Computed Tomographic Analysis of the Morphometrics and Dynamics of the Tricuspid Annulus in Secondary Functional Tricuspid Regurgitation

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Methods

Study Population
- MRI group (11 patients)
- TR<2+ group (11 patients)
- TR>2+ group (9 patients)
- DCMP group (21 patients)
- Healthy group (10 patients)

Cardiac CT-based TA reconstruction

Results

Table 1: Area predictors

<table>
<thead>
<tr>
<th>Area predictors</th>
<th>Univariate Analysis</th>
<th>Multivariate Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pearson's r</td>
<td>p</td>
</tr>
<tr>
<td>4D RA Area/BSA</td>
<td>0.545</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>4D RV Volume/BSA</td>
<td>0.546</td>
<td>&lt;0.001</td>
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<tr>
<td>IV/EF</td>
<td>-0.388</td>
<td>0.001</td>
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<tr>
<td>Group (Healthy, MR, DCMP)</td>
<td>0.408</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>TR grade</td>
<td>0.419</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Model Coefficient R²     | 0.496               |

Implications:
Cardiac CT is a useful tool for the diagnosis of TA dilatation.
In patients with MR and TR>2+, the tricuspid orifice is often dilated above the accepted cut-off value for concomitant tricuspid annuloplasty.
TA dilatation in secondary TR is independently related to both RV and RA enlargement.
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Glossary of abbreviation

- **AP**
  - 0°-180° diameter: anteroposterior diameter
- **BSA**: Body surface area
- **CT**: Computed tomography
- **DCMP**: Dilated cardiomyopathy
- **ED**: End diastole
- **ES**: End systole
- **FTR**: Functional tricuspid regurgitation
- **TA**: Tricuspid annulus
- **Max diameter**: Maximal diameter
- **Min diameter**: Minimal diameter
- **MCE**: Maximal centroid excursion
- **MPR**: Multiplanar reconstruction
- **MR**: Mitral regurgitation
- **RA**: Right atrium
- **RV**: Right ventricle
- **SD**: Standard deviation
- **TAPSE**: Tricuspid annular plane systolic excursion
- **TTE**: Trans-thoracic echocardiography
Central Picture: Tricuspid annulus 3D area/BSA according to groups and TR grade during the cardiac cycle.

Central message

Tricuspid annulus dilatation in secondary FTR depends on both right atrium and right ventricular enlargement.

Perspective statement

Cardiac CT is a useful tool to accurately measure the 2D projected area or 3D area of the tricuspid orifice, and the dilation of the right cavities that cause tricuspid annulus dilatation. It could help over echocardiography in the decision-making process of tricuspid annuloplasty concomitant to mitral degenerative disease correction.

Structured Abstract

Objectives

Secondary functional tricuspid regurgitation (FTR) management remains controversial mainly due to the lack of knowledge in its pathogenesis and the difficulties to measure the actual dimensions of tricuspid annulus (TA) with current imaging methods. Using a novel method based on multiphase cardiac CT-scan acquisition to accurately analyze the right atrioventricular junction size, we sought to explore modifications of TA morphometry and dynamics in secondary FTR.

Methods

Echocardiographic and cardiac CT studies were obtained from 21 patients with severe mitral regurgitation (MR group) and 21 patients with dilated cardiomyopathy (DCMP group). Using an in-house software, a 3D semi-automated delineation of the TA perimeter was assessed. Modifications of diameters, 2D/3D areas and perimeters were analyzed through time. These 2
groups of patients were compared to 30 healthy subjects, considering the presence of a significant
(≥2+) vs nonsignificant (<2+) FTR in each group.

Results

Maximum TA 3D areas were 7.0±1.2cm²/m² in healthy subjects at mid-to-late diastole and were
smaller than in the MR group (9.8±2.1cm²/m², p<0.001) and the DCMP group (9.2±3.0 cm²/m²,
p<0.001). In the MR group, patients with FTR<2+ had also larger TA areas and diameters than
healthy patients (p<0.01 for all 3D/2D parameters). TA shape was more circular only in the DCMP
group with FTR≥2+ compared to other patients (p<0.05 for eccentricity). In multivariate analysis,
both RA area (p<0.001) and RV volume (p=0.002) were independently related to TA dilatation.

Conclusion

Based on multi-phase CT image analyses, TA dilatation was directly related to RV and RA
enlargement. Patients with severe mitral myxomatous disease and non-dysfunctional tricuspid
valve had yet dilated TA which questioned the current cut-off recommendation for concomitant
tricuspid annuloplasty in this specific population.

Keywords: Tricuspid valve, cardiac CT, functional tricuspid regurgitation
The institutional ethics committee of the Assistance Publique des Hôpitaux de Paris approved the prospective analysis of clinically acquired data (IRB#00001072-IDFII_2015, April, 2015), and the need for written informed consent was waived since all the procedures performed were part of routine care and because the included patients gave their consent for their medical data to be used for research purposes.

