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Eur J Cardiothorac Surg 2010;38:400-406
DOI: 10.1016/j.ejcts.2010.01.060

This information is current as of October 5, 2011

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Aortic root and cusp configuration determine aortic valve function

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Received 30 September 2009; received in revised form 19 January 2010; accepted 21 January 2010; Available online 12 March 2010

Abstract

Objective: Normalisation of aortic root and cusp configuration is a prerequisite for successful aortic valve repair (AVR). Using transthoracic echocardiography, we studied aortic root dimensions relative to body size in normal subjects and AVR patients. Methods: Aortic roots of healthy volunteers (n = 130, age 27.9 ± 16.9 years) were examined for aortoventricular (AV), sinus (S), sinutubular-junction diameters (ST) and effective height (height difference between the AV plane and central coaptation point, eH) by transthoracic echocardiography. In 651 patients, after AVR residual aortic valve insufficiency (AI) and eH were determined. The relationships between eH versus root dimensions and eH versus residual AI were analysed by analysis of variance with Bonferroni post hoc testing. Results: Root dimensions correlated with each other and body size (r = 0.74–0.91). In addition, a correlation between AV (r = 0.73), sinus diameter (r = 0.76), body height (r = 0.77), body surface area (r = 0.81) and eH was found. After AVR, eH was 9.8 ± 0.9 mm in 235 patients without postoperative AI, 9.4 ± 1.1 mm in 370 with mild AI, 7.9 ± 1.4 mm in 43 patients with moderate AI and 6 ± 1 mm in three patients with severe AI. The difference in means of effective height between the groups was significant (p < 0.005). Of 497 AVR patients with an eH ≥ 9 mm, 309 had no or trivial AI, 186 had mild AI and only two had moderate AI. Conclusions: Parameters of aortic root dimensions follow a seemingly constant pattern in humans of different sizes. Effective height has a constant relationship to root dimensions and body size. In AVR, normalisation of eH leads to a high probability of normal or near-normal aortic valve function.

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Keywords: Aortic valve repair; Aortic root dimensions; Aortic cusp geometry; Echocardiography

1. Introduction

Aortic valve function has been shown to depend on the complex anatomic and dynamic relationship of aortic valve and root [1,2]. Insufficiency of the aortic valve may be the consequence of root dilatation only [3] or cusp deformation, in conjunction with either congenital anomaly or secondary cusp prolapse [4]. In addition, cusp deformation may be a consequence of root dilatation [5] and may even occur disproportionately with the enlargement of the aortic root.

Aortic valve reconstruction is emerging as a new therapeutic option for aortic valve insufficiency [6–8]. Different techniques have been developed to correct abnormalities of the aortic valve and root [9–12]. The goal of aortic valve repair (AVR) must be restoration of normal dimensions of the aortic root and cusps for normal function.

Therefore, normal values are necessary for root and cusp geometry as the goal of aortic root and valve reconstruction. Data have been published for normal aortic root dimensions in the presence of normal aortic valve function [13,14]. As yet, however, there are no data indicating normal or abnormal cusp configuration [15].

Cusp geometry is primarily determined by the length of free margin and aortic insertion, intercommissural distance, and cusp height, that is, the distance from insertion to free margin in its central portion. These values are difficult or impossible to measure by echocardiography or intra-operative measurements. We have previously proposed to use the relative height difference between insertion and free margin of the cusp (effective height) as a surrogate parameter of cusp configuration [16]. Normal values for effective height in intact aortic valves are scarce, and it is unknown how this parameter relates to size of the patient or dimensions of the aortic root. We have hypothesised that this parameter may serve as an indicator of normal cusp configuration and thus also aortic valve function in reconstructed aortic valves [16].

In this investigation, we sought to study normal values of cusp and root configuration and their relation to age and size of individuals. Furthermore, we investigated the relationship between effective height and post-repair aortic valve function.
2. Material and methods

Aortic roots were studied in healthy individuals with normal aortic valve function (control group) by transthoracic echocardiography. The same measurements were performed in individuals having undergone AVR. Informed consent was obtained from all adults or the individual’s legal guardian, and the institutional ethics committee agreed to the analysis and publication of the data in anonymised form.

The control group consisted of 130 healthy volunteers with 100 adults (50 were men, mean height: 1.75 ± 0.06 m, mean weight: 71.9 ± 0.9 kg) and 30 children (mean height: 1.18 ± 0.03 m, mean weight: 23.9 ± 1.5 kg). The age in the adults ranged from 19 years to 76 years (mean age: 33.8 ± 1.4 years), the body surface area varied from 1.35 m² to 2.4 m² (mean 1.87 ± 0.01 m²). In addition, 30 children (15 male) aged 4 months to 16 years (mean 5.8 ± 0.6 years) were studied. The body surface area varied from 0.29 m² to 1.55 m² (mean 0.88 ± 0.04 m²). Only individuals with a negative medical history for hypertension, heart failure and angina were included.

