The aortic interleaflet triangles annuloplasty: a multidisciplinary appraisal

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Abstract

Objective: Aortic interleaflet triangles annuloplasty (AITA) reduces interleaflet triangles’ circumferential extent through properly placed sutures. To achieve aortic root functional unit (ARFU) stabilization, we aimed at quantifying the effect of suture extent (SE) on aortic valve function and at finding general optimization criteria. Methods: A previously published ARFU finite element model was modified to simulate ARFU dilation and AITA, systematically varying the SE and quantifying the corresponding regurgitant orifice (RO), leaflets co-aptation area (CA) and annular diameter (D0). Computational outcomes were tested by comparison with postoperative virtual basal ring echo data of 105 successfully corrected ARFUs. Results: According to our finite element simulations of AITA, RA and CA depended linearly on SE, through a relationship that predicted optimal surgical results when SE was equal to 48% of the interleaflet triangle height (ITH). Follow-up data showed that, after AITA, ARFU diameter decreased from 23.4 ± 3.93 to 20.1 ± 1.8 mm, (p < 0.05) at the annulus, from 41.53 ± 6.347 to 38.2 ± 4.0 mm, (p < 0.01) at the sinuses, and from 41.3 ± 6.47 to 35.25 ± 5.95 mm (p = ns) at the sinotubular junction (STJ). The mean ITH was 11.18 ± 1.74 mm and the mean SE predicted by our model was 5.34 ± 0.6 mm, that is, 47.76% of the ITH, comparable to 48% of the computational model. Leaflet co-aptation length (CL) increased from 2.73 ± 1.25 to 7.56 ± 2.36 mm (p < 0.001), while the CA evaluated via finite element modeling changed from 8% to 48%. Conclusions: So far, the AITA seems to be a valuable technique to increase leaflet CL in aortic valve repair and in silico models seem to be able to predict the principles of the phenomena but not the individual complexity.

Keywords: Aortic valve repair; Aortic valve finite element models; Computational cardiac surgery; Aortic annuloplasty; Interleaflet triangles

1. Introduction

Aortic interleaflet triangles annuloplasty (AITA), first described by Cabrol et al. in 1969 [1], was a simple technique to achieve aortic root functional unit (ARFU) stabilization after aortic valve leaflet repair, improving leaflet co-aptation and functional valve reserve. For the parabolic shape of the interleaflet triangles (ITs) edges, the AITA was empirically performed at 50% of the IT height (ITH). However, the relationship between the height of the AITA and the clinical result in terms of virtual basal ring (VBR) [2] reduction, co-aptation area (CA), and regurgitant area (RA) are not known. Moreover, there are only a few data available about IT anatomy.

The aim of this study was to identify the optimal height to perform AITA using a multidisciplinary approach based on finite element modeling of the AR, post-mortem investigation of the IT anatomy, and analysis of echocardiographic data of several aortic valve repair procedures.

2. Methods

The study protocol encompassed a multidisciplinary approach based on three different investigational areas:

1. Bioengineering area: Development of AITA finite element modeling to simulate different procedures and to find out the mathematical relationship between AITA height and VBR diameter, CA and RA;
2. Anatomical area: To investigate the peculiar anatomical features of the three ITs and the differences among them; and
3. Clinical area: To compare postoperative echocardiographic data of our surgical aortic valve repair population.
with the information provided by the bioengineeristic and anatomical areas.

2.1. Bioengineeristic area

(a) Physiological finite element modeling

Geometry – The basis for the computational activity was previously published in an article by our research group;[3] hence, its main features are here briefly described. The model assumes three-leaflet symmetry and includes all of the ARFU sub-structures: ITs, valvular leaflets (VLs), valsalva sinuses (VSs) and the proximal tract of the ascending aorta (AA). The initial unloaded configuration of the system was assumed corresponding to the open valve one, with 80 mmHg pressure in the ventricle and in the AA and, thus, 0 mmHg transvalvular pressure drop.

