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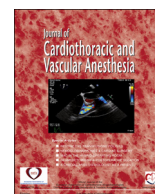
Original Article

Changes in Tricuspid Annular Geometry in Patients with Functional Tricuspid Regurgitation

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Objective: To determine whether the indices of tricuspid annular dynamics that signify irreversible tricuspid valvular remodeling can improve surgical decision making by helping to better identify patients with functional tricuspid regurgitation who could benefit from annuloplasty.
Design: Retrospective analysis study.
Setting: Tertiary hospital.
Participants: A total number of 55 patients were selected, 18 with functional tricuspid valve (TV) regurgitation and 37 normal nonregurgitant TVs.
Interventions: None.
Measurements and Main Results: When comparing the basal, mid, and longitudinal diameters of the right ventricle between the nonregurgitant valve (NTR) group and the functional tricuspid regurgitation (FTR) group, tricuspid annulus was more dilated ($p < 0.001$, $p = 0.001$, and $p = 0.006$, respectively) and less nonplanar ($p < 0.001$) in the FTR group. At end-systole (ES), the posterolateral-anteroseptal axis was significantly greater in the FTR group than in the NTR group (mean difference = 7.15 mm; $p < 0.001$). The right ventricle in the FTR group was also significantly dilated with greater leaflet restriction ($p = 0.015$).
Conclusions: As compared to NTR TVs, FTR is associated with identifiable indices of tricuspid annular structural changes that are indicative of irreversible remodeling.
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Key Words: echocardiography; tricuspid valve; cardiac anatomy; pathologic anatomy; functional tricuspid regurgitation; tricuspid annular geometry

THE SEVERITY OF tricuspid regurgitation (TR) and extent of tricuspid annular (TA) dilation are used to identify and select patients for annuloplasty. Treatment of severe TR can have positive outcome benefits. Functional tricuspid regurgitation (FTR) in patients undergoing left-sided surgery is associated with outcome consequences.[1,2] Whether or not tricuspid annuloplasty should be performed in these patients is debatable.[3,4] Echocardiographically obtained linear dimensions of the TA are used to

establish the extent of TA dilation that is considered a surrogate marker of TA remodeling. Traditionally, the septolateral (SL) axial dimension is measured during echocardiography to establish dilation of the TA. While being an echocardiographically convenient measurement, the SL axis is neither an anatomically well defined nor the most dynamic axis during the cardiac cycle.[5] Unlike mitral valve, the geometric indices of TA remodeling as a response to chronic volume overload are not well established.[6] Using three-dimensional (3D) imaging, it is now known that in nonregurgitant tricuspid valves (TV), the posterolateral-to-anteroseptal (PL-AS) axis displays maximal dynamism during the cardiac cycle.[7,8] Also, the TA has a complex nonplanar shape and motion with spatial variation in annular high and low points throughout the cardiac cycle.[8] Whether this dynamism is preserved in patients with FTR is not known. Possibly such geometric indices could be used to establish the extent of TA remodeling with consequent improvement in clinical decision making.

Due to its impact on outcome, TV annuloplasty is recommended in cases of severe FTR.[3,9] A few studies recommend a more aggressive approach of annuloplasty for a dilated TA even in the absence of significant TR.[2,10] However, the benefits of TV annuloplasty for mild-to-moderate FTR are debatable.[2,11] In either case, this decision is based on either the severity assessment of a load-dependent variable and/or a single static linear dimension of a complex nonplanar 3D structure.[12,13] The questionable benefit of annuloplasty could possibly be due to the authors' erroneous criteria for patient selection. Due to advances in 3D imaging, the traditional understanding of the dynamics of the TA has been challenged.[7,8] Precise spatial and temporal quantification of the dynamism of TA has demonstrated potential clinical value of 3D imaging that could be of value in surgical decision making.[7,8] Precise changes in mitral valve apparatus have been identified that specifically differentiate normal from ischemic mitral valves.[14,15] The same principle of assessment

