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A simplified D-shaped model of the mitral annulus to facilitate CT-based sizing before transcatheter mitral valve implantation

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Abstract

Background—The nonplanar, saddle-shaped structure of the mitral annulus has been well established through decades of anatomic and echocardiographic study. Its relevance for mitral annular assessment for transcatheter mitral valve implantation is uncertain.

Objective—Our objectives are to define the methodology for CT-based simplified “D-shaped” mitral annular assessment for transcatheter mitral valve implantation and compare these measurements to traditional “saddle-shaped” mitral annular assessment.

Methods—The annular contour was manually segmented, and fibrous trigones were identified using electrocardiogram-gated diastolic CT data sets of 28 patients with severe functional mitral regurgitation, yielding annular perimeter, projected area, trigone-to-trigone (TT) distance, and septal-lateral distance. In contrast to the traditional saddle-shaped annulus, the D-shaped annulus was defined as being limited anteriorly by the TT distance, excluding the aortomitral continuity. Hypothetical left ventricular outflow tract (LVOT) clearance was assessed.

Results—Projected area, perimeter, and septal-lateral distance were found to be significantly smaller for the D-shaped annulus (11.2 ± 2.7 vs 13.0 ± 3.0 cm²; 124.1 ± 15.1 vs 136.0 ± 15.5 mm; and 32.1 ± 4.0 vs 40.1 ± 4.9 mm, respectively; $P < .001$). TT distances were identical (32.7 ± 4.1 mm). Hypothetical LVOT clearance was significantly lower for the saddle-shaped annulus than for the D-shaped annulus (10.7 ± 2.2 vs 17.5 ± 3.0 mm; $P < .001$).

Conclusion—By truncating the anterior horn of the saddle-shaped annular contour at the TT distance, the resulting more planar and smaller D-shaped annulus projects less onto the LVOT, yielding a significantly larger hypothetical LVOT clearance than the saddle-shaped approach. CT-based mitral annular assessment may aid preprocedural sizing, ensuring appropriate patient and device selection.

Keywords

Mitral regurgitation; Mitral annulus; Transcatheter mitral valve; implantation; Transapical mitral valve; replacement; Computed tomography

1. Introduction

Because of its minimally invasive nature, transcatheter mitral valve implantation (TMVI) partially relies on preprocedural imaging.^{1–3} The assessment of mitral annular dimensions by cross-sectional imaging such as CT is of increasing relevance. It has been well established through decades of anatomic and echocardiographic study that the mitral annulus is a nonplanar, saddle-shaped, 3-dimensional (3D) structure,⁴ with the peaks of the saddle formed by distinct anatomic landmarks. The posterior peak is formed by the insertion of the posterior mitral valve leaflet (PML), extending posteriorly from the lateral to the medial fibrous trigone, and the anterior peak is described as being continuous with the aortic annulus,⁴ whereas the nadirs are located at the level of fibrous trigones. The anterior or aortic peak extends to the level of the aortic valve or annulus and is in part defined by the insertion of the noncoronary and left coronary cusp, thereby including the aortomitral continuity.

When the geometrically saddle-shaped annulus is assessed by 3D transesophageal echocardiography or CT, a projected 2-dimensional (2D) area is commonly reported.^{5,6} Average values for 2D annular area vary between 7 and 10 cm² for healthy subjects^{6–8} and 11 to 20 cm² in the setting of left ventricular (LV) dilatation and functional mitral regurgitation.^{6,8,9} Although the nonplanar configuration of the mitral annulus is well established anatomically, in the setting of TMVI, it may be less relevant for sizing a TMVI device, particularly as its projected area extends into the left ventricular outflow tract (LVOT). As a result, it is important to address the issue of the saddle-shaped mitral annulus vs the tubular prosthetic device and the difficulties these annular configurations present with respect to selection of a device size that has the lowest possible risk of paravalvular leakage while not jeopardizing the integrity of the annulus or obstruction of the LVOT. We hypothesize that the anterior peak of the saddle-shaped annulus should be excluded for mitral annular sizing in the context of TMVI.

