areas and volumes of MR and VS measured by 2DE and 3DE were tested. Because of the asymmetric distribution of the values, paired variants were compared using a Wilcoxon test. A t test after value log transformation was used to compare means. Interobserver and intraobserver agreement were assessed with linear regression (Bland-Altman method), and the average differences between readings were corrected for their mean. A value of \( p < 0.05 \) was considered to be significant.

**Results**

**Study population**

Thirty-one children with MR (17 patients) or VS (14 patients) were included. The mean age was 80 ± 29 months with a median age of 69 months (range, 1 month to 20 years). The mean weight was 20 ± 7 kg and mean body surface area was 0.74 ± 0.18 m².
Table 1  PISA shape according to the MR mechanism and VS anatomy.

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>PISA shape</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hemispherical</td>
</tr>
<tr>
<td>MR</td>
<td></td>
</tr>
<tr>
<td>Cleft</td>
<td>4</td>
</tr>
<tr>
<td>Restriction</td>
<td>5</td>
</tr>
<tr>
<td>Prolapse</td>
<td>5</td>
</tr>
<tr>
<td>Mitral annulus dilatation</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>15</td>
</tr>
<tr>
<td>VS</td>
<td></td>
</tr>
<tr>
<td>Perimembranous</td>
<td>10</td>
</tr>
<tr>
<td>Muscular</td>
<td>2</td>
</tr>
<tr>
<td>Infundibular</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>2</td>
</tr>
</tbody>
</table>

MR: mitral regurgitant; VS: ventricular shunt.

PISA shape

The measurement feasibility of the PISA shape using 3DE was 90% (impossible 3DE acquisition due to agitation or poor quality acquisition in three patients). Overall, data from 15 patients with MR and 13 with VS were analysed. The MR mechanism, VS anatomy and PISA shape distribution are reported in Table 1. In the total population, the PISA shape was hemispherical in 11%, prolate hemispheroid in 43%, oblate hemispheroid in 32% and hemiellipsoid in 14% (Figs. 2—5). In the MR group, there was a predominance of the oblate hemispheroid shape (47%) whereas in the VS group the prolate hemispheroid shape occurred more frequently (62%). The PISA shape varied with the MR mechanism. In patients with prolapse or restriction of the mitral valve, the PISA had an oblate hemispheroid shape in 60%, a prolate hemispheroid shape in 20% and a hemiellipsoid shape in 20% (none had a hemispherical shape). In cleft mitral valve patients, the PISA shape was hemispherical in 50%, oblate hemispheroid in 25% and prolate hemispheroid in 25% (none had a hemiellipsoid shape). In the single patient with mitral annulus dilatation, the PISA shape was hemispherical. In patients with VS, the PISA had a prolate hemispheroid shape in 62%, an oblate hemispheroid shape in 15% and a hemiellipsoid shape in 23% (none had a hemispherical shape).

2DE versus 3DE measurements

The MR and VS orifice area and volume were measured by 3DE in 24 patients (four patients with an ellipse PISA shape were excluded). All 2DE and 3DE measurements are reported in Table 2. The mean regurgitant (or shunt) orifices measured by 2DE and 3DE were significantly different (p = 0.019), as were the mean regurgitant (or shunt) volumes measured by 2DE and 3DE (p = 0.019). In the three groups (spherical, oblate and prolate spheroid), no significant differences

Figure 2. Hemispherical PISA shape: a: mathematic model; the three diameters (D1, D2 and D3) are equal; b: 3DE; the PISA in a patient with cleft mitral valve is viewed from the left ventricle.
Figure 3. Prolate hemispheroid PISA shape: a: mathematic model; the two smallest diameters are equal; b: 3DE; the PISA in a patient with ventricular septal defect is viewed from the left ventricle. The prolate hemispheroid PISA has a squeezed half lemon shape.

Figure 4. Oblate hemispheroid PISA shape: a: mathematic model; the two longest diameters are equal; b: 3DE; the PISA in a patient with mitral valve prolapse is viewed from the left ventricle. The oblate hemispheroid PISA looks like half of a cigar.

Figure 5. Hemiellipsoid PISA shape: a: mathematic model; the three diameters are different; b: 3DE; the PISA in a patient with restrictive mitral valve is viewed from the left ventricle.
Table 2 2DE and 3DE measurements of MR and VS orifice area and volume.