Tricuspid Valve Analysis Definitions
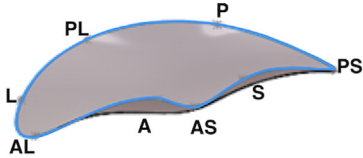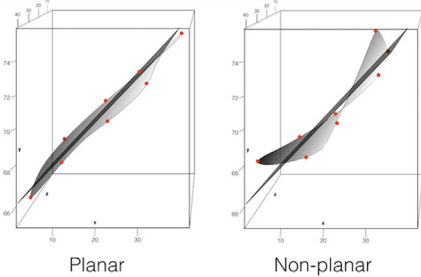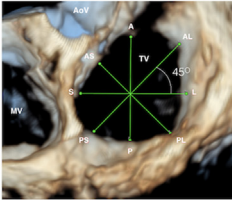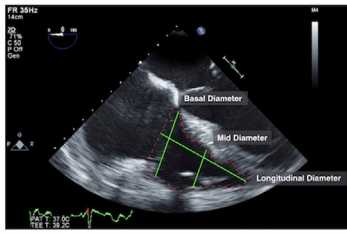
Parameters	Definitions	Illustration
Annular Area	Represents the total amount of space taken up by the 2D surface from the inside boundaries of a structure	
Perimeter	Represents the distance around the edge of the structure (blue circle line)	
Non-planarity	Occurs when the perpendicular distances from each annular point to a calculated regression plane are significantly different from each other at a specific cardiac cycle stage	
Axial Diameters	Represents 4 lines between the 8 hinge points (A-P, S-L, AS-PL and PS-AL), interacting at 45° angles	
Right Ventricle Diameters	Basal diameter: linear maximal transversal dimension at the base of the RV Mid diameter: linear maximal transversal dimension at the middle third of RV Longitudinal Diameter: linear maximal dimension from the middle point of the SL diameter to the apex	

Fig 1. Tricuspid valve analysis definitions. Area and perimeter: obtained using the SolidWorks *measure* tool. Nonplanarity: tricuspid valve plotted with a three-dimensional planar fit constructed via least squares regression to demonstrate nonplanarity and coplanarity. 2D, two-dimensional; A-P, anteroposterior; S-L, septolateral; PL, posterolateral; AL, anterolateral; RV, right ventricle.

Fig 2. 4D Cardio-View module of TomTec Imaging System, 3D images were viewed in sagittal, coronal, and transverse planes. *Lower right panel* demonstrates the rendered image. Step 1: Lateral, septal, anterior and posterior points across the tricuspid annulus were identified in the coronal and sagittal planes. Septolateral and anteroposterior diameters also were measured. Step 2: The plane was rotated in the transverse section to 45° identify 4 additional annular points. A, anterior; L, lateral; P, posterior; S, septal; TV, tricuspid valve.

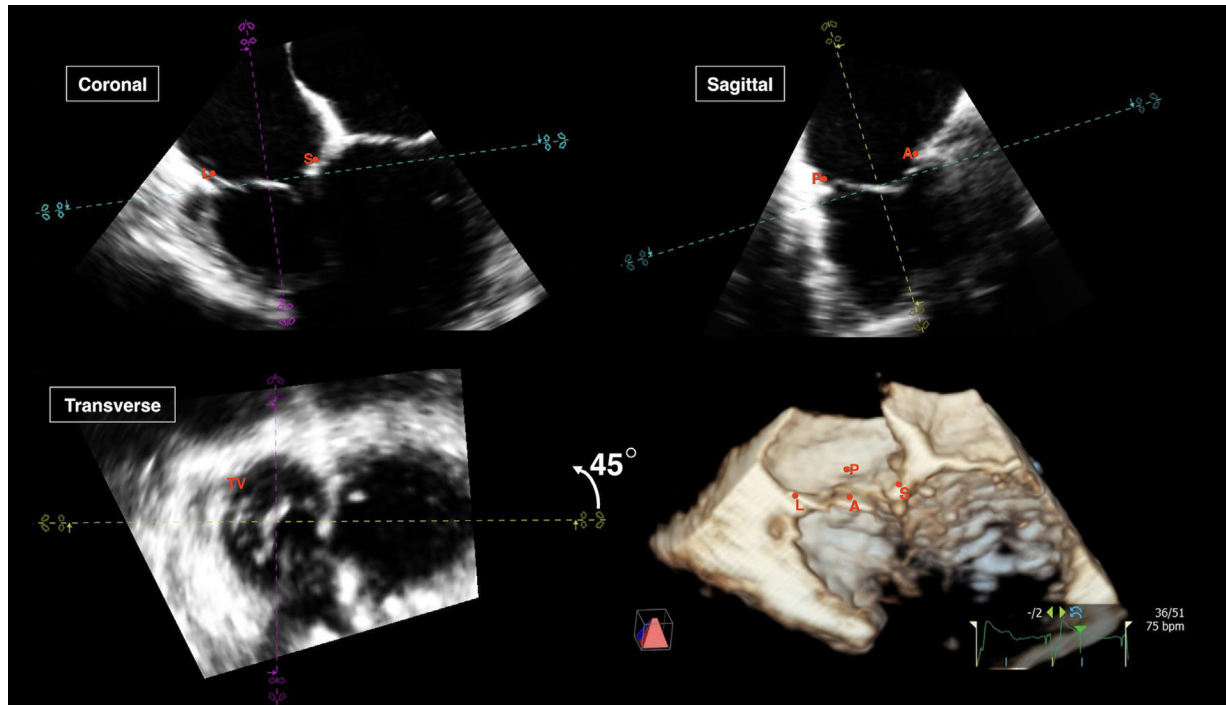could be extended to TV as well. A precise knowledge of the indices of TA remodeling can help better identify the patients with FTR who are unlikely to favorably respond to upstream pressure reduction alone during left-sided surgery. This also possibly can prevent unnecessary surgery on patients who do not have irreversible remodeling and may benefit from a more expectant approach. In order to identify indices of TA remodeling in cases of FTR, the authors compared the 3D dynamic geometry of the TA in patients with FTR and compared it to those without TR.
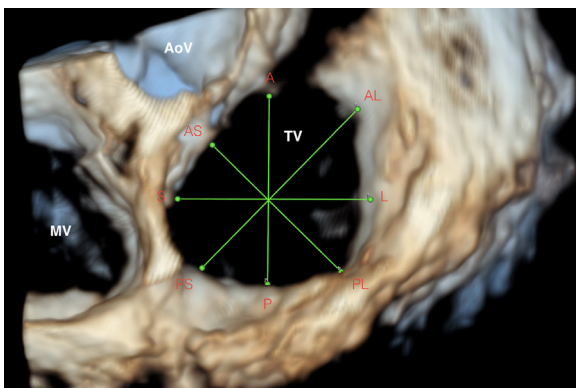
Fig 3. En-face view of the tricuspid annulus. The 4 axes of the tricuspid annulus. A, anterior; AL, anterolateral; AoV, aortic valve; AS, anteroseptal; L, lateral; MV, mitral valve; P, posterior; PL, posterolateral; PS, posteroseptal; S, septal; TV, tricuspid valve.