The objectives of this study were to define the methodology for CT-based, simplified, “D-shaped” mitral annular assessment for TMVI excluding the anterior horn and compare these measurements to traditional “saddle-shaped” mitral annular assessment in patients with functional mitral regurgitation (FMR) undergoing evaluation for minimal invasive mitral intervention including TMVI.

2. Material and methods

2.1. Study population

This retrospective study was approved by the institutional review board with a waiver for individual informed patient consent. The study population consisted of 28 patients with severe functional mitral valve regurgitation, who were referred for diagnostic workup before minimal invasive mitral valve intervention at 2 centers (St. Paul's Hospital, Vancouver, British Columbia and Heart Center Freiburg-Bad Krozingen, Bad Krozingen, Germany) including a dedicated retrospectively electrocardiogram (ECG)-gated CT study of the heart. FMR was defined as mitral regurgitation due to left ventricular remodeling and subsequently insufficient leaflet coaptation with normal leaflets and chordae. Both patients with ischemic and nonischemic FMR were included into this study.

2.2. CT protocol

CT examinations were performed using either a 64-slice Discovery HD 750 high-definition or volume CT scanner (GE Healthcare, Milwaukee, WI) or a first- or second-generation dual-source scanner (Siemens Healthcare, Erlangen, Germany). For contrast-enhanced data acquisition, 90 to 110 mL of iodinated contrast agent (Imeron 350, Bracco Imaging) was injected at a flow rate of 4 to 5 mL/s via an 18-gauge needle in an antecubital vein, followed by a 50-mL saline bolus chaser. Tube current and tube voltage settings were adapted from routine cardiac CT angiography protocols using retrospective ECG-gated data acquisition without dose modulation. The scan range extended from the carina to the diaphragm to ensure coverage of the entire left atrium.

2.3. Image reconstruction

CT data were reconstructed in 10% intervals throughout the cardiac cycle with a section thickness of 0.6 mm and an increment of 0.4 mm using a medium soft-tissue convolution kernel. In case of severe arrhythmia, manual ECG-editing was performed to ensure optimal image quality. All data sets were transferred to a dedicated post-processing work-station equipped with 3mensio Structural Heart (version 7.0; Pie Medical Imaging, Maastricht, Netherlands). For mitral annular assessment, mid- to late-diastolic image reconstructions were identified in accordance to previous reports that have demonstrated larger annular dimensions in mid-diastole to late diastole.^{5,6} Specifically, we assessed atrial dimensions on 85% to 95% reconstructions, depending on the presence of atrial contraction with the goal of evaluating the annulus on the last reconstruction before the atrial contraction.

2.4. Traditional mitral annulus assessment

Using the late-diastolic reconstructions, the mitral annulus was tracked by manually placing 16 segmentation points for cubic spline interpolation along the insertion of the PML and along the contour of the anterior peak comprising the fibrous intervalvular continuity by stepwise rotation of a long axis view aligned to the left ventricular long axis (Fig. 1). In more detail, the insertion of the PML at the atrial-ventricular junction was defined as the transition zone of the ridge-like appearing thinned left ventricular myocardium in the setting of left ventricular dilation and the PML. In the area of the aortomitral fibrous continuity, the