ITs and VSs geometry was based on echocardiographic data from 112 healthy subjects. VL configuration was set according to the Thubrikar[4] method, using an annulus diameter equal to 24 mm, with the aim to make the modeled ARFU configuration comparable to the one adopted in other studies from literature [5]. The AA proximal segment was assumed cylindrical, 11 mm long, and with a diameter equal to the diameter of the sinotubular junction (STJ). The main dimensions of the model are synthesized in Table 1. The whole physiological root model was discretized with 32 722 4-node shell elements with reduced integration (Fig. 1(a)). Shell thickness was set to 2.13, 1.64, 0.71, and 2.30 mm for AA, VSs, VLs, and ITs, respectively, on the basis of literature data [6].

Tissues mechanical response – All tissues were assumed as linear, elastic, isotropic materials; the Young Modulus was assumed equal to 1 MPa for VLs and ITs and 2 MPa for VSs and the AA [5]. A 0.45 Poisson ratio was assumed for all tissues [7]. The density was set to 1.1×10⁻⁰⁴ kg mm⁻³ for the aortic valve and 2.1×10⁻⁰⁴ kg mm⁻³ for the AA, that is, two orders of magnitude higher than the corresponding real values, to account for blood inertia effects [3,5,8,9].

Boundary conditions and contact interactions – ARFU function was simulated during the entire cardiac cycle. The nodes of the aortic annulus were constrained with respect to translations, while radial expansion or contraction of the distal end of the AA was allowed. Blood pressure acting on root structures was modeled using time-dependent pressure loads; a physiological transvalvular pressure drop ranging from 0 to 107 mmHg was applied to VLs, while a relative aortic pressure ranging from 0 to 40 mmHg was applied to VSs and the AA. VL co-aptation and interactions between VLs and the surrounding structures were modeled assuming a 0.05 friction coefficient.

Simulations were run using the commercial solver ABAQUS/Explicit 6.4-1 (Simulia, Dessault Systèmes). (b) Pathological finite element modeling

The model of dilated ARFU with aortic insufficiency differed from the physiological model only by its geometrical features. These were defined accordingly with criteria identified by expert cardiac surgeons: the annulus diameter was increased to 31.2 mm and the VSs were dilated until their maximum diameter was increased by 30%. VLs’ insertion line extent and VLs’ surface were dilated until their maximum diameter was increased by 15% and ITH was decreased from 8.5 to 6.3 mm. The main dimensions of the model are shown in Table 1. The corresponding geometrical model, which was discretized into 33 696 four-node shell elements with reduced integration, is depicted in Fig. 1(b).

(c) AITA model

The AITA model was obtained through two steps. In the first step, the suturing of ITs was simulated on the

<table>
<thead>
<tr>
<th>Geometrical feature</th>
<th>Physiological model [mm]</th>
<th>Pathological model [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>d_a</td>
<td>24.00</td>
<td>31.20</td>
</tr>
<tr>
<td>h_a</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>d_1</td>
<td>35.52</td>
<td>36.05</td>
</tr>
<tr>
<td>h_1</td>
<td>6.00</td>
<td>6.00</td>
</tr>
<tr>
<td>d_m</td>
<td>39.12</td>
<td>39.12</td>
</tr>
<tr>
<td>h_m</td>
<td>12.24</td>
<td>12.24</td>
</tr>
<tr>
<td>d_2</td>
<td>38.64</td>
<td>38.64</td>
</tr>
<tr>
<td>h_2</td>
<td>18.00</td>
<td>18.00</td>
</tr>
<tr>
<td>d_STJ</td>
<td>30.24</td>
<td>30.24</td>
</tr>
<tr>
<td>h_STJ</td>
<td>24.00</td>
<td>24.00</td>
</tr>
<tr>
<td>l_1</td>
<td>16.80</td>
<td>16.80</td>
</tr>
<tr>
<td>l_2</td>
<td>8.52</td>
<td>8.52</td>
</tr>
<tr>
<td>l_fm</td>
<td>36.57</td>
<td>36.57</td>
</tr>
<tr>
<td>l_m</td>
<td>31.10</td>
<td>35.58</td>
</tr>
<tr>
<td>ITH height</td>
<td>8.48</td>
<td>6.30</td>
</tr>
</tbody>
</table>

