Four-dimensional Computed Tomography Study of the Tricuspid Annulus Deformation During the Cardiac Cycle

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***Abstract*—The tricuspid valve undergoes a series of geometrical deformations throughout the cardiac cycle. Right ventricular function and left ventricular diseases were associated with the tricuspid valve behavior. The purpose of this study was to determinate if the tricuspid annulus (TA) deformation could be assessed by multiphase computed tomography (CT) imaging. With this technique, 3D volumes can be acquired in ≈10 instants of the cardiac cycle with high spatial resolution. Besides collecting several morphological features of the TA, we looked for the best-fit plane to the dataset using a principal component analysis to evaluate the TA planarity. Algorithms were tested using images from a 67 years old patient. TA area was estimated in 3D and in 2D projecting the points into the fitted plane. In our patient, mean TA areas were 17.7 ± 0.9 and 16.4 ± 0.9 cm^2, respectively. Average root mean square errors of the fitting plane were 2.8 ± 0.3 mm. The was no correlation between TA area and planarity. The use of a 4D multiphase CT technique, which adds the time dimension to the standard 3D together with image processing algorithms, was a reliable method to assess geometrical deformation of the TA.**

***Keywords*— Multiphase computed tomography, tricuspid annulus, tricuspid valve deformation.**

***Resumen*— La válvula tricúspide experimenta una serie de deformaciones geométricas durante el ciclo cardíaco. La función ventricular derecha y ciertas patologías del ventrículo izquierdo están asociadas al comportamiento de la válvula tricúspide. El propósito de este estudio fue determinar si es posible evaluar la deformación del anillo tricuspídeo (AT) mediante tomografías computadas (TC) multifásicas. Con esta técnica se pueden adquirir volúmenes 3D en ≈10 instantes del ciclo cardíaco con gran resolución espacial. Además de calcular distintas características geométricas del AT, se buscó el plano de mejor ajuste mediante un análisis de componentes principales para evaluar la planaridad del AT. Los algoritmos planteados fueron probados con imágenes pertenecientes a una paciente de 67 años de edad. El área del TA fue calculada en 3D y en 2D, proyectando los puntos al plano ajustado. Las áreas 3D y 2D medidas fueron 17.7 ± 0.9 y 16.4 ± 0.9 cm^2 respectivamente. El error cuadrático medio del plano de ajuste fue de 2.8 ± 0.3 mm. No se encontró correlación entre el área y la planaridad del AT. Se concluyó que la técnica de TC multifásica 4D, la cual agrega la dimensión del tiempo al 3D estándar, junto con algoritmos de procesamiento de imágenes, constituyen un método confiable para evaluar las deformaciones geométricas del AT.**

***Palabras clave*— Tomografía computada multifásica, anillo tricuspídeo, deformación de la válvula tricúspide.**

I. Introduction

There is no reliable imaging method for the evaluation of right ventricular function (RVF). The gold standard method that is currently employed is the ejection fraction (EF) estimation, computed from magnetic resonance imaging (MRI) methods. However, this calculation is relatively complex and might be influenced by the heart loading conditions [1,2]. The left ventricle operates in resistance, whereas the right ventricle does it in capacitance. Accordingly, measures of RVF may vary from day to day associated with changes in patient's blood volume.

In echocardiography studies, RVF is not estimated through the EF because of the characteristics of the right ventricle morphology. In this case, the parameters used are, essentially, the tricuspid annular plane systolic excursion (TAPSE) [3] and the S wave [4]. Both quantify the movement of a single point from the anterolateral portion of the tricuspid annulus (TA). It has been shown that these two parameters have the highest correlation to the EF obtained with MRI. Additionally, they are the least dependent on load conditions [5]. Nevertheless, TAPSE and S wave might depend on these conditions and frequently fail if there is either significant tricuspid insufficiency or if the right ventricle is adhered to the wall (e.g. pericarditis, anterior intervention).

It was shown that there is a strong relationship between tricuspid valve (TV) deformation and RVF [6]. Accordingly, there might be several advantages of studying deformation and movement of the TV: i) it would help to understand how a normal valve is shaped and its deformations through the cardiac cycle, ii) parameters that are least dependent on load conditions (and thus permits to evaluate RVF) could be determined, iii) the progression of the deformations of the

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annulus through the most frequent TV pathologies (both rheumatic and functional) could be assessed.