Material and Methods

This study was conducted as part of an ongoing Institutional Review Board-approved protocol for intraoperative 3D transesophageal echocardiographic (TEE) data collection with waiver of informed consent. The data were collected between January 2015 and January 2017. In this study, patients undergoing elective cardiac surgery with normal nonregurgitant TV (NTR) and moderate FTR were included. Inclusion criteria, which were based on intraoperative TEE assessment for NTR group, included sinus rhythm, elective coronary artery bypass graft (CABG) surgery, normal biventricular dimensions and systolic function, normal valvular function, and absence of TA dilation > 35 mm or any congenital abnormality.[16] The FTR group included patients undergoing elective cardiac surgery with moderate TR in the absence of any structural abnormalities (prolapse, flail, restriction) of the TV. Intraoperative TEE examination was performed immediately after induction of general anesthesia and prior to initiation of cardiopulmonary bypass. While there was no protocol or restriction on fluid administration, image acquisition was completed in all patients with 500 mL of intravenous fluid administration without use of any vasopressor or inotropic therapy. Experienced echocardiographers certified by the National Board of Echocardiography performed all the intraoperative TEE examinations. Philips iE-33 and EPIQ-7 Ultrasound System with an X7-2t TEE probe (Phillips Healthcare, Andover, MA) was used for 3D image acquisition.

Image Acquisition Protocol

Immediately after induction of the general anesthesia, the esophagus was intubated with the TEE probe, and a comprehensive TEE examination was carried out and suitability for inclusion/exclusion was established. For acquisition of the TV quantitative data, with the patient in the neutral position and during a period of apnea, the TEE probe was positioned in the midesophagus. In this position, the midesophageal 4-chamber, 2-dimensional (2D) image was optimized to include the entire TA and right ventricle apex. A multi-beat R-wave gated (4-6 beats) volumetric acquisition was performed during this apneic period with the absence of any motion or electrical interference. The acquired 3D dataset was immediately accessed online for quality assurance. The 3D datasets were selected for further analyses based on the absence of any stitch or dropout artifacts and visualization of the entire TA within the field of view. These data were copied from ultrasound machine through a hard drive in Digital Imaging for Communication format with *raw* data for offline analysis.

Assessment of TR Severity

The severity of TR was assessed in real time during image acquisition using the jet area and vena contracta (VC) method. For assessment of TR severity, the color-flow Doppler box was placed over the right atrium with appropriate adjustment of the Nyquist limit between 55 and 65 cm and midline position of the baseline. The jet area was initially observed in multiple standardized TEE echo windows to visualize the largest jet area. The largest visualized jet area was measured using the generic caliper function of the ultrasound system. The VC was measured in the midesophageal 4-chamber window using the zoom function and cine control; the largest diameter of the narrowest portion of the TR jet was visualized in a specific frame and was measured. Moderate TR was defined as jet area 5 to 10 cm^2, which was confirmed with

VC less than 0.7 cm.[17] A VC width of > 0.7 cm was diagnosed as severe TR.