distal margin of the left atrial myocardium over the fibrous tissue defines the contour of the anterior peak of the mitral annulus.¹⁰ The lateral and medial fibrous trigones, the 2 major collagenous structures at the site of inflection of the anterior and posterior mitral valve, were manually identified and tracked for further annulus segmentation. More precisely, the fibrous trigones were identified on the long axis views as the area where mitral leaflet insertion separates from the atrioventricular junction to further follow the contour of the fibrous continuity with the aortic root. Importantly, the trigones define the border between the anterior circumference (aortic peak) and posterior circumference (posterior peak). The resulting saddle-shaped annulus was displayed in a 3D fashion (Figs. 2 and 3). The mitral annular area was computed as an area projected onto the least squares plane fitted to the 3D annular contour as described by Legget et al.¹¹ The 3D perimeter was computed as the path length of the 3D annular contour. A 2D perimeter was computed by projecting the 3D annular contour on the least squares plane.¹¹ Both the 3D perimeter and the projected 2D perimeter were noted for the entire annulus, the anterior circumference, and the posterior circumference separately. The annular height was assessed as the perpendicular distance from the highest peak to the lowest nadir of the 3D contour parallel to the least squares plane. The trigone-to-trigone (TT) distance and the septal-lateral (SL) distance were noted.

Parameters were defined as (with subscript “S” denoting the saddle-shaped approach)

- A_S = projected annulus area of saddle-shaped mitral annulus,
- TT = TT distance,
- SL_S = projected SL distance from the aortic peak to the posterior peak perpendicular to TT,
- 3D- P_S = 3D circumference of the entire saddle-shaped annulus,
- 2D- P_S = projected circumference of the entire saddle-shaped annulus,
- 3D- $P_{S-Anterior}$ = 3D circumference of the anterior peak,
- 3D- $P_{S-Posterior}$ = 3D circumference of the posterior peak,
- 2D- $P_{S-Anterior}$ = projected circumference of the anterior peak,
- 2D- $P_{S-Posterior}$ = projected circumference of the posterior peak, and
- H_S = annular height.

2.5. “D-shaped” annulus

Given the tubular nature with a D-shaped configuration of the recently introduced Tiara (Neovasc Inc, Richmond, Canada) transcatheter mitral device,¹ as well as the observation that the mechanical hinge of the anterior mitral leaflet does not follow the anterior peak but is located below the fibrous continuity, the septal or anterior margin of the “D-shaped” annulus was defined by a virtual line connecting the lateral and medial trigone identical to the TT distance. The TT line thus excluded the aortomitral continuity and the anterior aortic peak (Figs. 2 and 3). The posterior margin was defined by the insertion of the posterior mitral leaflet, identical to the contour of the posterior peak of the saddle-shaped traditional annulus. The D-shaped annulus was achieved by truncating the saddle-shaped annulus at the

TT distance, whereas the posterior peak and TT distance remained unchanged. A separate geometric axis was identified.

Parameters were defined as (with subscript “D” denoting the D-shaped approach)

- A_D = projected annulus area of D-shaped mitral annulus,
- SLD = projected SL distance from the aortic peak to the posterior peak perpendicular to TT,
- $3D-P_D$ = 3D circumference of the entire D-shaped mitral annulus,
- $2D-P_D$ = projected circumference of the entire D-shaped mitral annulus, and
- H_D = annular height.

By definition and methodology, $3D-P_{\text{Posterior}}$ was identical for both the traditional and the D-shaped approach.

2.6. Intraobserver and interobserver variability

All annular measurements were initially performed by 1 observer blinded to patient identifying information. After a 4-week interval, measurements were repeated by the same observer and a second observer for 15 patients.

2.7. Hypothetical LVOT clearance

Projected LVOT clearance, simulating hypothetical TMVI with a tubular device deployed with similar dimensions as the projected area and SL distance of the mitral annulus and with the same orientation as the geometric axis perpendicular to the plane of least squares, was measured and defined as the distance between the septal bulge and the margin of the projected annulus area in a perpendicular fashion to the geometric long axis of the mitral annulus at 15 mm and 20 mm into the left ventricle. Measurements were performed for both the saddle-shaped annulus and the D-shaped annulus (Fig. 4).