INTRODUCTION

Functional tricuspid regurgitation (FTR) is the most common cause of tricuspid valve (TV) dysfunction[1, 2]. FTR is characterized by valve regurgitation, in the absence of leaflets/chordae damages, due to tricuspid annulus (TA) dilatation and/or right ventricle (RV) enlargement and thus functionally corresponds to either type I or Type IIIb of Carpentier’s classification[3]. FTR has recently been divided in two types: 1- Isolated FTR mainly occurring in the setting of atrial fibrillation and atrial enlargement, and 2- Secondary FTR mainly related to RV dilatation and increased afterload[4]. Secondary FTR occurs in up to 30% of patients with severe mitral regurgitation[5, 6] and frequently increases even after successful correction of the mitral valve. TA dilatation is considered as the better predictor for worsening TR after left heart valve surgery than the degree of FTR itself[7, 8]. Since late significant secondary FTR was associated with increased morbidity and mortality, a more aggressive surgical approach towards correction of annular dilatation with or without significant FTR has been recommended at the time of left sided heart surgery[9, 10]. For current guidelines at the time of left valve surgery, a TA diameter >40mm or >21mm/m² obtained from echocardiographic 4-chamber view at end-diastole has to be considered for concomitant TV annuloplasty[11, 12]. Still, this approach remains controversial, particularly in mitral myxoid valve disease where some authors report very small incidence of significant FTR late after MV valvuloplasty[13]. Furthermore, the time-varying and
frequently asymmetric geometry of the TA makes the assessment of TA size complex with 2D echocardiography. Moreover, the latter technique is not appropriate to analyze the actual size of right cavities which could be potential determinants of TA dimensions. In order to explore the specific aspects of TA 3D geometry and dynamics in patients with various degrees of TA dilatation and secondary FTR, we conducted a comparative study on patients addressed for severe mitral regurgitation (MR) or dilated cardiomyopathy (DCMP) using 4D multiphase cardiac CT which has been shown to be reliable for TA morphometric and dynamic analyses[14]. The analysis of the determinants of TA dilation in this population was the secondary objective of this study.

MATERIALS AND METHODS

Patient Population

Subjects were selected among all patients who underwent an echocardiogram and a multiphase cardiac CT at our institution for detecting coronary artery disease (CAD) before cardiac surgery for severe MR due to myxomatous MV degeneration (Barlow’s disease) between January 2017 and June 2019. Eight patients with a bad right-side opacification or atrial fibrillation were excluded and finally 21 patients were recruited for this study (MR group). During the same period, 21 consecutive patients in sinus rhythm were also selected with DCMP (LVEF<40%) undergoing cardiac CT as part of routine assessment of the disease (DCMP group). Reported etiology of DCMP was ischemic in 9 patients, toxic/metabolic in 4 and idiopathic in 8 patients. The 42 patients with MR or DCMP were divided in two subgroups according to the FTR grade (<2+ and ≥2+). A total of 20 patients had ≥2+ FTR (9 with severe MR and 11 with DCMP). Furthermore, 30 patients in sinus rhythm were retrospectively selected as case-controls (Healthy group). These patients have had a recent echocardiogram showing normal systolic myocardial function and no structural heart anomaly (notably absence or trace of tricuspid insufficiency), had performed a CT-scan for atypical chest pain and coronary screening, and the later was considered normal. Upon admission, all subjects included in the present study signed a document
consenting to the use of all data from their medical records for research purposes and scientific publications, including those from cardiac images.

**Transthoracic echocardiography**

All selected patients for having CT had 2D echocardiography within 48 hours, including continuous, pulsed and color Doppler performed by an experienced cardiologist with commercially available ultrasound system (Vivid-7, General Electric Vingmed, Horton, Norway or Epic Cvx Phillips, Andover, MA, USA) at our institution. Severity of TR was evaluated using a multiparametric approach[15]. Transthoracic echocardiography diameter (TTE diameter) was measured at the tricuspid annulus at end-diastole from an apical 4-chamber view.

**Cardiac CT Protocol**

All CT examinations were performed on a 192-slice Dual Source CT system (SOMATOM Force, Siemens Medical Solutions, Forchheim, Germany) with a collimation of $2 \times 192 \times 0.6$ mm, and a temporal resolution of 66ms. Tube voltage was selected semi-automatically. Cardiac CT started by continuous injection of a bolus of 80 mL iomeprol 350 mg/mL, followed by 30 mL saline solution into an antecubital vein via an 18-gauge catheter (injection rate 3-5 mL/s). Retrospective ECG-gated acquisition was performed from the level of the carina to the apex of the heart in a cranio-caudal direction. Electrocardiography-based tube current modulation was applied in all patients for a reduced radiation dose. Images were reconstructed at 10%–100% of the R-R interval in 10% increments. End-systole (ES) was identified as the phase of aortic valve closing and end-diastole (ED) as the phase of mitral valve closing. Temporal phases were expressed as a percentage of the RR interval relative to the ES phase.