Right Ventricular Quantification

Measurement of right ventricular diameters was measured in 2D in the midesophageal 4-chamber view. Basal, mid and longitudinal right ventricular (RV) diameters were measured at end-systole (ED) (Fig 1).[18,19] Fractional area change (FAC) was calculated as: $\frac{ED_{RV\ area} - ES_{RV\ area}}{ED_{RV\ area}} \times 100\%$. Function of the RV was quantified with visual qualitative estimation in multiple echo windows. Tenting height of the TV was measured in the midesophageal 4-chamber window at ES. It was defined as the perpendicular distance between the point of coaptation and the SL TA plane.

Offline Image Analysis Protocol

Offline analyses were performed on the acquired data using the Image Arena software with the 4D Cardio-View module (TomTec Imaging System, Unterschleissheim, Germany). In the 4D Cardio-View module, 3D images were viewed in sagittal, coronal, and transverse planes (Fig 2). At ES (last frame before the tricuspid valve starts to open), the TV was identified in orthogonal views and septal, lateral, anterior, and posterior TA points were identified (Fig 2). The multiplanar reformatting plane was then rotated 45° in the transverse section to identify 4 additional points across the TA: posteroseptal (PS), anterolateral (AL), anteroseptal (AS), and posterolateral (PL). Four diameters were thereby obtained: SL, anteroposterior (AP), PL to AS (PL-AS), and AL to PS (AL-PS) (Fig 3). The entire protocol of identification of anatomical landmarks was repeated at ED (last frame before the tricuspid valve starts to close). For each patient, the 8 points at ES and ED were exported as Cartesian coordinates for further analysis.

Area and Perimeter Measurement

The Cartesian coordinates were imported into SolidWorks (Dassault Systems, Paris, France) for reconstruction and computational measurement of TA area and perimeter (Fig 1). The Cartesian coordinates were used to generate a closed spline curve using the *curve through XYZ points* function in

Table 1
Demographics of the Patient Population

	NTR (n = 37)	FTR (n = 18)
Sex		
Male	26 (70)	11 (61)
Female	11 (30)	7 (39)
Age (mean ± SD)	69 ± 10	65 ± 14
BMI (mean ± SD)	28.75 ± 5.63	27.19 ± 5.00
BSA (mean ± SD)	1.98 ± 0.25	1.89 ± 0.24
Procedure		
CABG/CABG concurrent	19 (51)/3 (8)	1 (6)/2 (12)
Valvular surgery with TV annuloplasty	0	5 (27)
Valvular surgery without TV annuloplasty	0	2 (12)
Others	15 (41)	8 (43)
CVP, mmHg	9.18 ± 3.70	17.15 ± 3.48

NOTE. Sex and procedure are reported as counts (%), whereas BMI, BSA, and age are represented as a mean ± standard deviation (SD).
Abbreviations: BMI, body mass index; BSA, body surface area; CABG, coronary artery bypass grafting; CVP, central venous pressure; FTR, functional tricuspid regurgitation; NTR, nonregurgitant valve; TV, tricuspid valve.

Table 2
Right Ventricular Parameters

RV Measurements (mm)	NTR (n = 37)	FTR (n = 18)	p	Normal range[*]
Basal diameter	40.62 ± 6.06	48.30 ± 4.22	< 0.001	25-41
Mid-diameter	30.93 ± 5.35	36.71 ± 6.37	< 0.01	19-35
Longitudinal diameter	64.92 ± 9.92	73.16 ± 10.12	< 0.01	59-83
Tenting height	3.57 ± 3.17	5.98 ± 3.60	< 0.05	N/A
Fractional shortening, %	39.47 ± 11.92	33.74 ± 16.14	0.192	≥ 35%

Abbreviations: FTR, functional tricuspid regurgitation; NTR, nonregurgitant valve; RV, right ventricle.
*Normal range value according to ASE guideline, 2015.

SolidWorks. The closed curve sketch that was generated was then selected and its surface was filled, allowing for area and perimeter to be obtained via the *measure* tool within the SolidWorks evaluation functions. TA area and perimeter were computed in SolidWorks at ES and ED for each patient.

Statistical Analysis

A linear regression plane was fit to the 8 points of the TA by a first-order polynomial in both the x and y direction to the response direction (ie, z). The perpendicular distance from each point to the regression plane was then calculated, and a one-way ANOVA was used to assess whether there was a relationship between average perpendicular displacement from each annular

point to the regression plane at ED and ES in both groups. A significant difference indicates nonplanarity (Fig 1).

A paired t-test was used to assess whether the 4 diameters, area, and perimeter changed significantly between ED and ES in both groups. A Student's t-test was used to assess whether those parameters differed significantly between the 2 groups at both cardiac cycle stages.