2.8. Mitral annulus to left ventricular long axis angulation

The geometric mitral annular axis was computed as an axis through the centroid of and perpendicular to the least squares plane for both the saddle-shaped approach and the D-shaped approach. The left ventricular long axis was manually identified as a line transecting through the left ventricular apex and the centroid of the mitral annulus. The mitral annulus to left ventricular long axis angulation was then assessed as the smallest angle within the 3D space between the left ventricular long axis and the mitral annular axis for both the saddle-shaped and D-shaped approach.

2.9. Statistical analysis

Continuous variables are reported as means $\pm$ 1 standard deviation when equally distributed as assessed by Kolmogorov-Smirnov tests. Paired Student *t* tests were used to test for significant differences between continuous variables. The Bland-Altman analysis was performed to assess intraobserver and interobserver variability.¹² All statistical analyses

were performed using SPSS software (SPSS 17.0; SPSS Inc., Chicago, IL). A P value $< .05$ was considered statistically significant.

3. Results

3.1. Study population

Patient characteristics are provided in Table 1. All patients had 3+ mitral regurgitation as graded by echocardiography in setting of left ventricular dilation. Mean end-diastolic LV diameter was 67.3 ± 8.0 mm (range, 61–84 mm), mean LV ejection fraction was $28.5\% \pm 8.2\%$ (range 10%–40%). Mitral annular calcification was present in 9 patients (32%).

3.2. Annulus dimensions

Annular contours could be successfully segmented in all patients. An example is given in Figure 5. The mean area of the saddle-shaped annulus A_S was 13.0 ± 3.0 cm² (range, 7.0–20.4 cm²), and was found to be significantly larger than A_D (mean, 11.2 ± 2.7 cm²; range, 6.1–17.7 cm²; $P < .001$) with a mean difference of 1.8 ± 0.4 cm² (range, 0.9–2.7 cm²).

For the saddle-shaped annulus, mean 3D- P_S was 136.0 ± 15.5 mm (range, 100.5–173.0 mm) and was significantly larger than the projected 2D- P_S (mean, 128.2 ± 14.8 mm; range, 94.2–163.7 mm; $P < .001$), with a mean difference of 7.8 ± 2.1 mm (range, 4.7–11.5 mm). The discrepancy between the 3D circumference and the projected 2D circumference was most pronounced for the anterior peak (mean 3D- $P_{S-Anterior}$ 44.6 ± 4.7 mm vs mean 2D- $P_{S-Anterior}$ 38.5 ± 3.9 mm; $P < .001$) and only subtle for the posterior peak (mean 3D- $P_{S-Posterior}$ 91.4 ± 12.1 mm vs mean 2D- $P_{S-Posterior}$ 89.7 ± 10.9 mm; $P < .001$), with 77% of the discrepancy between the 3D perimeter and the projected 2D perimeter attributable to the anterior peak. Both the 3D and projected 2D circumference were significantly smaller for the D-shaped annulus than the corresponding mean values of the saddle-shaped annulus reported previously (3D- P_D : mean, 124.1 ± 15.1 mm; range, 93–165 mm; 2D- P_D : mean, 122.4 ± 15.0 mm; range, 91–162 mm; $P < .001$). Mean difference between 3D- P_D and 2D- P_D was 1.7 ± 0.7 mm (range, 1–3 mm; $P < .001$). By definition, 3D circumference of the posterior peak was identical for both the saddle-shaped and the D-shaped approach.

Mean TT was 32.7 to 4.1 mm (range, 24–45 mm), and was by definition identical for both the saddle-shaped and the D-shaped approach.

The SL distance was significantly smaller for the D-shaped approach (mean SL_D , 32.3 ± 4.0 mm; range, 25.1–40.3 mm) when compared with the saddle-shaped approach (mean SL_S , 40.1 ± 4.9 mm; range, 30.7–48.5 mm; $P < .001$).

For the D-shaped approach, annular contours were found more planar than for the saddle-shaped approach reflected by a significantly smaller annular height (mean H_D , 2.4 ± 1.0 mm; range, 0.8–4.7 mm; mean H_S , 10.6 ± 1.8 mm; range, 7.4–14.0 mm; $P < .001$).