Specifically, the presence of functional tricuspid regurgitation (TR) has been found in patients with left-side heart deficiencies [7-9]. It was believed that surgical therapy of the mitral valve (MV) would improve TR severity. However, mild to moderate TR during MV surgery not only tended to recur postoperatively but it was also associated with reduced functional recovery [10]. As a result, it is becoming common to treat mild to moderate TR with annuloplasty as an adjunct procedure of MV surgery [9,11]. It is known that the tricuspid annulus undergoes different geometrical changes (e.g. dilatation, flattening) before clinical manifestation of TR [12]. This demonstrates why the geometry of the TA is now receiving significant attention [13,14].

The aim of this work was to propose a novel method to evaluate geometrical features of the TA deformation through the cardiac cycle. Enhanced computed tomography (CT) images were employed to delineate the TA perimeter through time in a multiphase study. Several geometric descriptors were employed to quantify TA deformation and evaluate its temporal evolution during the cardiac cycle.

II. Materials and Métodos

A. Data processing

Four-Dimensional CT (4DCT) is a relatively new imaging technique that consists of acquiring consecutive three-Dimensional CT scans in a short period of time. For this study, retrospective ECG-gated 4DCT was performed in a healthy 67-year-old female patient.

The functional data set is axially reconstructed by using a segmental reconstruction algorithm at 0.37mm thickness at every 11% of the RR interval on a 512x512 matrix on a cardiac field of view using a soft tissue convolution kernel. This yields 9 cardiac phases (ranging from 0% to 89%). Visual analysis of these data on cine mode provides information regarding cardiac kinetics. Manual measurements of the TA contour for each time phase were made by an expert using the commercial software OSIRIX (Pixmeo, Bernex, Switzerland).

To delineate the TA, an experienced physician (JJ) pinpointed 20 points around the TA perimeter for each of the 9 phases. Points were set in 3D using a multiplanar view, turning around the TA center in steps of ≈18 degrees. For each step, a pair of opposing annular points were marked, until the entire annulus was represented. Cartesian coordinate data were exported to MATLAB (Mathworks, Natick, MA) for processing.

These points were used to calculate specific geometric features to describe the TV anatomy: TA 3D and 2D area, perimeter, contraction, axial excursion of the TA centroid and the mean distance of the points to an interpolated fitting plane (i.e. the root mean squared error or RMSE). Calculation details are presented in sections B and C.

B. Geometrical features.

TA area and perimeter were calculated in every time phase. To estimate the TA area, we first computed the geometric center (or centroid) of the 20 points (for each phase). Then, we set this point as the origin of coordinates. Between every pair of consecutive points and the centroid, a triangle was formed. The TA area was calculated as the sum of these triangle areas, expressed by the following formula:

$$Area = \frac{1}{2}\left(|P_N \times P_1| + \sum_{i=1}^{N-1} |P_i \times P_{i+1}| \right) \quad (1)$$

where P_i are the N points set by the expert on the TA perimeter and $|\ \ |$ represent the norm. The 2D area was computed with the same formula but projecting the Pi points on a single fitted plane as explained in section C.

The distances between every pair of opposite points were also calculated, obtaining 10 values per phase. The equivalent TA diameter of each phase was estimated as the mean value of these opposite distances. We will denote the maximum and minimum diameters of all phases as d_{max} and d_{min}, respectively. TA contraction was defined as:

$$c = \frac{d_{max} - d_{min}}{d_{max}} \times 100\% \quad (2)$$

Another feature calculated in this work was the axial centroid excursion. To obtain this value, we calculated the distance in the vertical axis between every pair of centroids and took only the maximum into account.

C. Best-fit plane

The best-fit plane to describe the points in each phase was calculated with a principal component analysis approach. First, we calculated the covariance matrix C as:

$$C = X^T X \quad (3)$$

where X is a matrix containing the N centered points. The eigenvectors of this matrix form an orthonormal basis of the dataset. The eigenvectors corresponding to the two highest eigenvalues are the directions that express the highest variability of the points. For this reason, these two vectors defined the best-fit plane, whose normal was determined by the third eigenvector.