The percentage of area and perimeter change as metric of dynamism was calculated as: $\frac{ED_{area/perimeter} - ES_{area/perimeter}}{ED_{area/perimeter}} \times 100\%$ in both groups. A Mann-Whitney U test was used to assess whether the percentage of area and perimeter change has significantly difference between the 2 groups.

A p value of 0.05 was considered statistically significant for all tests. IBM SPSS Statistics 24 software (IBM Armonk,
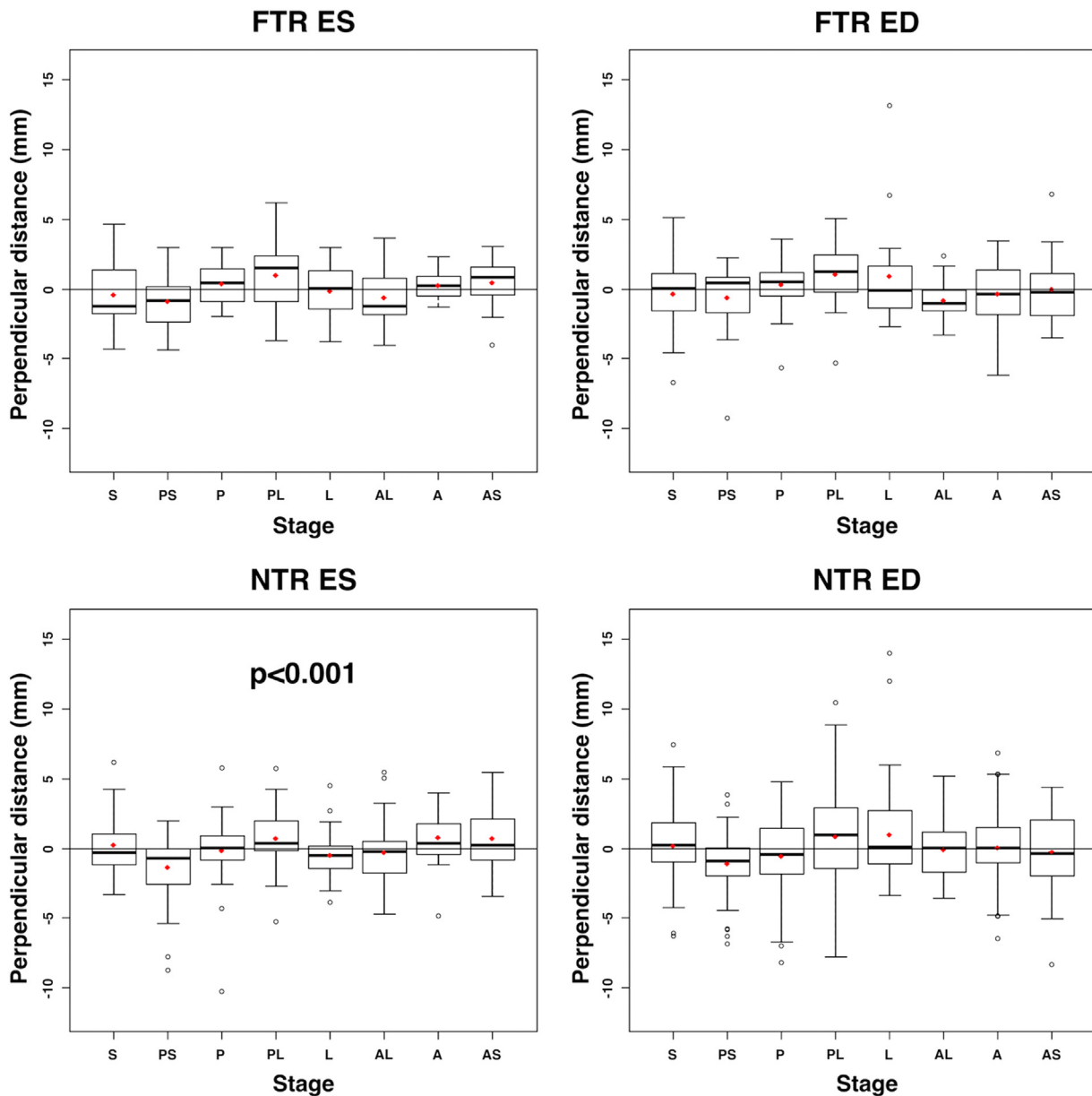

Fig 4. Perpendicular distance from point to regression plane at each point, subdivided by group and cardiac cycle stage. A, anterior; AL, anterolateral; AS, anteroseptal; ED, end-diastole; ES, end-systole; FTR, functional tricuspid regurgitation; L, lateral; NTR, nonregurgitant valve; P, posterior; PL, posterolateral; PS, posteroseptal; S, septal.

New York) and R (R Core Group, Vienna, Austria) were used for statistical analyses.