3.3. Intraobserver and interobserver variability

Mean difference and limits of agreement by Bland-Altman analysis for both repeat measurements by the same and second observer are listed in Table 2. Similar limits of

agreement were found for area, 3D and 2D perimeters, as well as SL distances when comparing the saddle-shaped annulus and the D-shaped annulus. Importantly, intraobserver and interobserver variability tended to be lower for projected 2D variables than for 3D variables.

3.4. Hypothetical LVOT clearance

The hypothetical LVOT clearance based on a TMVI device with a tubular configuration deployed with similar dimensions as the projected annular area was significantly larger for the D-shaped annulus than for the saddle-shaped annulus. At 15 mm into the LV, projected LVOT clearance was 10.7 ± 2.2 mm for the saddle-shaped annulus and 17.5 ± 3.0 mm for the D-shaped annulus ($P < .001$). At 20 mm into the LV, projected LVOT clearance was 8.1 ± 3.9 mm for the saddle-shaped annulus and 16.7 ± 4.6 mm for the D-shaped annulus ($P < .001$).

3.5. Mitral annulus to left ventricular long axis angulation

Mitral annulus to left ventricular long axis angulation was significantly lower for the D-shaped mitral annulus compared with the saddle-shaped annulus ($7.5 \pm 3.5^\circ$ vs $11.4 \pm 4.3^\circ$; $P < .001$).

4. Discussion

In our analysis of patients with FMR undergoing evaluation for potential TMVI or minimal invasive mitral valve repair, we found that the historical definition of the mitral annulus does not appear appropriate for TMV sizing and device selection. In all subjects in our cohort, if a device were to be implanted with similar dimensions to the projected area and SL distance of the traditional saddled annular size, severe LVOT obstruction would likely have occurred, as predicted by a significantly reduced projected hypothetical LVOT clearance. In contrast to the concept of the saddle-shaped mitral annulus, our proposed annular sizing methodology focuses on truncating the saddle-shaped mitral annulus along a virtual line connecting both fibrous trigones rather than extending up to include the aortomitral continuity. The resulting D-shaped annulus has a more planar shape, as demonstrated by a significantly reduced height. Most importantly, the projected area and in particular the SL distance are smaller, whereas the TT distance remains unchanged.

The D-shaped mitral annulus corresponds to the planar annular landing zone and to the D-shaped cross-sectional area of current TMVs under investigation, such as the Tiara device¹ or the Tendyne valve (Tendyne Holdings Inc., Roseville, MN).¹³ It is conceivable that the refined concept of the D-shaped annulus allows for more appropriate device selection by ensuring adequate oversizing while not compromising the LVOT. In fact, this concept is currently used at our institution to assess the anatomic suitability for TMVI in patients with severe FMR.

Importantly, although it has been previously demonstrated that CT is capable of providing detailed anatomic and geometric information on the mitral valve apparatus in patients with mitral regurgitation,^{14–16} it is likely that similar measurements may be obtained by 3D echocardiography although we did not assess this in our study.

CT has been shown to yield highly reproducible measurements of the aortic annulus.^{17–19} A similar extent of intraobserver and interobserver variability was observed in the present study for mitral annular measurements, demonstrating excellent reproducibility. CT, enabled by its high spatial resolution and isotropic voxels and standardized acquisition, allows for consistent image reconstruction and excellent anatomic detail. Beyond these inherent advantages of CT, the methodology used for our analysis is carefully prescribed and highly automated. We feel that this standardization of measurement will serve as a strength of preprocedural CT in procedure planning for TMVI, allowing the proceduralist to be confident in the granular assessment of the functional mitral annulus geometry. The need for preprocedural imaging is further highlighted by the broad spectrum of annular dimensions observed in this study, ranging from approximately 6 to 18 cm² for the D-shaped annulus.

