3D Evaluation of Tricuspid Annulus Morphology in Patients with Pulmonary Hypertension

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Abstract

Tricuspid valve (TV) dilatation is associated with tricuspid regurgitation and right ventricular failure. Pulmonary hypertension (PH) secondary to mitral valve disease is a common cause of TV dilatation. Decision regarding when to surgically repair the TV, while operating on the mitral valve, is a topic of debate, and is frequently based solely on 2D echocardiographic measurement of TV diameters. To facilitate decision-making, we sought to develop software for 3D analysis of TV morphology from real-time 3D echocardiographic images.

Novel custom software was used to trace and measure TV annulus (TA) in 10 patients with PH and 10 control subjects (CTRL). To trace the TA, 10 rotated planes (18° apart) were displayed and two TA points were selected in each plane. Points were interpolated using smooth splines. The following parameters were automatically computed in 3D: area, perimeter, height, eccentricity, segment lengths, diameters and segmental annulus curvature.

Compared to CTRL, in patients with PH, the TA was: (1) bigger and less planar; (2) less elliptical, i.e. more round. Interestingly, changes in annular shape were not uniform, as the anterior and posterior segments showed altered segment lengths and curvature, while the septal segment remained unchanged. Our new software revealed that PH affects both size and shape of the TA, suggesting that 3D analysis may be useful for pre-surgical evaluation of TV pathology.

1. Introduction

The Tricuspid Valve (TV) is the anatomical structure that separates the right atrium from the right ventricle. Tricuspid valve assessment plays an important role in the diagnosis and management of a variety of cardiac disease states [1]. In particular, in cases of left-sided valvular disease, decisions regarding when to surgically repair the TV, when operating on the mitral valve, is a topic of debate, and is frequently based solely on the severity of the tricuspid regurgitation jet which is load dependent and less frequently on the measurements of TV diameters using 2D echocardiography [2]. The aim of this study was to develop and test in patients with normal and abnormal tricuspid valves a new tool to quantify the morphological parameters of TV geometry from 3D echocardiographic images (fig. 1).

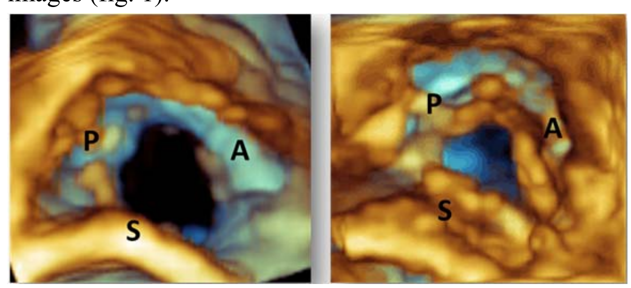

Figure 1. 3D transthoracic echocardiography derived volume rendering of the tricuspid valve as viewed from the right ventricular perspective. Septal (S), Posterior (P) and Anterior (A) leaflets are shown in a patient with a normal valve (left) and a patient with PH (right).

2. Methods

2.1. Patient population

Real-time 3D transesophageal echocardiographic images were acquired using Philips iE33 with the matrix-array X7 probe on 10 normal control subjects (CTRL) and 10 subjects with invasively confirmed pulmonary hypertensions (PH). Inclusion criteria for the control group were: 1) normal TV and mitral valve function; 2) Ejection fraction ≥60%. Two consecutive beats, synchronized with ECG R-wave, were acquired using zoom mode in order to have maximal spatial resolution, to avoid stitch artifacts and to allow complete cardiac cycle acquisition.

2.2. Tricuspid annulus detection

Real-time 3D echocardiographic data were exported to Cartesian format using proprietary Philips Qlab plug-in. Cartesian data were then loaded into our custom software that provides multi-planar visualization as well as 3D visualization of cut-planes (fig. 2). This was achieved by programming using the Visualization Tool Kit (VTK, Kitware Inc.), graphic user interface was developed using QT tools (http://qt.digia.com/) and automatic parameter extraction was implemented in C++.