d_a, annulus diameter; h_a, annulus height; d_m and h_m, maximum width and related distance from the annular plane of the VSs; d_1 and h_STJ, STJ diameter and its position with respect to the annular plane; d_2, two intermediate widths; h_1 and h_2, corresponding intermediate positions; l_1, leaflet radial length; l_2, leaflet commissural length; l_fm, leaflet free margin length; l_m, leaflet insertion margin length; IT, interleaflet triangles.
unloaded pathological model, as schematized in Fig. 2. The nodes on the symmetry plane of each IT were moved radially inward by 1 mm, and the nodes located on the junction between the VSs and ITs, within a threshold distance (AITA level = H) from the zenith of the ITs in the long-axis direction, were symmetrically displaced onto the IT’s symmetry plane, so as to coincide two by two. Subsequently, coincident nodes were tied together via kinematic constraints to simulate the presence of the stitch. To test the effects of different locations of the simulated stitches, three different values of H were considered in three different AITA models: 1.8, 2.4, and 3.0 mm. In the second step, the VSs’ profile, which was affected by the manipulations just described, was smoothed by applying a 26 mmHg pressure on VSs inner surface, while preventing the annulus and the AA distal end from translating. The final configuration of the corrected ARFU was exported and re-imported in ABAQUS/Explicit to simulate ARFU function during the cardiac cycle. For this purpose, the same boundary conditions described for the physiological model were applied.

2.2. Anatomical area

We studied 16 formol-fixed human hearts with normal aortic roots to specifically review the morphological features of the ITs together with their mode of connection to the adjacent structures. Mean cadaver age was 74 ± 16 years (range 26—93 years), all Caucasian; nine were female. The specimens were prepared for measurements by trimming the AA 1 cm above the STJ, and circumferentially dissecting the left ventricular outflow tract 1 cm below the nadir of the VSs. Specimen analysis was made after opening the ARFU longitudinally through the middle portion of the non-coronary VSs, to keep the ITs intact and spreading the

opened ARFU on a flat surface without stretching it. The specimens were then photographed using a 6.1-megapixel digital camera (Nikon D70) at a standard distance of 30 cm, both with the leaflets in place and after removing them. Pictures were subsequently reviewed using a computer-aided design software (Auto CAD®, Autodesk, 2004) for indirect structures’ measurements. A centimeter ruler was placed under each specimen and included in the pictures allowed for software calibration and image sizing. A 10-fold magnification was used to precisely contour the different ARFU parts to be analyzed and to measure the ITs’ relationship (Fig. 3).

2.3. Clinical area

Between September 2003 and February 2008, we enrolled a total of 105 patients with a diagnosis of aortic valve regurgitation. The mean age was 59.5 ± 15.2 years; 67 patients were male and 38 female. All subjects were diagnosed based on echocardiography criteria and scheduled for aortic valve surgical repair after signing an informative paper on the planned repair procedures and their results from literature. Patients were excluded, if affected by valve stenosis with complete fusion and calcification of the three leaflets, regardless of the ventriculo-aortic gradient (Δ) and if affected by a bicuspid aortic valve. None of the patients had co-morbidities that could influence the modalities adopted for AITA, nor VSs’ dilation requiring a sparing procedure. Coronary catheterization was performed in patients aged > 45 years or in the presence of significant surgical risk factors. Preoperative transthoracic echocardiography (TTE) was performed to assess aortic valve pathology, left ventricular function, and to rule out the presence of associated mitral or tricuspid disease. The degree of valvular regurgitation was evaluated as grade 0 to IV. Before cardiopulmonary bypass, transesophageal echocardiography (TEE) was performed to assess the mechanism of regurgitation according to the El Khoury Classification [10], and to measure the ARFU features as described by Anderson [2,11]: VBR, aortic root, STJ and AA.

The chest was opened through a median sternotomy incision and the patient was placed on cardiopulmonary
bypass with cannulation of the AA and of the right atrium appendage or, if a mitral or tricuspidal repair was necessary, of both venae cavae. After induction of cardiac arrest by infusion of cold crystalloid cardioplegia (St. Thomas Solution®) into the coronary ostia, the aortic valve and root were inspected to add ‘surgical-oriented’ information to TEE analysis, and the ARFU repaired by the association of different surgical techniques (Table 2).