Similar to Transcatheter Aortic Valve Replacement (TAVR), paravalvular regurgitation may be observed in TMVI, thought to be related to deployment of a prosthesis too small for the individual mitral geometry.¹ On the other hand, it is conceivable that gross oversizing in an attempt to prevent paravalvular regurgitation may result in LVOT obstruction. By integrating novel image post-processing tools, we have shown that CT can play an important role in identifying those patients that may be at an increased risk of LVOT obstruction and Paravalvular regurgitation (PVL). The greatest degree of risk appears to be imparted by gross oversizing of the annulus through the inclusion of the anterior peak in annular sizing and device selection. There is, however, significant variability in the degree of LVOT clearance driven by a number of issues including the mitral valve to LVOT angulation, septal thickness, and LV aortic angulation. These anatomic measures and geometric relationships are uniquely identified on multi detector CT and, as shown herein, can be routinely measured. The degree that this anatomic data and variability will impact device design and procedural planning is not known, but it seems clear that this data can only serve to better inform the proceduralist of patient-specific anatomy and allow for a more informed decision regarding device and patient selection and procedural planning.

The concept of the D-shaped annulus is not only limited to D-shaped devices such as the Tiara device but is rather an important anatomic concept that is playing an important role in the evaluation of patient suitability and device sizing in the early stage of TMVI development. Further study will be needed to determine the relevance of the simplified D-shape annulus with regards to other new devices and with the evolution of this new procedure.

Finally, mitral annular calcium was present in 32% of patients evaluated. The extent of mitral annular calcium can range from spotty calcifications to severe caseous calcifications. Although spotty calcifications can be a largely ignored, caseous calcifications represent space-occupying structures, which most likely act as mechanical counter bearings and were thus being excluded from the annular contour (Fig. 6).

4.1. Study limitations

Although our analysis is informed by early experiences with transcatheter mitral devices, most of the subjects evaluated in this study have not undergone TMVI. In addition, the cohort, while historically speaking is quite large, it remains limited in size. Although

patients with both FMR and degenerative mitral regurgitation or mitral valve prolapse were evaluated for minimal invasive mitral repair at our institutions, we only included patients with FMR into this analysis, as these patients will most likely constitute most patients potentially undergoing TMVI in early clinical trials. However, the concept of the D-shaped annulus almost certainly applies the mitral annulus more broadly, independent of the underlying pathology as the adaptation is the exclusion of the anterior fibrous continuity, whereas the segmentation of the posterior horn remains unchanged.

Similar to the aortic annulus,²⁰ the mitral annulus is subject to dynamic changes throughout the cardiac cycle with largest dimensions found in mid-diastole to late diastole, as reported by Alkadhi et al and Flachskampf et al.^{5,6} FMR patients typically show less dynamism compared with patients with degenerative mitral valve disease or healthy subjects.^{5,6} Although the impact of dynamism on device sizing in TMVI is not yet understood, it has to be emphasized that CT-based assessment of mitral annular geometry is dependent on image quality, which is usually best at time of the least movement, such as middiastole to late diastole for the mitral annulus.

The concept of the reported hypothetical LVOT clearance is limited by assuming implantation of a tubular device with similar dimensions as the projected annular area and SL distance. LVOT clearance will also depend on the device flaring or coning and the device protrusion into the LVOT. However, this concept is mainly used to highlight the close relationship of the anterior horn and the LVOT and the fact that the projected area of the anterior peak of the saddle-shaped annulus extends into the LVOT.

Finally, the measurements described are proposed for TMVI devices that are designed to be deployed and positioned at the level of the mitral annulus. The relevance of these measurements for nonannular TMVs that may be developed in the future is uncertain.

5. Conclusion

The historically established methodology for sizing the mitral annulus appears inappropriate for TMVI and in particular device selection and sizing. A focus on the D-shaped annulus with CT appears to allow more comprehensive evaluation before TMVI, allowing for device sizing and detailed geometric evaluation of the landing zone

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Fig. 1.