**Tricuspid annulus segmentation**

Measurements of the TA size and shape for each time phase were automated with a in house software developed at the Favaloro University (Lattido®, Buenos Aires, Argentina). The complete description
of the TA reconstruction method using Lattido® has been described elsewhere[14]. In brief, this
software displays 9 planes orthogonal to the TA plane in steps of 20 degrees around the normal axis
(Figure 1). In each of the 9 planes, two seed points were manually pinpointed by the operator in the
TA border using the long axis reformatted plane. By convention, the first orthogonal plane (0-180°)
was aligned to the commissure between the right and the non-coronary cusps of the aortic valve.

**Best-fit plane and geometric descriptors**

The software used the 3D position of the seeding points to adjust a best-fit plane and to calculate
specific geometric features to describe the temporal and spatial change of the TA anatomy in 3D. The
best-fit plane was adjusted to the 3D seed points of each time phase using a principal component
analysis approach as described before[14].

In the reference plane, the value of the antero-posterior length between \( P_{0°} \) and \( P_{180°} \), was called the
\( \text{AP}_{0-180°} \) diameter. For a better description of the elliptical shape of the TA the shortest distance between
every pair of opposite points around the TA (i.e., \( P_i \) and \( P_{i+180} \) in Figure 1) was adopted as the value
of minimal diameter (Min Diameter). The largest distance between each pair of opposing points was
taken as the Maximum Diameter (Max Diameter) and the ratio of the maximum diameter to the
diameter orthogonal to it (orthogonal diameter) was used to calculate the eccentricity of the ring using
the following formula as:

\[
\text{Eccentricity Index} = 1 - \frac{\text{Orthogonal Diameter}}{\text{Maximal Diameter}}
\]

Smaller values of eccentricity representing a more circular TA shape. We also measured the orientation
angle of the maximal and minimal diameters at each phase. Angles were expressed between 0° and
180° as explained previously[14].

Additionally, the TA perimeter was divided into three segments of 7 contiguous points: septal (\( P_{0°} \) to
\( P_{120°} \)), posterior (\( P_{120°} \) to \( P_{240°} \)) and anterior (\( P_{240°} \) to \( P_{360°} \)) for sectorial analysis.
The distance between the two farthest centroids of the TA projected in the best-fit planes within the RR interval was calculated as the maximal centroid excursion (MCE) of the TA. Finally, RV contours at end-systole (ES) and end-diastole (ED) measured by multiplanar curvilinear reconstruction (MPR) method were used to estimate RV volumes, and RV ejection fraction (RVEF) as the ratio between RV volumes in ED and ES. Using the MPR method, RA contouring was also performed in the middle transverse orthogonal plane to TA at ED and ES to estimate transverse RA area (RA area).

**Statistical analysis**

Analysis was done using IBM SPSS 26.0 (IBM Corp, Armonk, NY). Continuous variables were reported as mean ± SD and their normality of distribution was tested using the Shapiro-Wilk test. Shortening was defined as the ratio of maximum and minimum values. All morphometric indices such as diameters, perimeters, areas were indexed on the body surface area (BSA). Comparison of data between groups was performed by a two-paired -t-test for continuous variables and χ² or a Fischer exact test for categorical variables. Bonferroni correction was made for multiple testing and the p-value was adjusted accordingly. Statistical significance was defined as p<0.05. Pearson’s correlation coefficients were used to assess the correlations between 2D and 3D areas and/or perimeters comparisons as relations between diameters, perimeters and areas. Univariate analyses were performed to identify the significant determinants of the maximum 3D area of the TA among clinical, echocardiographic and CT parameters evaluated by MPR. The most significant variables from this analysis were included in a final model selected to be best associated with the maximum 3D surface of the TA.

**RESULTS**

**Baseline characteristics & Morphometry**
Baseline characteristics, echographic and CT morphometric TA parameters mean values of the study population and comparisons between groups and subgroups are reported in Table 1. Minimum and maximum values obtained during one RR interval of each TA morphometric parameters are presented in a Supplementary Table.

Although 3D and 2D TA areas values were comparable between MR and DCMP groups, there was a tendency for some parameters such as 3D perimeter, $A_{P_{0\text{-}180^\circ}}$ diameter and $A_{\text{max}}$ diameter to be greater in the MR group compared to the DCMP group ($p=0.061$, $p=0.052$ and $p=0.031$, respectively).