The initialization of the tricuspid annulus (TA) consisted of the following steps: after loading the data, the user selects a mid-systolic frame, identifying the TA points on several 2D cut-planes, reviews tracing and finally saves data.

After loading the volume, the user is asked for end-diastolic and end-systolic frame identification, then a frame in between is identified as mid-systole and used for TA tracing. On this frame, the user has to find the 4-chamber view, the right ventricular 2-chamber view and the tricuspid plane. Subsequently the program traces an initial guess of the TA, centered on the intersection of the previously identified planes. In the 4-chamber view, two dots representing the intersection of computed TA with that plane are displayed, and the user has to move them in the position corresponding to the intersection of the TV leaflet and the ventricular wall. Then the 2-chamber view is displayed with the corresponding TA dots, and again the user is asked to select TA points. After this, the procedure is repeated as many time as necessary on planes rotated around the TA center in steps of 30°. In order to allow for fast and consistent annulus delineation, TA points are interpolated in real time using smooth spline algorithm [3] with variant weights. According to this method, the coefficient of the cubic spline function $y = S(x)$ can be written as the minimization of a two-term function:

$$\sum_{i=1}^{n} w_i (y_i - S(x_i))^2 + \rho \int (S''(x))^2 dx.$$

Where ρ is the smoothing parameter and w_i are the weights of TA points. The first term represents the least-square minimization and provides the cubic spline fitting of the points on TA. The second term is a penalty function, which suppresses nonlinearity by imposing constraints on the second derivative. When $\rho \to 0$, the

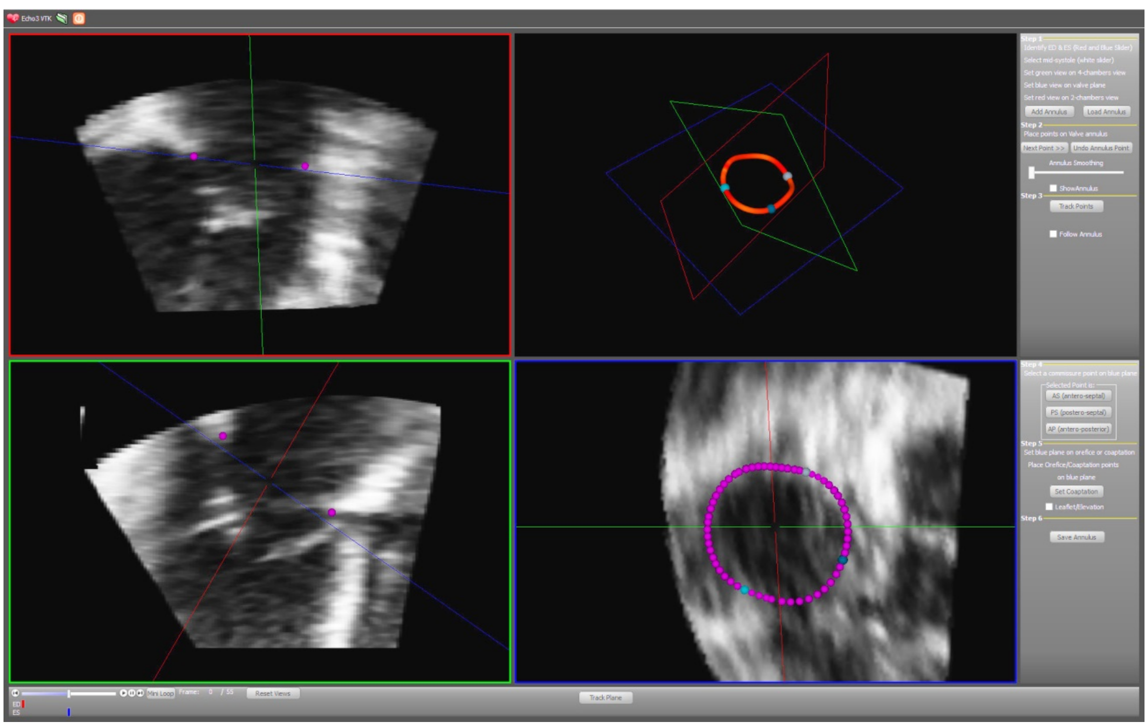

Figure 2. Graphic user interface of the developed tool. Top left: 2-chamber view. Top right: 3D visualization of the interpolated tricuspid annulus (TA). Bottom left: 4-chambes view. Bottom right: 2D slice on the TV plane with superimposed TA interpolation. Right bar: step-by-step guide to perform TA tracing. Bottom bar: frame controls (play, stop, etc.).