Results

There were a total of 18 patients in the FTR group and 37 patients in the normal NTR group. Patient demographics and the related procedures were documented (Table 1). The geometric analyses were performed to specifically compare annular area, annular perimeter, axial dynamism, and non-planarity of the TA (Fig 1).

Right Ventricular Remodeling

Compared with NTR group, the basal, mid, and longitudinal diameters of the RV were significantly dilated (p < 0.001, p = 0.001, and p = 0.006, respectively) in the FTR group (Table 2). Basal RV diameter was measured at the base of the RV at the linear maximal transverse dimension at the level of TA (Fig 1). Also, the leaflets were significantly more restricted (tenting height) in FTR valves as compared to the NTR group (p = 0.015) (Table 2). While there was no significant difference between the 2 groups in FAC of the RV, the mean

value in FTR group was lower than the normal range (Table 2).

Nonplanarity

There was a difference in the planarity between the 2 groups. In the NTR group, there was a significant perpendicular displacement of the TA points from the regression plane only in ES (p < 0.001), but not ED; while in FTR group, the relationship was not statistically significant in either ES (p = 0.074) or ED (p = 0.302) (Fig 4).

Axial Dynamism and Dilation

On calculating the dynamism using the above-mentioned formula, it was found that there were significant differences in axial dynamism between the 2 groups. In the NTR group, only the PL-AS axis demonstrated significant changes in dynamism throughout the cardiac cycle (p < 0.001). In the FTR group, none of the 4 axes demonstrated dynamism (Fig 5). However, PL-AS was the most dilated axis both at ES and ED in the FTR group (mean difference = 7.15 mm; p < 0.001 and p = 0.026, respectively).
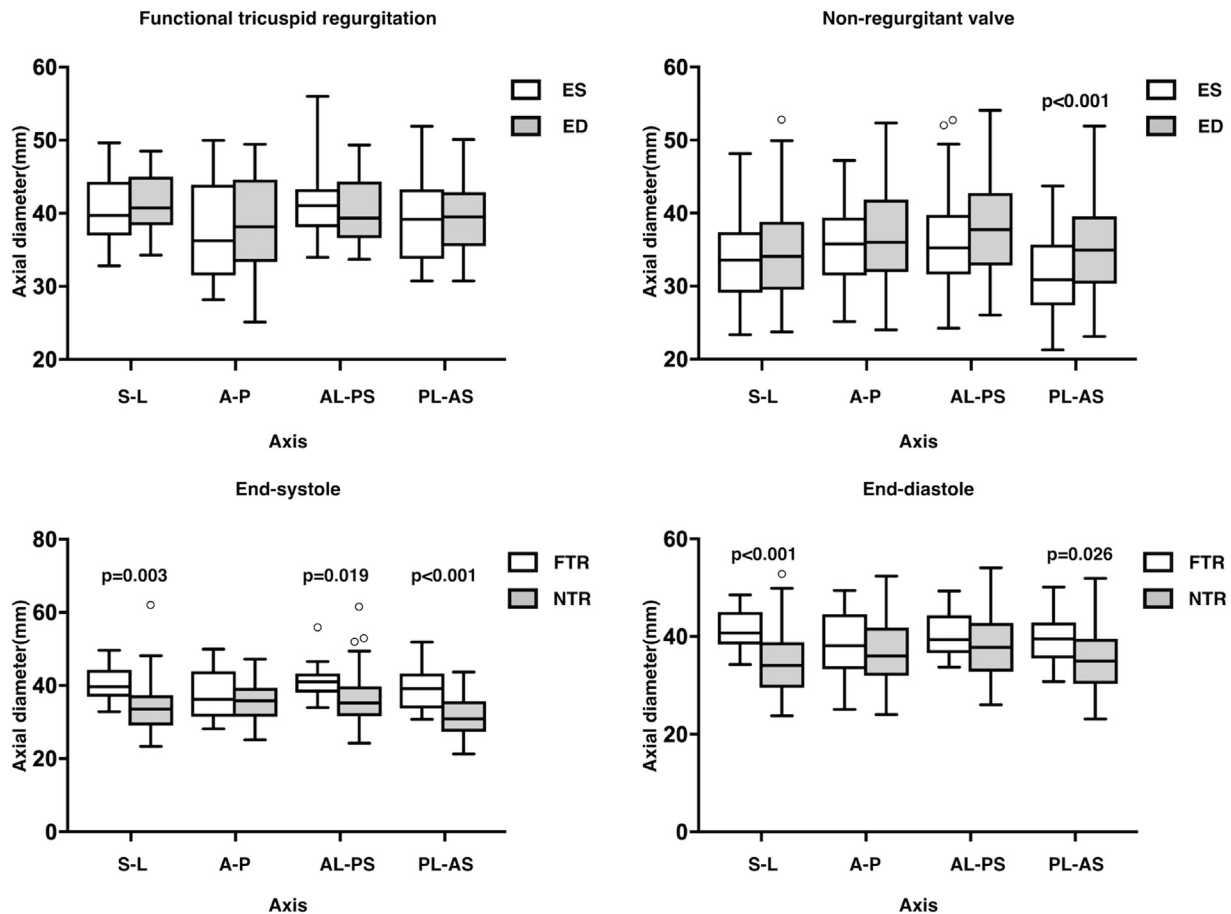