In the MR group, TA area was significantly greater in patients with $FTR\geq2+$ grades than in patients with $FTR<2+$ ($p=0.049$ and $p=0.042$, respectively). However, TTE diameters as well as all other CT diameters were not significant different between these two subgroups. In contrast, in the DCMP group, all areas and diameters CT measurements were significantly higher in the subgroup of patients with $FTR\geq2+$ compared to patients with $FTR<2+$ ($p<0.01$). Additionally, only patients with DCMP and $FTR\geq2+$ had a lower Eccentricity index ($p=0.004$).

Dynamics analysis of the TA

Global fraction of shortening of TA parameters during the cardiac cycle are reported in Table 2. Fraction of shortening of $TV_{3D}$ area occurring during the cardiac cycle was reduced in both MR and DCMP groups compared to the healthy group ($p=0.050$ and $p=0.008$, respectively). However, significant alteration of horizontal TA deformations concerned only the first third of the perimeter ($P_{0^\circ}\text{-}P_{120^\circ}$ septal segment) in MR patients ($p=0.008$) whereas dynamics of almost all 2D parameters was altered for patients with DCMP, notably, fraction of shortening of $A_{P_{0\text{-}180^\circ}}$ diameter was reduced in DCMP patients compared to patients with MR (14.4±3.9% vs 18.6±7.0%, $p=0.006$).

Time analysis revealed that maximal values of 3D parameters occurred in mid-to-late diastole (ES+30% and ES+40%) in all subjects regardless the presence of tricuspid insufficiency (Figure 2 and Figure 3). Fraction of TA 3D area reduction between ES+30%-ES+40% and ES+50%-ES-40% was
56.4+/−39.4% for the Healthy group and was comparable to pathological groups (59.4+/−33.0% and 57.7+/−35.7% for MR and DCMP groups, respectively, p non-significant). On the contrary, minimal values were most frequently seen in end-systole (between ES-20% and Ref ES for TR≥2+ patients, whereas they occurred in early-systole for FTR<2+ patients (ES-40% and ES-30%) whatever the group of patients, MR or DCMP.

Morphometric and dynamical values of RA and RV are also presented in Table 2. As expected, compared to the MR group, patients with FTR≥2+ in the DCMP group had a reduced RV systolic function as characterized by TAPSE, MCE and RVEF (p=0.015, p<0.001 and p= 0.007, respectively). These patients had also more dilated RA and RV (p<0.001 and p=0.003, respectively) and lesser global RA and RV concentric strains compared to FTR<2+ patients with DCMP (p=0.001 and p=0.10, respectively).

The shortening fraction of TA area was related to both CT RVEF (r=0.434, p<0.001) and to systolo-diastolic displacements of the TA directly estimated by MCE (r = 0.327, p=0.005)

Predictors of tricuspid annular dilatation

Table 3 shows the results of univariate and multivariate analysis on predictors of maximal value of indexed TA 3D area. ED RA area and ES RV volume were independently associated with TA dilatation (p<0.001 and p=0.002, respectively).

DISCUSSION

TA measurement remains crucial for optimal management of patients who undergo valvular interventions. However, knowledge on human TA morphometry and dynamics under physiological and pathological conditions is lacking to accurately evaluate TA dimensions and the best imaging method for clinical practice remains to be found. Using the high spatial resolution of cardiac CT and a dedicated software to reconstruct the TA of 3 groups of patients in 3D + time, we demonstrated that:

i) TA dimensions were increased in patients with MR due to myxoid mitral valve disease even without
significant secondary FTR, ii) the ovoid and saddle shape of the TA is globally maintained in patients with TA enlargement secondary to MR or DCMP, iii) the second half of ventricular filling is the time-phase when TA dimensions are maximal and iv) ES RV Volume and ED RA Area are the main determinants of the maximum TA 3D Area and independent of each other.

Morphometry of the TA

The accuracy of cardiac CT measurements in the analysis of TA dilatation in the presence of FTR has already been shown[16–19]. Some authors[20] even found a better correlation between the actual intraoperative TA diameter and its measurement by CT scan rather than 2D TTE. Hassani et al.[17] have also shown that in secondary FTR, even non-gated thoracic CT is efficient to measure TA diameter and to detect significant TR. Our results here confirm the small differences observed between the 3D imaging method which considers the saddle-shaped configuration of the tricuspid annulus and the 2D method which corresponds to the projection in best-fit plane. This result suggests that 2D planar measurements, which are easily accessible to standard software, will be valid for routine CT TA analysis. Maximal 3D areas values obtained in the present study are thoroughly comparable to those previously reported in ED by Praz et al.[18] who also used CT-scan and a semi-automated method for TA analysis. In the MR group, patients with FTR≥2+ did not show a significant increase in TTE TA diameter compared to those with FTR<2+, whereas the minimum diameter and more importantly the 2D/3D areas estimated by the cardiac CT were significantly increased. These results call into question the reliability of TTE diameter estimates as a reference method for defining a threshold value of TA dilatation as indicated before mitral valve surgery in recent guidelines[11, 12].