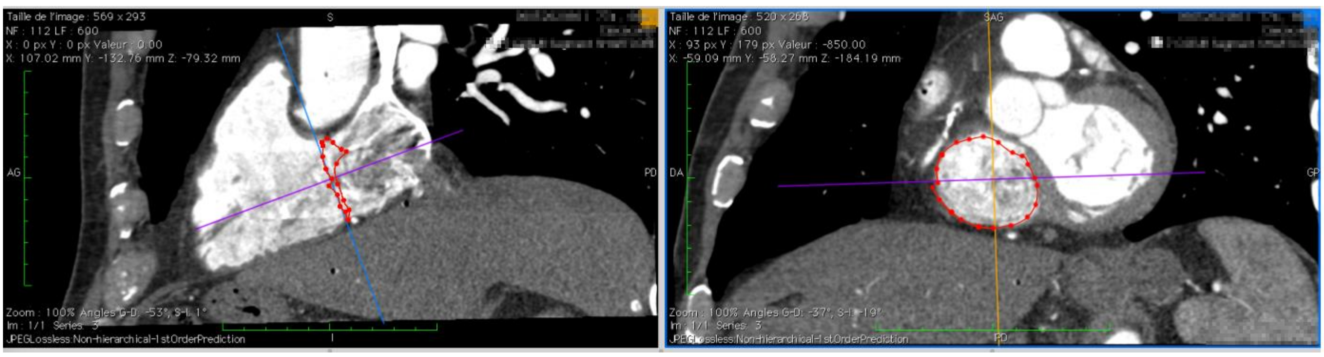

Fig. 1. 3D points set by an expert to delineate the tricuspid annulus using ORISIX MD.