Fig 5. Four-axes diameters across the tricuspid annulus, subdivided by group and cardiac cycle stage. A-P, anteroposterior; AL-PS, anterolateral to posteroseptal; ED, end-diastole; ES, end-systole; FTR, functional tricuspid regurgitation; NTR, nonregurgitant valve; PL-AS, posterolateral to anteroseptal; S-L, septolateral. (Color version of figure is available online.)

Annular Area and Perimeter

In the FTR group, both annular area and perimeter were significantly more dilated than in the NTR valves (Fig 6). Annular area is significantly different between ED and ES in NTR valves (p = 0.049) (Fig 6). The FTR valves did not exhibit any significant difference in ES and ED annular area (p = 0.191) or perimeter (p = 0.079) (Fig 6). The percentage change in annular area (p < 0.001) and perimeter (p = 0.002) from ED to ES in FTR valves exhibited significantly less change than in the NTR valves (Fig 6).

Discussion

These results demonstrate that specific 3D geometric indices can be used to identify a remodeled TA as compared to a normal TA. The authors have demonstrated that the TA in FTR TVs undergoes significant geometric remodeling with chronic volume overload that is manifested as annular dilation and loss of axial dynamism and its nonplanar shape. Specifically, the TA in patients with FTR had a larger annular area at baseline as compared to the NTR valves and did not show any significant annular contraction during the systolic phase.
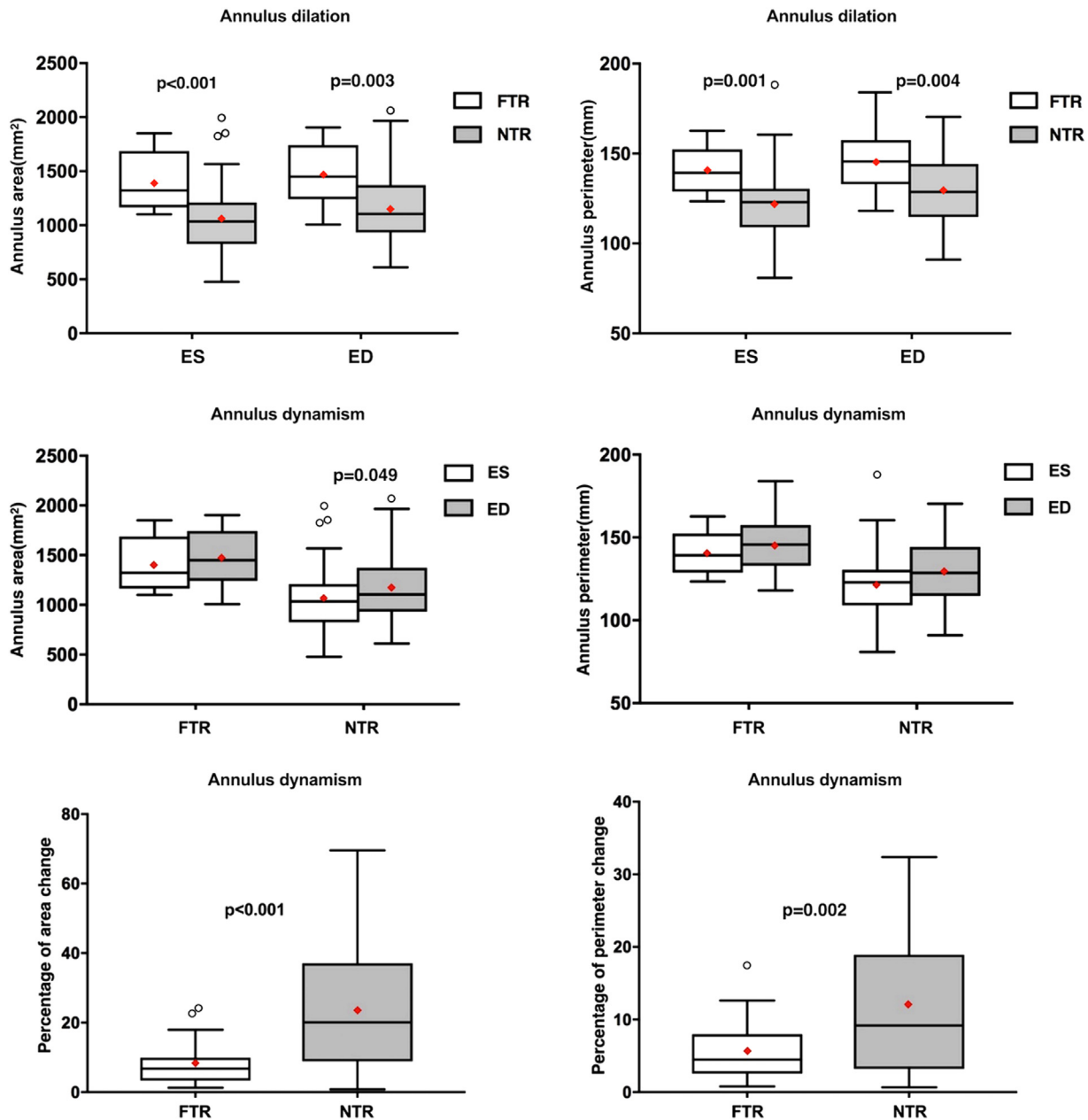