Shape of TA

The ovoid shape remained globally preserved in the different groups of our study population. Contrary to the results generally reported in the literature, we did not find that the eccentricity index was significantly modified in our MR group specifically composed of patients with myxomatous disease.
demonstrating enlarged TV orifice even when FTR<2+. Van Rosendeal et al.[19] also reported absence of TA circular remodeling in patients with FTR secondary to aortic valve stenosis undergoing TAVI treatment, although the same authors more recently showed that circular remodeling of the TA is an independent prognostic factor of FTR grade after TAVI treatment[16]. In DCMP patients though, we have observed more circularity on dilated TAs in the presence of FTR≥2+ since eccentricity was smaller and, although it was not statistically relevant, Max diameter was more septo-laterally oriented. Noteworthy, Utsunomiya et al. [21] showed that TA dilatation was more anteroposteriorly oriented in primary FTR compared to secondary FTR. Such data tended to suggest that, within the population of FTR, etiopathogenesis as severity of disease may influence TA shape and size and must be considered when evaluating TA dimensions with 2D imaging methods.

**TA dynamics**

Time analysis also revealed that maximal values of TA morphometric parameters are invariably observed at ES+30% and ES+40%, during the second half of ventricular filling. This temporal aspect needs to be considered in tricuspid orifice maximal measurements which should focus on the second third of the diastole. Our timing analysis further confirmed that the biphasic pattern of the TA area curve over time, with contraction during systole and expansion during end-diastole, is globally preserved in patients with secondary FTR[22], even though TA contraction is globally reduced. Our dynamic analysis also demonstrates that systolic contraction of the TA is delayed at ES between patients with and without FTR, explaining the significant difference observed by Maeaba et al.[23] in the absence of RV dilatation. As it has been shown for the mitral valve, this delay is probably responsible for the onset of TR at the beginning of the RV systole.

**Determinants of TA size**

Our data showed that in sinus rhythm patients with left-sided heart disease, regardless of FTR grade and PAPs elevation, TA dilatation was independently related to RV dilatation but also to RA dilatation.
The fact that RV dilatation is a major determinant of TA dilation was expected in secondary FTR but the role of RA dilatation requires some argumentation. In the recent concept of atrial “isolated” FTR, without left heart involvement, right atrial dilatation has been associated with annulus dilatation leading to leaflet malcoaptation in systole[24]. But, in this disease, the role of atrial fibrillation appears to be of major importance and involved in atrial dilatation[25]. Our study shows for the first time the independent and major relationship of right atrial dilatation with tricuspid annular dilatation in subjects with secondary FTR. Furthermore, we have shown here that the contractility of the TA during the cardiac cycle is related to the contractility of the RV represented by its ejection fraction but, RVEF was found not significantly related to TA dilation in our multivariate model (p=0.056). Thus, it is therefore important to emphasize here that in patients in sinus rhythm, RV pre-load conditions are more responsible for the TA dilation compared to systolic function.

**Limitations**

The main limitation of this study is related to the limited number of patients in each group and overall, in each subgroup. Many comparisons of morphometric parameters between groups are just below statistical significance which diminishes the power of this study. The time curves presented in this study are derived from mean values of parameters at each time point. The different profiles of each patient were not specifically analyzed and could be very different from the mean values. It should be noted that although we favor cardiac CT over echocardiography it implies the use of ionizing radiations. However, this modality remains less invasive than coronary angiography and has been increasingly used in the preoperative evaluation of patients undergoing left-sided valve disease with a low probability of having coronary disease. Finally, we have shown that the size of the TA, which is a recognized factor favoring the occurrence of FTR following mitral surgery, is maximal during second half of diastole, i.e. during the acquisition period used by the cardiac scanner to correctly visualize the coronary arteries. The work presented here also suggests that 2D or 3D surface measurements of annular size by CT are more satisfactory than diameter measurements for separating patients with or
The 2D CT area measurement of the TA can be done simply and quickly in less than a minute on a reformatted image by standard software[16, 19].