Annulus segmentation. The saddle-shaped mitral annulus is segmented by placing 16 seeding points along the insertion of the posterior mitral leaflet and along the contour of the fibrous continuity while the long axis view is rotated in an automated fashion every 22.5° aligned to the long axis of the left ventricle (yellow line denotes the orientation of the left ventricular long axis). Upper left, 4-chamber view; upper right, 2-chamber view; lower left, 3-chamber view. The short-axis view (lower right) indicates the position of the 16 seeding points projected on 1 imaging plane.

Fig. 2.

Saddle-shaped and D-shaped mitral annulus: geometric assessment. After generating the 3-dimensional (3D) mitral annulus contour, the annular height and 3D perimeter are assessed. Area, 2D perimeter, and trigone-to-trigone (TT) and septal-lateral (SL) distances are assessed based on projected dimensions by means of the least squares method. The orange dots indicate the position of the fibrous trigones which define the TT distance and thus the anterior border of the D-shaped annulus. 2D-P_{Posterior}, projected circumference of the posterior peak; 2D-P_{S-Anterior}, projected circumference of the anterior peak; 3D-P_{Posterior},

3D circumference of the posterior peak; A_D , projected annulus area of D-shaped mitral annulus; A_S , projected annulus area of saddle-shaped mitral annulus; SL_D , projected septal-to-lateral distance from the aortic peak to the posterior peak perpendicular to TT of the D-shaped annulus; SL_S , projected septal-to-lateral distance from the aortic peak to the posterior peak perpendicular to TT of the saddle-shaped annulus.

Saddle-shaped annulus

D-shaped annulus

Fig. 3. Saddle-shaped and D-shaped mitral annulus: Definition and 3-dimensional structure. Left traditional saddle-shaped annulus defined by the insertion of the posterior mitral leaflet at the atrioventricular junction (red line, posterior peak) and the fibrous continuity (white line, anterior peak), comprising the intervalvular fibrous continuity; nadirs at fibrous trigones (orange dots). Right D-shaped or functional annulus formed by the insertion of the posterior mitral leaflet at the atrioventricular junction (red line, posterior peak) and a virtual line (white line); the medial and lateral fibrous trigones (orange dots) corresponding to the intertrigonal line. AML, anterior mitral leaflet; LC, left coronary cusp; NC, non-coronary cusp.

Saddle-shaped annulus

D-shaped annulus

Fig. 4.

Hypothetical LVOT clearance. Projected LVOT clearance was assessed as the distance between the septal bulge and the margin of the projected annulus area in a perpendicular fashion to the geometrical long axis of the mitral annulus at 15 mm and at 20 mm below the nadir of the annulus for the saddle-shaped annulus (left) and the D-shaped annulus (right). LVOT, left ventricular outflow tract.

Fig. 5. Comparison of measurements for the saddle-shaped and D-shaped mitral annulus approach. Measurements performed at end diastole in a 55-year-old man with severe left ventricular dilation and functional mitral regurgitation FMR. Short-axis images (left column) centered through the geometrical axis of the annulus. Three-chamber view (right column). 2D-P_D, projected circumference of the entire D-shaped mitral annulus; 2D-P_{S-Anterior}, projected circumference of the anterior peak; 2D-P_{Posterior}, projected circumference of the posterior peak; 3D-P_D, 3-dimensional circumference of the entire D-shaped mitral annulus; 3D-P_{Posterior}, 3-dimensional circumference of the posterior peak; 3D-P_S, 3-dimensional circumference of the entire saddle-shaped annulus; A_D, projected annulus area of D-shaped mitral annulus; A_S, projected annulus area of saddle-shaped mitral annulus; SLD, projected SL distance from the aortic peak to the posterior peak perpendicular to TT; SL_S, projected septal-to-lateral distance from the aortic peak to the posterior peak perpendicular to TT; TT, trigone-to-trigone distance.