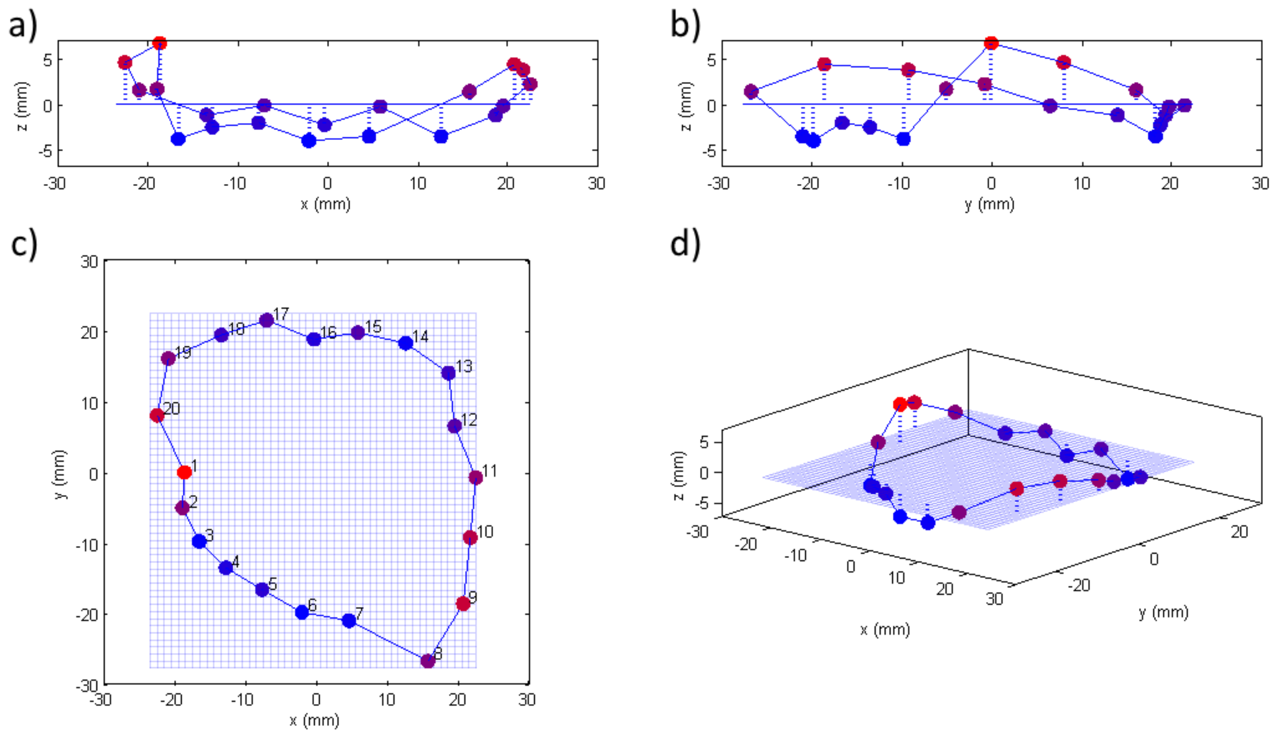

Fig.2 Shape of the TA at the time of minimum area viewed from different perspectives. a), b) and c) show the *xz*, *yz* and *xy* view, respectively. d) shows a 3D view. The red and blue points are located above and below the best-fit plane respectively. The positive values of *z* are closer to the right atrium and the negative values are closer to the apex.

RMSE is the square root of the mean of the squared differences between the plane and the data. In other words, the averaged distance of the points to the plane. Because of this, RMSE was employed as an indicator of TA planarity (or tortuosity). Small values of RMSE indicate a more planar annulus.

III. Results

The TA expert points for one representative phase in a multiplanar view are shown in Fig. 1. It is clear from the left image in Fig. 1 that the points do not remain inside a single plane. Fig. 2 shows the 20 points in 3D. All TA geometric descriptors are shown in Table I. The 3D TA area changed 2.6 cm^2 throughout the cycle. The maximum area was 7.1% higher than the average and the minimum was 7.6% lower. The perimeter seemed to be less variable: it was 3.4% higher than the average at the peak and 5.4% lower at the minimum.

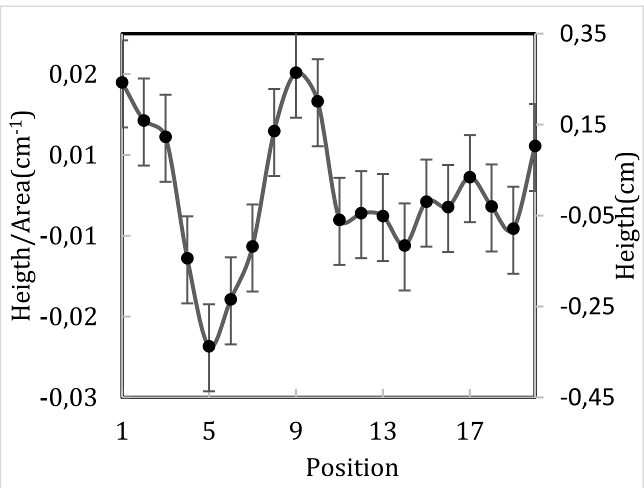

Fig. 3. Distance from the TA to the best fit plane vs point number (see point number in Fig. 2 c)). Values are expressed as Mean ± Standard Error.

Fig. 3 shows the average distance of the TA points to the best-fit plane. Two peaks and two valleys are seen, following the classical saddle shape described in the literature [15,16].

The 3D area of the TA is shown in Fig. 4, together with the 2D area projected on the fitted plane (dotted line). 2D area was systematically lower (7.5%).

IV. Discussion

Structural changes are known to happen in the right heart during several pathologies. These changes include dilatation and other geometrical changes in the TV. The aim of this study was to present an original method to quantify these geometrical changes through 4DCT data analysis. Our study shows that 4DCT scans can be successfully employed in the analysis of TV anatomy and its changes during the cardiac cycle.