CONCLUSION

Using the high spatial resolution of multiphase cardiac CT acquisitions, we showed that TA dilatation in secondary FTR is independently correlated to both RA and RV enlargement. In patients with myxomatous mitral valve disease, even in the absence of significant TR, the tricuspid orifice is dilated compared to the standard population and diameters are often above the accepted cut-off value for concomitant tricuspid annuloplasty (Figure 4). By providing accurate measurement of the orifice area and right cavities size, Cardiac CT represents an added value to TTE for deciding on preventive intervention on the tricuspid valve during mitral surgery. Further specific clinical studies using cardiac CT will be needed to define the thresholds of abnormal TA surface to predict postoperative FTR after mitral surgery.
REFERENCES


Table 1: Baseline, and echocardiographic and TA morphometric characteristics in each group and each subgroup (Mean±SD)

<table>
<thead>
<tr>
<th></th>
<th>Healthy patients (n=30)</th>
<th>MR Group (n=21)</th>
<th>DCMP Group (n=21)</th>
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<td>All MR Patients</td>
<td>TR&lt;2+ (n=12)</td>
<td>TR≥2+ (n=9)</td>
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<tr>
<td>BSA</td>
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<td>1.79±0.18</td>
<td>1.82±0.16</td>
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<td>52.5±14.9</td>
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<tr>
<td>Female Gender n (%)</td>
<td>15 (50.0)</td>
<td>11 (52.4)</td>
<td>6 (50.0)</td>
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<tr>
<td>NYHA Class</td>
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<td>1.8±0.7</td>
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<td>21.7±4.7†</td>
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<tr>
<td>sPAP, mmHg</td>
<td>30.7±9.4</td>
<td>33.3±9.2</td>
<td>31.6±5.6</td>
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<tr>
<td>3D Area /BSA, cm²/m²</td>
<td>6.2±1.1</td>
<td>8.9±1.8†</td>
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<tr>
<td>Projected 2D Area / BSA, cm²/m²</td>
<td>6.0±1.1</td>
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<td>7.9±1.8†</td>
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<td>3D Perimeter /BSA, cm²/m²</td>
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<td>8.3±1.1†</td>
<td>7.9±1.1†</td>
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<td>Septal perimeter/BSA, cm²/m²</td>
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<td>2.8±0.4†</td>
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<td>26.0±4.3†</td>
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<tr>
<td>Max Diameter/BSA, mm²</td>
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<td>28.2±4.2†</td>
<td>27.1±4.4†</td>
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<tr>
<td>Max Diameter Orientation, °</td>
<td>135.3±38.8</td>
<td>128.2±53.4</td>
<td>131.1±49.1</td>
</tr>
<tr>
<td>Eccentricity Index</td>
<td>0.58±0.12</td>
<td>0.59±0.12</td>
<td>0.61±0.13</td>
</tr>
<tr>
<td>Min Diameter /BSA, mm²</td>
<td>17.9±2.3</td>
<td>21.0±3.1†</td>
<td>19.7±2.7†</td>
</tr>
<tr>
<td>Min Diameter Orientation, °</td>
<td>63.9±43.0</td>
<td>66.3±21.8</td>
<td>60.2±20.8</td>
</tr>
</tbody>
</table>
BSA, body surface area. TTE, transthoracic echocardiography, s PAP, systolic pulmonary arterial pressure. AP0-180° Diameter, antero-posterior diameter, Max Diameter, maximal diameter, Min Diameter, minimal diameter, NA, not applicable.

Comparison vs healthy: † p<0.05
Table 2: RA, RV morphometrics and TA dynamical parameters in each group and subgroup. The shortenings are the ratio of the difference between the maximum and minimum values to the maximum value (%)