interpolation is simplified to cubic spline fitting, while when $\rho \rightarrow \infty$, the result is the smoothest possible line, thus a straight line. This procedure allow for 1D interpolation. Considering the ellipsoidal shape of the TA, we transformed the Cartesian coordinates of TA points into a cylindrical coordinate system centered at the TA center and with the z-axis orthogonal to the TV plane. Consequently, we transformed (x, y, z) into (r, φ, z') defined as: the radial distance r from the z' axis; the angle φ between the reference direction; and distance z' from the TV plane in azimuth direction. Thus the smooth spline interpolation is applied twice (for $S(x)= r$, radial distance and $S(x)=z'$, azimuthal distance), while radial angle is considered as abscissas ($x= \varphi$). The parameters w_i and ρ change during the tracing procedure. Every time the user moves a point to a specific position, the weight w_i of that point is increased so that least-square fitted line is "forced" to pass close to user identified points. In contrast, ρ decreases according to how many points the user has placed on the TA, so that at the beginning, the smoothing of the annulus is strong, while proceeding with tracing reduces the effects of regularization. This procedure allows coarse to fine interpolation of the TA (fig. 3). Finally, the user manually identifies on the TA the three commissural points: antero-septal commissure (ASC), postero-septal commissure (PSC) and antero-posterior commissure (APC).

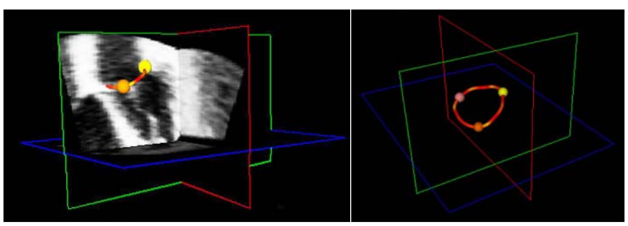

Figure 3. Three-dimensional visualization of the tricuspid annulus, superimposed on the 3D echocardiographic data (left) and with plane outline (right). Dots represent the commissures and spline colors represent local curvature.

2.2. Tricuspid Annulus detection

Once the semi-automatic tracing of the TA is completed, the software automatically extracts the following morphological parameters:

- Percentage of R-R loop on which TA was traced.
- TA Perimeter as the sum of distances between adjacent interpolated points.
- TA Surface Area as the area in 3D of the mesh created by applying Delaunay triangulation to the TA points.
- Mean TA Radius as the radius of the circumference with the same area as the TA.
- Long Axis as TA longest diameter.
- Short Axis as TA shortest diameter.
- Axis Ratio with longest axis in the denominator.
- Eccentricity is a parameter that denotes how much the TA deviates from being circular (circle=0 parabola=1).
- Annulus Height computed as the distance between the highest and the lowest TA points in the direction orthogonal to TV (z').
- Segment length as the perimeter of each of the three annular segments adjacent to the anterior, posterior and septal leaflets.
- Mean Segment Curvature as the inverse of the average radius of the tangential circumferences to each annular segment.
- Mean Segment radius as the average of the distance of each point to TA center.
- Curvature at commissure (AS-PS-AP) as the inverse of the radius of the tangential circumference at each commissural points.

Computed parameters are saved in a tab-spaced file that can be opened in Microsoft Excel for further analysis.

3. Results

Numerical results are listed in table 1. Differences between parameters computed in CTRL and in PH groups were considered statistically significant if the p-value of the unpaired two-tailed t-test was smaller than 0.05. Acquired data had 57 ± 25 frames with a temporal resolution of 31.2 ± 10.8 ms. TA annulus in 3D was found to have a saddle-shape, similar to that of the mitral valve but less accentuated in its non-planarity. In PH patients, the TA was bigger, rounder and more non-planar. Interestingly, the dilatation of TA in PH patients was not uniform, showing no differences solely in septal length and radius. In addition, curvature at the APC commissure was found to be smaller, indicating a less acute conjunction between anterior and posterior leaflet, compared to CTRL.