Previous works used invasive methods to assess these changes. For example, ultrasonic crystals were implanted in sheep, where similar morphologies of TA curves were found

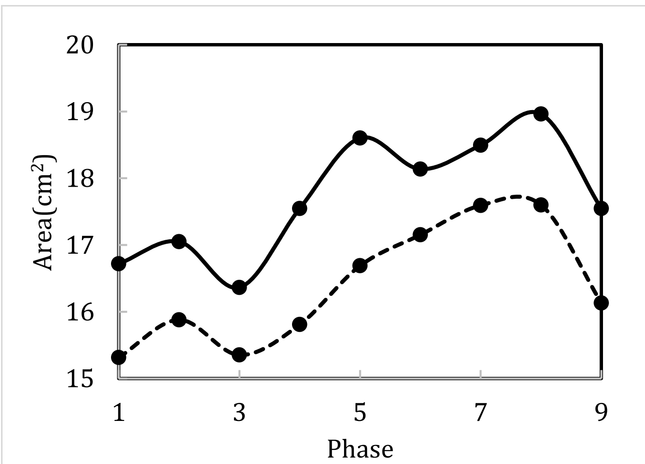

Fig. 4. Solid line shows the 3D area and dotted line shows the 2D projected area.

TABLE I
RESULTS

Quantity	Max	Min	Mean ± SD
3D area(cm^2)	19.0	16.4	17.7 ± 0.9
2D area (cm^2)	17.6	15.3	16.4 ± 0.9
Perimeter(cm)	16.5	15.1	16.0 ± 0.4
Maximum Diameter(cm)	5.6	5.0	5.3 ± 0.2
Minimum Diameter(cm)	4.5	4.1	4.1 ± 0.2
Plane Distance(mm)	6.7	0.02	2.0 ± 1.6
Normalized Plane Distance(cm^{-1})	0.04	$1x10^{-4}$	0.01 ± 0.01
Contraction	-	-	11.6%
RMSE(mm)	3.3	2.5	2.8 ± 0.3
Centroid axial excursion(mm)	-	-	5.0

Geometrical features and changes of the TA.

[17,18]. Additionally, 3D Echocardiography and CT angiography were employed [14,19-21]. For human studies, only non-invasive techniques are acceptable. 4DCT presents a much higher resolution than echocardiography and it does not imply anesthetizing the patient. Furthermore, it allows a precise positioning of the user points in 3D to describe the TA geometry. This measurement is time demanding and can be significantly reduced with the implementation of new image processing algorithms. On the other hand, 4DCT presents a radiation burden, which is around 7–15mSv, with respect to a radiation free technique as echocardiography.

Differing from previous works, in our single patient we did not find a biphasic pattern neither in the 3D nor in the 2D area time curves [18]. This difference might be associated with the method to fit the plane to the TA points. Generally, other studies employed a linear regression analysis and not a principal component analysis. Linear regression means fitting a plane minimizing vertical distances instead of orthogonal distances. The linear regression technique presents higher errors when the TA spatial configuration is more vertical. Minimizing orthogonal distances solves the problem independently of the position of the annulus, because distances are calculated orthogonal to the plane.

Additionally, we analyzed whether the changes in 2D area meant an actual expansion of the TA or if they were caused by changes in its planarity. The correlation between changes in RMSE and 2D area was not significant in our single case (data not shown), suggesting that the latter hypothesis is more probable. Nevertheless, further studies with more patients are needed to validate these preliminary results.

As for the shape, our analysis showed, in average, a saddle-shaped annulus which is similar to the shape of the MV, although there are some anatomical differences [22]. Nevertheless, this shape was not static and its peaks and valleys did not stay in the same location throughout the cardiac cycle.

The analysis presented in this study has a potential interest not only in describing normal and abnormal TA geometry but also as a tool for the design of new and more specific annuloplasty rings.

Some limitations need to be mentioned. In this study, we are exposing the results of the analysis of a single patient, so no conclusions about the normal (or abnormal) geometry of the TV can be made. A larger study with more subjects would be required to better understand the TA deformation through time. It would also be useful to have a better spatial understanding of the 3D data. That is, knowing to which segment of the TV corresponds each segment of the reconstructed valve. Accordingly, a new automated platform is currently developed to help the user to position the TA points and to adjust the plane to each multiphase study.

V. Conclusion

In this study, we assessed the planarity and geometry of the tricuspid annulus through the analysis of multiphase computed tomography imaging. Differing from previous works, we minimized the error when measuring a more vertical tricuspid annulus by using a principal components analysis. Further studies with both healthy and non-healthy patients should be done to better understand the tricuspid annulus deformation throughout the cardiac cycle.

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