Fig 6. Area and perimeter of the tricuspid annulus obtained using the SolidWorks *measure* tool, subdivided by group and cardiac cycle stage. The percentage of area and perimeter change was calculated as: $\frac{ED_{area/perimeter} - ES_{area/perimeter}}{ED_{area/perimeter}} \times 100\%$. ED, end-diastole; ES, end-systole; FTR, functional tricuspid regurgitation; NTR, nonregurgitant valve.

Importantly, the TA in patients with FTR also had a loss of nonplanar shape and assumed a more flat disposition. In the NTR group, the PS-AL axis demonstrated the maximal relative dynamism as compared to the routinely measured SL dimension. The results of this study are significant in that the authors have identified specific geometric 3D indices of the TA structure that can be used to assess the presence and possibly track progression of remodeling. This information also can be used possibly for stratification of patients with FTR as a criterion for annuloplasty versus conservative management.

Other than the severity of TR and TA dimensions, there is little to guide intraoperative decision making for patient selection for annuloplasty.[11] Knowledge of structural alterations that can be used as indices of irreversible remodeling significantly can improve and refine surgical decision making. With advances in 3D imaging, the shape and dynamic behavior of the TA has been appreciated with a degree of precision.[8,9,20–22] Leaflet tethering and tenting of the TV has been described as a marker of the severity of remodeling.[19,23] This is based on the understanding that apical displacement of the coaptation represents chronic and significant RV remodeling.[22] Geometric changes that reliably differentiate a normal from a remodeled TA possibly can provide additive value in identifying and selecting patients for annuloplasty. Comparison of 3D TA geometric changes between FTR and normal TVs with 3D imaging has not been demonstrated in the past. Whereas the diagnosis of nonplanarity requires post-acquisition reconstruction and analyses, the various axial diameters and TA area calculation described in this study can be feasibly measured intraoperatively.

Unlike the mitral valve, the indices of TA remodeling are not well established. The various clinical criteria used to assist in decision making are either load-dependent variable (regurgitation) or based on axial dimensions measured with 2D and based on erroneous assumptions of the TA anatomy.[5] Structural criteria that are based on long-term indices of remodeling have shown value in predicting recurrence of ischemic mitral regurgitation after repair. Application of the same principles to TA geometry can help us identify patients with significant or irreversible remodeling who are unlikely to respond to upstream pressure reduction alone. Possible loss of annular dynamism and nonplanarity can have the same predictive value for TA remodeling. These results are intuitive in that the TA in FTR patients seems to assume a *passive non-sphincteric* role during the cardiac cycle with progressive dilation and loss of coaptation reserve. Future studies with follow-up will demonstrate the outcome value of these markers.

This study had a few limitations. First, this study had a small sample size. However, the authors' methodology has been well established and the number of variables analyzed provides a robust statistical significance. Therefore, the authors are confident in the validity of their results. Second, part of the authors' analysis required post-acquisition offline user input. However, the majority of the most clinically relevant indices (tenting height, annular area, AS-PL axis of TA) can be readily performed in almost real-time fashion. For example, in using generic on-cart quantification software, all the described TA diameters can be measured easily. Third, the authors do not have outcome data to demonstrate the outcome value of these geometric distortions. Separate follow-up studies will be needed to establish this.

In conclusion, the authors have described echocardiographically obtained indices of TA remodeling in patients with FTR that distinguish them from patients with normal NTR TVs. These include dilation along the PS-AL axis, loss of dynamism, and nonplanarity of the TA. These indices can be possibly used to diagnose the presence and quantify the extent of remodeling of TA.

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