<table>
<thead>
<tr>
<th></th>
<th>2DE</th>
<th>3DE</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR or VS orifice area (cm²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hemispherical</td>
<td>0.06 [0.02—0.18]</td>
<td>0.06 [0.01—0.46]</td>
<td>0.95</td>
</tr>
<tr>
<td>Prolate hemispheroid</td>
<td>0.11 [0.05—0.25]</td>
<td>0.08 [0.03—0.20]</td>
<td>0.058</td>
</tr>
<tr>
<td>Oblate hemispheroid</td>
<td>0.18 [0.10—0.33]</td>
<td>0.14 [0.06—0.31]</td>
<td>0.124</td>
</tr>
<tr>
<td>Total</td>
<td>0.12 [0.08—0.19]</td>
<td>0.09 [0.06—0.16]</td>
<td>0.019</td>
</tr>
<tr>
<td>MR or VS volume (mL)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hemispherical</td>
<td>8 [3.5—17]</td>
<td>8 [1—54]</td>
<td>0.95</td>
</tr>
<tr>
<td>Prolate hemispheroid</td>
<td>10 [5—21]</td>
<td>7 [3—17]</td>
<td>0.058</td>
</tr>
<tr>
<td>Oblate hemispheroid</td>
<td>23 [14—37]</td>
<td>17 [9—35]</td>
<td>0.124</td>
</tr>
<tr>
<td>Total</td>
<td>13 [9—20]</td>
<td>10 [6—17]</td>
<td>0.0191</td>
</tr>
</tbody>
</table>

2DE: two-dimensional echocardiography; 3DE: three-dimensional echocardiography.

were found between the two methods. In the prolate hemispheroid group there was a tendency to overestimate both regurgitant (or shunt) orifices and volumes measurements by 2DE compared with 3DE (p = 0.58).

Reproducibility

Interobserver and intraobserver variability of the 3DE PISA shape were analysed in all patients. On the same full volume acquisition of the PISA, each observer measured the three diameters of the PISA with the described method. The mean interobserver difference of MR and VS volume was 5.9 ± 15 mL (r = 0.89, p < 0.0001). Intraobserver variability was assessed by comparing the measurements given by the same observer after an interval of more than a week between the two measurements. The mean intraobserver difference of MR and VS volume was 2 ± 8 mL (r = 0.92, p < 0.0001).

Discussion

The aim of our study was to evaluate the true shape of the PISA using colour Doppler 3DE in a paediatric population with MR or VS. In our series, the PISA shape was not hemispherical in almost 90% of cases. In the MR group, the oblate hemispheroid shape was dominant, while in the VS patients (with a circular-shaped regurgitant orifice) the prolate hemispheroid shape was dominant. This finding is not surprising, considering the predominant aetiologies of MR in children (cleft, prolapse or pure congenital restriction), whereas the VS shape is sometimes anfractuous. In the only adult series that analysed the PISA shape using 3DE, its form was hemiellipsoid in most cases [7]. For an easier understanding of our classification, one could liken the spheroid oblate shape to a squeezed half lemon and the spheroid prolate shape to an elongated ‘hemisphere’ like half of a cigar. The regurgitant or shunt orifice area has the shape of a circle only when it is a hemispherical or prolate hemispheroid PISA. In the case of an oblate hemispheroid or a hemiellipsoid PISA, it has the shape of an ellipse.

The non-spherical geometry of the PISA has direct consequences on orifice area and volume assessment of MR and VS. PISA evaluation by 2DE is based on a hemispherical hypothetical shape. The orifice area is overestimated by the hemispherical model of 2DE PISA compared with colour Doppler 3DE calculation, the latter being based on formulae, which allow a more accurate estimation of the PISA surface according to its shape. Thus, this non-spherical surface is smaller because it integrates the smallest diameter of the PISA in the transversal plane, whereas 2DE PISA is based only on the PISA radius in the longitudinal plane. As orifice area is used to calculate MR and VS volume, the latter is also overestimated by 2DE PISA. The PISA method also has some general technical limitations: confinement of the convergence zone, variation of regurgitant orifice area throughout systole in prolapse and multiple regurgitation jets [1,5,7].

The major limitation of colour Doppler 3DE for the accurate shape and surface assessment of PISA in MR or VS patients is poor temporal resolution. Image resolution on the crop plane realised with the QLab system needs improvement to increase accuracy. Angle measurements should be included to measure the hemiellipsoid surface. The PISA method also has some general technical limitations that are encountered frequently in the paediatric population due to the shape of the ventricular septal defect and the specific aetiologies of MR [8—12]. Another limitation was our small patient population; power may have been insufficient to find a significant difference between regurgitant or shunt orifice area using 2DE and 3DE in shape subgroups. The clinical importance of the more accurate assessment of MR and VS severity by 3DE PISA is to be addressed in a large multicentre prospective study.

Conclusion

3DE describes the true surface of the PISA shape, which is rarely hemispherical in a paediatric population with MR or VS, but is more often prolater or oblate hemispheroid. Compared with 3DE, 2DE using the PISA method overestimates the MR and VS orifices and volumes.
Conflicts of interests

None.

References