3. Data analysis

The statistical analysis of data was performed using Statistical Package for Social Sciences (SPSS®) 13.0 software (SPSS Inc., Chicago, IL, USA). Normal distribution was tested using both the Kolmogorov–Smirnov statistics with a Lilliefors’s significance level and the Shapiro–Wilk test. Continuous data are presented as means ± standard deviations. The Student’s Paired t-test was used after evidence of normality. Nominal data are presented as absolute frequencies or percentages. Analysis of categorical variables was performed by the χ² test or Fisher’s exact test where appropriate. A two-tailed p value < 0.05 was considered statistically significant.

4. Results

4.1. Bioengineeristic area

Given the purpose of the present study, the analysis of computational data focused on leaflet CA, on aortic valve RA and on the annular diameter (Dₐ in the finite element model and VBR in surgical terminology) corresponding to the three simulated AITA configurations. All of the mentioned parameters were assessed at maximal diastolic transvalvular pressure drop. CA was quantified as the fraction of leaflet surface characterized by a non-zero contact pressure, and RA was estimated as the fraction of valvular orifice area not occluded by VLs in a short-axis view. The values of the mentioned parameters are reported in Table 3 for the physiological, pathological, and AITA models. According to AITA simulations, all of them depended linearly on H in the considered range of configurations (Fig. 4). The AITA repair simulation with H equal to 3 mm seemed to be the optimal correction to perform; in this simulated postoperative configuration, valve competence was restored (RA = 0%). CA and Dₐ values were very similar to the ones estimated for the physiological model. The CA value increased up to 48%.

4.2. Anatomical area

The mean ITH measured on the three ITs of 16 human hearts was 11.1 ± 1.7 mm (range 6.1—14.7 mm). The mean apex angle was 48 ± 12° (range 28—62°).

4.3. Clinical area

No patient underwent emergency surgery. One patient died within 30 days from the procedure (operative mortality: 0.95%) due to aortic wall rupture.

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Table 2. Percentage of aortic valve repair techniques associated to AITA.

<table>
<thead>
<tr>
<th>Concomitant surgical technique</th>
<th>Percentage of patients (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ascending aorta replacement</td>
<td>67.6</td>
</tr>
<tr>
<td>Shaving</td>
<td>35.2</td>
</tr>
<tr>
<td>Free margins reinforcement</td>
<td>27.6</td>
</tr>
<tr>
<td>Leaflet plicature</td>
<td>11.4</td>
</tr>
<tr>
<td>Free margins remodelling</td>
<td>10.5</td>
</tr>
<tr>
<td>STJ plicature</td>
<td>9.5</td>
</tr>
<tr>
<td>Triangular resection</td>
<td>2.9</td>
</tr>
<tr>
<td>Leaflet patch</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Table 3. Computational outcomes defining aortic valve competence: regurgitant area (RA), leaflets coaptation area (CA), annular diameter (Dₐ), aortic interleaflets annuloplasty (AITA), suture extent (SE).

<table>
<thead>
<tr>
<th>Model</th>
<th>RA [%]</th>
<th>CA [%]</th>
<th>Dₐ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physiological</td>
<td>0</td>
<td>45</td>
<td>24.0</td>
</tr>
<tr>
<td>Pathological</td>
<td>10</td>
<td>0</td>
<td>31.2</td>
</tr>
<tr>
<td>AITA SE 1.8 mm</td>
<td>9</td>
<td>8</td>
<td>29.6</td>
</tr>
<tr>
<td>AITA SE 2.4 mm</td>
<td>5</td>
<td>32</td>
<td>28.0</td>
</tr>
<tr>
<td>AITA SE 3.0 mm</td>
<td>0</td>
<td>48</td>
<td>26.4</td>
</tr>
</tbody>
</table>