<table>
<thead>
<tr>
<th></th>
<th>Healthy patients (n=30)</th>
<th>MR Group (n=21)</th>
<th>DCMP Group (n=21)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>All MR Patients TR≥2+ (n=12)</td>
<td>TR&gt;2+ (n=9)</td>
</tr>
<tr>
<td><strong>Echocardiography</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAPSE, mm</td>
<td>20.8±3.2</td>
<td>21.5±5.3</td>
<td>20.7±5.4</td>
</tr>
<tr>
<td>S-Wave, m.s⁻¹</td>
<td>12.2±1.6</td>
<td>13.9±2.7</td>
<td>14.2±1.2†</td>
</tr>
<tr>
<td>LVEF</td>
<td>61.0±6.8</td>
<td>60.4±6.8</td>
<td>57.9±8.0</td>
</tr>
<tr>
<td>LV ED Diameter, mm</td>
<td>44.7±5.4</td>
<td>56.1±5.3†</td>
<td>56.7±6.0†</td>
</tr>
<tr>
<td>LA Volume, mL./m²</td>
<td>25.0±12.7</td>
<td>58.3±29.0†</td>
<td>57.2±32.6†</td>
</tr>
<tr>
<td>RA Area, cm²</td>
<td>14.9±1.7</td>
<td>15.7±3.5</td>
<td>15.8±3.7</td>
</tr>
<tr>
<td><strong>Cardiac CT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TA MCE, mm</td>
<td>-18.1±3.9</td>
<td>-20.5±5.2</td>
<td>-18.4±5.7</td>
</tr>
<tr>
<td>3D Area Shortening, %</td>
<td>24.1±7.2</td>
<td>20.7±4.9†</td>
<td>19.2±4.5†</td>
</tr>
<tr>
<td>Shortening of Septal Perimeter, %</td>
<td>27.4±6.7</td>
<td>22.7±4.6†</td>
<td>22.0±4.9†</td>
</tr>
<tr>
<td>Shortening of Posterior Perimeter, %</td>
<td>26.0±5.8</td>
<td>23.2±7.5</td>
<td>23.1±10.1</td>
</tr>
<tr>
<td>Shortening of Anterior Perimeter, %</td>
<td>23.4±6.2</td>
<td>21.3±9.3</td>
<td>21.7±8.0</td>
</tr>
<tr>
<td>AP&lt;sub&gt;90&lt;/sub&gt; Diameter Shortening, %</td>
<td>21.0±7.2</td>
<td>19.1±6.0</td>
<td>18.6±7.0</td>
</tr>
<tr>
<td>RA Area ED/BSA, cm²/m²</td>
<td>9.0±2.2</td>
<td>10.8±3.4</td>
<td>11.8±5.0†</td>
</tr>
<tr>
<td>RA Area ES/BSA, cm²/m²</td>
<td>12.9±2.6</td>
<td>14.6±4.21</td>
<td>14.0±3.8</td>
</tr>
<tr>
<td>RV Volume MPR ED / BSA, mL/m²</td>
<td>78.7±17.4</td>
<td>92.0±27.6</td>
<td>101.8±16.4</td>
</tr>
<tr>
<td>RV Volume MPR ES / BSA, mL/m²</td>
<td>38.2±12.6</td>
<td>51.6±16.5†</td>
<td>60.6±17.9†</td>
</tr>
<tr>
<td>RVEF MPR, %</td>
<td>51.2±8.9</td>
<td>46.6±10.9</td>
<td>51.0±9.5</td>
</tr>
</tbody>
</table>
BSA, body surface area. AP_{0-180°} Diameter, antero-posterior Diameter, TAPSE, tricuspid annular plane systolic excursion. TA MCE, tricuspid annulus maximal centroid excursion. RA, right atrium. RV, right ventricle, RVEF, right ventricular ejection fraction, MPR, multiplanar reconstruction with CT

Comparison vs healthy: † p<0.05.
Table 3: Univariate and multivariate analysis to assess determinants of the maximum 3D area/BSA of the TA.

<table>
<thead>
<tr>
<th></th>
<th>Univariate Analysis</th>
<th>Multivariate Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pearson’s r</td>
<td>p</td>
</tr>
<tr>
<td>ED RA Area/BSA</td>
<td>0.545</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>ES RV Volume/BSA</td>
<td>0.546</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>RVEF</td>
<td>-0.388</td>
<td>0.001</td>
</tr>
<tr>
<td>Group (Healthy, MR, DCMP)</td>
<td>0.408</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>TR grade</td>
<td>0.419</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>sPAP</td>
<td>0.32</td>
<td>0.007</td>
</tr>
<tr>
<td>TAPSE</td>
<td>-0.148</td>
<td>0.241</td>
</tr>
<tr>
<td>Age</td>
<td>-0.023</td>
<td>0.851</td>
</tr>
<tr>
<td>Sex</td>
<td>0.026</td>
<td>0.832</td>
</tr>
<tr>
<td>Model Coefficient R²</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SD, Standard Deviation. BSA, body Surface Area. ED RA Area, end-diastolic right atrium area. ES RV Volume, end-systolic right ventricle volume. RVEF, right ventricular ejection fraction. TR, tricuspid regurgitation. sPAP, systolic pulmonary arterial pressure. TAPSE, Tricuspid Annular Plane Systolic Excursion.
Supplementary Table: Minimal and maximal values (mean±SD) of all TA parameters measured at each phase of the cardiac cycle.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Healthy patients (n=30)</th>
<th>MR Group (n=21)</th>
<th>DCMP Group (n=21)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All MR Patients</td>
<td>TR&lt;2+ (n=12)</td>
<td>TR≥2+ (n=9)</td>
</tr>
<tr>
<td>Area 3D /BSA Min, cm²/m²</td>
<td>5.3±1.0</td>
<td>7.7±1.6†</td>
<td>7.1±1.6†</td>
</tr>
<tr>
<td></td>
<td>6.8±1.2</td>
<td>9.8±2.1†</td>
<td>9.1±2.1†</td>
</tr>
<tr>
<td>Area 3D /BSA Max, cm²/m²</td>
<td>5.1±1.0</td>
<td>7.5±1.5†</td>
<td>6.9±1.6†</td>
</tr>
<tr>
<td>Projected 2D Area / BSA Min, cm²/m²</td>
<td>6.8±1.2</td>
<td>9.5±2.0†</td>
<td>8.8±2.1†</td>
</tr>
<tr>
<td>Projected 2D Area / BSA Max, cm²/m²</td>
<td>6.5±0.8</td>
<td>7.8±1.1†</td>
<td>7.3±0.98†</td>
</tr>
<tr>
<td>Posterior perimeter/BSA Max, cm²/m²</td>
<td>2.4±0.3</td>
<td>2.8±0.5†</td>
<td>2.6±0.4</td>
</tr>
<tr>
<td>Septal perimeter/BSA Min, cm²/m²</td>
<td>1.7±0.3</td>
<td>2.2±0.4†</td>
<td>2.0±0.3</td>
</tr>
<tr>
<td>Septal perimeter/BSA Max, cm²/m²</td>
<td>2.7±0.4</td>
<td>3.2±0.6†</td>
<td>3.0±0.5</td>
</tr>
<tr>
<td>Posterior perimeter/BSA Min, cm²/m²</td>
<td>2.0±0.3</td>
<td>2.4±0.4†</td>
<td>2.3±0.3</td>
</tr>
<tr>
<td>Max Diameter/BSA Min, mm²</td>
<td>18.8±4.0</td>
<td>22.9±3.9†</td>
<td>21.8±4.0†</td>
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<tr>
<td>Max Diameter/BSA Max, mm²</td>
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<td>27.0±5.3</td>
</tr>
<tr>
<td>Eccentricity Index Min</td>
<td>0.43±0.15</td>
<td>0.45±0.13</td>
<td>0.45±0.13</td>
</tr>
<tr>
<td>Eccentricity Index Max</td>
<td>0.70±0.10</td>
<td>0.70±0.11</td>
<td>0.70±0.12</td>
</tr>
<tr>
<td>Min Diameter /BSA Min, mm²</td>
<td>15.8±2.3</td>
<td>18.6±2.4†</td>
<td>17.9±2.3</td>
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<tr>
<td>Min Diameter / BSA Max, mm²</td>
<td>19.8±2.6</td>
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</tr>
</tbody>
</table>