Fig. 6. Mitral annular calcifications. Annular segmentation performed in a 65-year-old man with caseous mitral annular calcifications involving the P1 and P2 segment. Caseous calcifications are usually space occupying and were thus excluded from annular segmentation.

Table 1

Demographic and clinical characteristics.

Variable	Value
Age (y), mean $\pm$ SD	73 $\pm$ 10.2
Male, n (%)	19 (69)
Body surface area (m ²), mean $\pm$ SD	1.8 $\pm$ 0.2
Left Ventricular End Diastolic diameter (mm), mean $\pm$ SD	67.3 $\pm$ 8.0
Left Ventricular Ejection Fraction (%), mean $\pm$ SD	28.5 $\pm$ 8.2
Diabetes, n (%)	6 (21)
Smoking history, n (%)	6 (21)
Hypertension, n (%)	19 (68)

SD, standard deviation.

Table 2

Intraobserver and interobserver variability.

Variable	Intraobserver agreement, mean $\pm$ SD (range)	Interobserver agreement, mean $\pm$ SD (range)
A _S (cm ²)	0.1 $\pm$ 0.4 (−0.7 to 0.9)	0.1 $\pm$ 0.5 (−0.9 to 1.0)
A _D (cm ²)	0.1 $\pm$ 0.5 (−0.8 to 1.1)	−0.1 $\pm$ 0.4 (−0.9 to 0.7)
3D-P _S (mm)	0.5 $\pm$ 4.1 (−7.6 to 8.6)	−0.2 $\pm$ 3.7 (−7.4 to 6.9)
3D-P _D (mm)	0.1 $\pm$ 3.3 (−6.4 to 6.5)	−0.3 $\pm$ 3.7 (−7.6 to 7.0)
2D-P _S (mm)	0.3 $\pm$ 2.3 (−4.2 to 4.8)	0.2 $\pm$ 2.1 (−4.0 to 4.3)
2D-P _D (mm)	−0.2 $\pm$ 2.4 (−4.8 to 4.5)	0.3 $\pm$ 2.8 (−5.2 to 5.8)
TT (mm)	0.1 $\pm$ 1.3 (−2.5 to 2.7)	0.3 $\pm$ 1.3 (−2.3 to 2.9)
SL _S (mm)	0.0 $\pm$ 1.2 (−2.3 to 2.3)	0.0 $\pm$ 1.3 (−2.5 to 2.4)
SL _D (mm)	0.1 $\pm$ 1.3 (−2.1 to 2.5)	0.0 $\pm$ 1.0 (−2.1 to 1.8)
3D-P _{Posterior} (mm)	0.0 $\pm$ 3.4 (−6.7 to 6.7)	−0.6 $\pm$ 3.8 (−8.0 to 6.8)
2D-P _{Posterior} (mm)	−0.2 $\pm$ 2.6 (−5.2 to 4.9)	0.0 $\pm$ 2.6 (−5.1 to 5.1)

2D-P_D, projected circumference of the entire D-shaped mitral annulus; 2D-P_{Posterior}, projected circumference of the posterior peak; 2D-P_S, projected circumference of the entire saddle-shaped annulus; 3D-P_D, 3-dimensional circumference of the entire D-shaped mitral annulus; 3D-P_{Posterior}, 3-dimensional circumference of the posterior peak; 3D-P_S, 3-dimensional circumference of the entire saddle-shaped annulus; A_D, projected annulus area of D-shaped mitral annulus; A_S, projected annulus area of saddle-shaped mitral annulus; SD, standard deviation; SL_D, projected septal-to-lateral distance from the aortic peak to the posterior peak perpendicular to TT for the D-shaped annulus; SL_S, projected septal-to-lateral distance from the aortic peak to the posterior peak perpendicular to TT for the saddle shaped annulus; TT, trigone-to-trigone distance.