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Fig. 4. Interpolation of CA, RA and Dₐ data obtained for the three simulated AITA configurations showing their linear dependency on the suture extent SE.
After the repair procedure, there was an increase of coaptation length (from $2.7 \pm 1.2$ to $7.6 \pm 2.4$ mm (significant $p = 0.01$) and a decrease of the diameters of the VBR (from $23.4 \pm 3.9$ to $20.1 \pm 1.8$ mm (significant; $p = 0.03$) of the aortic root (from $41.5 \pm 6.3$ to $38.2 \pm 4.0$ mm (significant: $p = 0.0003$) and of the STJ (from $41.3 \pm 6.5$ to $35.2 \pm 5.9$ mm (significant; $p = 0.003$). Aortic regurgitation echocardiographic grade $\geq II$ was found preoperatively in 102 patients and at discharge in three patients (significant $\chi^2 = 181.9$, $p = 0.001$). The mean and maximum ventriculo-aortic gradient did not change significantly ($\Delta_{\text{max}}$ from $19.5 \pm 10.2$ mmHg to $21.8 \pm 11.7$ mmHg, $ns: p = 0.13$; $\Delta_{\text{mean}}$ from $11.8 \pm 7.4$ mmHg to $12.8 \pm 6.9$ mmHg, $ns: p = 0.31$). The left ventricular end-diastolic volume decreased from $56.9$ ml to $52.4$ ml (ns: $p = 0.6$); the left ventricular end-diastolic diameter changed from $56.1 \pm 7.7$ mm to $52.4 \pm 8.6$ mm (ns: $p = 0.12$). During a follow-up of 7 years, two patients were re-operated for aortic regurgitation grade $> 2$.

5. Data synopsis

The in silico model returned a linear relation between the VBR diameter and the AITA level in terms of height:

$$\text{VBR(diameter)} = -2.68 \cdot \text{AITA level} + 34.43$$

Resolving the equation for the AITA level, we obtained:

$$\text{AITA level} = \frac{34.43 - \text{VBR(diameter)}}{2.68}$$

Our follow-up data included the postoperative VBR (diameter) of each patient measured by long-axis intraoperative TEE view. Thus, we could use this equation to calculate the estimate height ($eH_i$) of the stitch for each patient:

$$eH_i = \frac{34.43 - \text{Postoperative VBR}_i}{2.68}, i = 1, \ldots, 105$$

We then estimated the corresponding mean value and standard deviation for our AITA procedures, thus obtaining $eH = 5.34 \pm 0.6$ mm.

The anatomical study reported a medium ITH of $11.18 \pm 1.74$ mm; our $eH$ mean value represented $47.76\%$ of the ITH mean value:

$$eH\% = \frac{eH}{\text{ITH}} = \frac{5.34}{11.18} \cdot 100 = 47.76\%$$

6. Discussion

The AITA was first introduced by Cabrol et al. in 1966 (Cabrol stitch) [1] to repair the aortic valve in presence of aortic valve regurgitation due to VBR dilatation. His technique consisted in a U suture reinforced by two Teflon pledgets in the apex of the IT to correct the STJ dilatation and at a non-defined height toward the left ventricle to correct what he called ‘the inferior aortic diameter’ (currently VBR). The issue of non-defining a height or an easy procedure to calculate an adequate height where to perform the AITA led this technique to a non-standardization. El Khoury et al. [10] redefined these ideas with the concept of the functional aortic annulus (STJ + VBR) as the natural stent of the aortic valve responsible for inducing regurgitation when dilated, and described the importance of AITA without defining an adequate height value. Fraser and Cosgrove [12] in 1994 underlined the importance of providing improved support for the cusp after valve closure, increasing with this technique the area of leaflet co-apptation, called lunula. This part that in the model we call CA seems to be dependent on the level at which the sutures are placed in the ITs. Moreover, the authors cautioned about avoiding an excessive AITA depth leading to potential valve stenosis without explaining how to calibrate the surgical maneuver or the mechanism involved.