Max, maximal, Min minimal, BSA, body surface area. TTE, transthoracic echocardiography, s PAP, systolic pulmonary arterial pressure. AP, antero-posterior, RA, right atrium. RV, right ventricle, RVEF, right ventricular ejection fraction

Comparison vs healthy: † p<0.05.
FIGURES LEGENDS

Figure 1

Descriptive representation of the semi-automatic method used to locate the tricuspid annulus (TA) at each phase of the cardiac cycle. Multiplanar reconstruction is used to approximatively identify the plane and centre of the tricuspid valve (TV) orifice. Our custom software generates 9 orthogonal planes which rotate every 20° around the normal axis of the TA approximative plane passing through this centre. By convention, the first orthogonal plane (Plane 0-180°) is aligned towards the anteroseptal (AS) commissure of the TV orifice which is located just below the right-to-noncoronary (R-NC) commissure of the aortic valve (AV). Each of these 9 orthogonal planes intercept TA at 2 opposite points which are pinpointed by the examiner $P_i$ and $P_{i+180°}$. The 18 consecutive points of the TV orifice border are interpolated by cubic spline to reconstruct the entire TA.
Figure 2
TA 3D areas / BSA according to groups and TR grade during the cardiac cycle.

TA, tricuspid annulus. BSA, body surface area. MR, Mitral Regurgitation. TR, Tricuspid Regurgitation. DCMP, Dilated Cardiomyopathy. ES, end-systole. ED, end-diastole

Figure 3
Variation of TA diameters / BSA according to groups and TR during the cardiac cycle:

a. AP$_{0-180^\circ}$ diameter

b. Max diameter

TA, tricuspid annulus. BSA, body surface area. MR, Mitral Regurgitation. TR, Tricuspid Regurgitation. DCMP, Dilated Cardiomyopathy. ES, end-systole. ED, end-diastole
Figure 4: Graphical Abstract

Computed Tomographic Analysis of the Morphometrics and Dynamics of the Tricuspid Annulus in Secondary Tricuspid Regurgitation

Methods

- Study Population
  - MR group (31 patients)
  - TR ≥ 2+) patients
  - MR+TR ≥ 2+ patients
  - Healthy group (10 patients)

Cardiac CT-based 4D TA visualization

Results

- TA 4D area (% of one cardiac cycle)
- Groups
  - Healthy
  - MR+TR ≥ 2+

<table>
<thead>
<tr>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Implications:
Cardiac CT is a useful tool for the diagnosis of TA dilatation.
In patients with MR and TR ≥ 2+, the tricuspid orifice is often dilated above the accepted cut-off value for concomitant tricuspid annuloplasty.
TA dilatation in secondary TR is independently related to both RV and RA enlargement.
Finite CT Analysis of Morphometrics & Dynamics of the right atrio-ventricular junction (RAVJ) in secondary FTR

J. Jouan, MD, PhD, Cardiothoracic Surgery, Limoges, France