4. Discussion

Scientific literature regarding 3D measurements of TV geometry offer partial evaluation of TV morphology and the alterations caused by different disease states; the first studies on the TV using 3D echocardiography were published in 2006. These studies described the TV as a saddle-shaped structure with the antero-septal and postero-lateral segments located closer to the right atrium, while antero-lateral and postero-septal segments being displaced toward the right ventricle. Our results were compatible with those previously described for 3D echocardiography [1,2] and MRI measurements [4]. However, we were expecting the TA in PH subjects to be more planar compared to CTRL as previously reported [1]. Also, significant differences between the TA height

Table 1. Tricuspid annulus parameters computed for the two study groups.(* t-test p-value < 0.05)

	CTRL (n=10)	PH (n=10)
Percentage (%) of R-R loop	13.2 ± 24.3	
Perimeter (cm)	10.5 ± 1.2*	13.1 ± 1.1
Surface Area (cm²)	8.0 ± 1.6*	12.4 ± 2.2
Mean Radius (cm)	1.6 ± 0.2*	2.0 ± 0.2
Long Axis (cm)	3.5 ± 0.5*	4.2 ± 0.3
Short Axis (cm)	2.5 ± 0.4*	3.4 ± 0.4
Axis Ratio (%)	73.2 ± 9.7*	81.4 ± 7.3
Eccentricity (circle=0 parabola=1)	0.7 ± 0.1*	0.6 ± 0.1
Annulus Height (mm)	5.0 ± 1.3*	6.4 ± 1.3
Anterior Segment length (cm)	4.0 ± 0.6*	5.1 ± 0.9
Posterior Segment length (cm)	3.2 ± 0.5*	4.1 ± 0.6
Septal Segment length (cm)	3.3 ± 0.7	3.8 ± 0.6
Mean Anterior Segment Curvature (1/cm)	0.065 ± 0.011*	0.051 ± 0.007
Mean Posterior Segment Curvature (1/cm)	0.064 ± 0.017*	0.048 ± 0.009
Mean Septal Segment Curvature (1/cm)	0.067 ± 0.011	0.060 ± 0.011
Mean Anterior Segment radius (mm)	15.9 ± 2.5*	20.1 ± 2.6
Mean Posterior Segment radius (mm)	16.9 ± 5.2*	21.4 ± 3.3
Mean Septal Segment radius (mm)	15.4 ± 2.6	17.2 ± 2.7
Curvature at ASC (1/cm)	0.067 ± 0.028	0.046 ± 0.030
Curvature at PSC (1/cm)	0.046 ± 0.030	0.037 ± 0.026
Curvature at APC (1/cm)	0.074 ± 0.023*	0.048 ± 0.031

normalized by TV area in subjects with tricuspid regurgitation were previously reported [2]. In our data, when applying TV area normalization, we found no significant differences among the two study groups. Our hypothesis, also supported by a previous study [2], is that the mechanism underlying TA deformation secondary to valve dilatation has a regional nature. Consequently, the global height of the TA depends on the localized deformation of the TV and by leaflet morphology (i.e. high tenting area or prolapsed leaflets). In our patients, the septal annular segment did not change in size during annular dilatation with dilatation occurring in only the anterior and posterior annular segments. This result is similar to what has been previously reported [2], with free-wall of the RV being predominantly dilated in patients with functional tricuspid regurgitation. Further studies in different patient populations will provide better understanding of TV remodeling. In these studies, our software may provide useful, reliable and fast parameter extraction for TV characterization.

5. Conclusions

Our new software allowed semi-automatic measurement of tricuspid valve geometry from 3D echocardiographic images revealing that pulmonary hypertension affects both the size and shape of the tricuspid annulus. This 3D analysis may be useful for pre-surgical evaluation of TV pathology.

References

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