In our experience, AITA has been used both to reduce the VBR and to stabilize the surgical repair in the long-term, borrowing the idea from mitral valve repair. We started empirically performing AITA at 50% of the ITH. The motivation of this choice is that, from an anatomical standpoint, the IT is not a triangle but a structure formed by two rounded sides of parabolic shape and a curve line connecting the nadir of the two adjacent cusps. In their upper half, from the STJ to 50% of the ITH, the two sides are almost parallel, and, in their lower half, they start to diverge to reach the nadir of the correspondent cusp (Fig. 5). Closing the upper part with a pledge-reinforced braided suture would increase the CA without significantly impinging leaflet motion or left ventricle-aortic root pressure drop, while going after this landmark would alter the valve cinematic generating pressure drop and stresses. On this basis, we built our computational model to identify the best AITA height in terms of RA minimization, CA and VBR diameter size restoration. According to our numerical results, the optimal AITA suture height corresponds to 48% of ITH; in this configuration, CA was increased nearly up to its physiological extent (48% vs 45% physiological value), valve competence and normal VBR diameter were restored (RA = 0%, VBR diameter = 26.4 mm vs 24 mm physiological value). In preliminary in vitro analyses carried out in an ad hoc pulsatile mock loop, whose detailed description is beyond the goals of the present study, we...
observed that an over-reduction of VBR diameter allows co-aptation of the lower part of the lunula, but induces the opening of its upper part, as in a funnel-like configuration. This configuration is of course non-physiologic and is likely to be suboptimal from a functional standpoint. This experimental evidence, although preliminary, supports our conclusions based on numerical results.

The knowledge of the human ITs anatomy and our measures by the anatomical area allowed us to define as normal an IT with an apex angle < 60° and a medium height of 10.7 ± 1.8 mm. To best standardize these measures, we preferred to calculate mean values and standard deviation for the complete series of 48 triangles, without grouping for anatomical position.

Using the three linear regression formulas, obtained from finite elements, which expressed CA, RA, and VBR as a function of AITA suture height, we confirmed both the adequacy of the suture height we previously adopted in our surgical practice due to an empirical criterion, and the model capability to explain the main relationships in the aortic root functional unit corrected by an AITA procedure. The starting hypothesis of performing the AITA at 50% of ITH was confirmed by the result of the estimated height eH% (47.7%) and the identification by the model of the 48% as the best place where to perform the AITA.

We confirm from our experience the feasibility of the AITA procedure in association with all the other aortic valve repair techniques both to reduce the VBR and to stabilize the result obtained. No Kaplan—Meier analysis was performed on this group of patients, representing a part of the aortic valve repair patients treated in our hospital, identified to match the computational studies. The possibility of performing asymmetric AITAs depending on the insertion of the leaflets on the commissures, to restore a symmetric lunula, could expand the use of this technique where the use of an external or internal complete ring appears to be not adequate. Moreover, the observation by Dagum et al. concerning subcommissural triangle. If we also have a pathology of the ventricular-aortic junction, we strongly believe that could be a powerful tool for the possibility of tailoring this height in the three triangles in order to obtain the best result. So if you have a ventriculo-aortic junction huge dilatation, with an apex angle of more than 60 degrees, we can be more aggressive going down with the stitch to achieve more closure of the triangle. Otherwise, 50% of the interleaflet triangles height is a good option.

So far, the AITA seems to be a valuable technique to increase leaflet co-aptation length in aortic valve repair and in silico models seem to be able to predict the principles of the phenomena but not the individual complexity.

In conclusion, AITA stitch positioning at 50% of ITH allows optimal leaflet co-aptation and RA reduction, without impinging blood flow through the VBR. These features make it ideal not only to correct aortic valve regurgitation but also to stabilize aortic valve repair procedures, preventing future VBR dilation.

References

unit. If the leaflet is small and the triangle is small, this could stabilize your long-term results.

*Dr El Khoury (Bruxelles, Belgium):* Andrea, from your model I understand that doing the subcommissural annuloplasty at 50% of the height maybe can improve the coaptation, but I can’t see very well how it can stabilize the horizontal plane or whatever of the aorto-ventricular junction.

*Dr Mangini:* The virtual basal ring?

*Dr El Khoury:* I understand that 50% maybe is very good at the level of the right main or the left-right, but between the main and left maybe we have to go even, we have to go deeper anyway, because we want to stabilize the repair by improving the coaptation but also by reducing and really stabilizing the aorto-ventricular junction.

*Dr Mangini:* At 50% you already reduce the annulus. The problem is, and we clearly demonstrate it by our mock loop simulation, that going down the 50% you start to dramatically increase the pressure drop. We don’t want, of course, to create a valve stenosis by hampering the leaflet motion. The aortic interleaflets triangles annuloplasty performed at 50%, produces a virtual basal ring reduction without hampering their motion.