In a second study, out of 832 patients operated on due to isolated aortic valve insufficiency in the period from October 1995 to March 2008, follow-up was available for 651. The patients’ details are shown in Table 1. In 228 of these patients, preoperative root dimensions were normal, and in 423 individuals, dilatation of the aorta was initially present. Aortic dilatation was treated by supracommissural aortic replacement in 147 patients, root remodelling in 257 patients or aortic valve reimplantation in 19 patients. Details of the surgical techniques have been reported previously [6,8,17]. Patients undergoing concomitant cardiac procedures (mitral valve repair (n = 75), aortic arch replacement (n = 220) or coronary artery bypass grafting (n = 195)) were included.

2.1. Echocardiography

For transthoracic echocardiography, we used a Siemens Accuson Sequoia 512 (Nuremberg, Germany) with a 4.5 MHz handheld transducer. Echocardiograms were performed in the left decubitus position. The aortic valve and the left ventricular outflow tract were examined with colour Doppler and continuous wave Doppler for pathological findings before the measurement of the aortic root. Aortic root dimensions were measured using the leading edge technique during end-diastole confirmed by electrocardiogram (ECG) in the long parasternal axis. Maximum diameters were measured of the aortoventricular junction, sinuses of Valsalva and sinutubular junction. In addition, the height of the sinus Valsalvae was determined (Fig. 1(A)).

In addition, the height difference between the central free margins and the aortoventricular junction was measured. We have termed this dimension ‘effective height’ as opposed to the two-dimensional cusp height termed ‘geometrical height’ (Fig. 1(B)).

The presence of aortic valve insufficiency was determined by colour Doppler in the parasternal long and short axis views, and in the apical long-axis five-chamber view. The degree of aortic valve insufficiency was determined according to the guidelines for the management of patients with valvular heart disease by the American Heart Association [18].

In 651 patients after AVR, we performed follow-up studies at 1 week, 3, 6 and 12 months and every 12 months thereafter. A mean follow-up duration of 50.8 ± 2.1 months resulted. Echocardiography was performed by blinded observers. These data were collected prospectively and analysed retrospectively.

Table 1

<table>
<thead>
<tr>
<th>Patient group.</th>
<th>Mean ± standard deviation</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>56 ± 16</td>
<td>14—86</td>
</tr>
<tr>
<td>Body height (m)</td>
<td>1.75 ± 0.14</td>
<td>1.45—2.05</td>
</tr>
<tr>
<td>Body weight (kg)</td>
<td>80.3 ± 15.8</td>
<td>36—145</td>
</tr>
<tr>
<td>Body surface area (m²)</td>
<td>1.9 ± 0.4</td>
<td>1.33—2.89</td>
</tr>
<tr>
<td>Effective height (mm)</td>
<td>9.44 ± 1.17</td>
<td>5—13</td>
</tr>
<tr>
<td>Grade of aortic insufficiency (°)</td>
<td>0.65 ± 0.64</td>
<td>0—3</td>
</tr>
</tbody>
</table>

Age, body size, effective height and grade of residual aortic insufficiency after aortic valve repair in the patients’ group are displayed as mean ± standard deviation and range.

Fig. 1. Aortic root dimensions at different levels and effective height measured by transthoracic echocardiography in the long parasternal axis (A) and a schematic drawing (B). STJ: sinutubular junction; Sinus: maximum sinus diameter, gH: geometric height; eH: effective height; AVJ: aortoventricular junction.
2.2. Statistical analysis

Results were expressed as the mean ± standard deviation. All continuous variables were evaluated for normal distribution with the Kolmogorov–Smirnov test. A p < 0.05 was considered as statistically significant.

In the control group, Pearson correlation coefficients were calculated for age, body surface area and aortic root dimensions. In addition, a multivariable linear regression analysis was performed to determine the combined effect of age and body surface area on the aortic root dimensions.

In the patient group, differences of the aortic root dimensions depending on the size of aortic valve insufficiency were determined by analysis of variance with Bonferroni post hoc test. To further investigate the predictive value of postoperative effective height for residual aortic valve insufficiency, a receiver operating characteristic (ROC) curve was calculated. A cutoff value of 9 mm (sensitivity 100%, specificity 81%) was determined as predictor for an acceptable residual aortic valve insufficiency (moderate, mild or none).

All statistical analyses were performed with SPSS Release 17 (SPSS Inc., Chicago, IL, USA).

3. Results

Aortic root dimensions (Table 2) were normally distributed in the control group. In every individual, the diameter of the sinutubular junction was larger than the aortoventricular diameter. Effective height was also normally distributed in the control group. Values in the control children ranged from 4 mm to 9 mm and in the adults from 7 mm to 12 mm.

All aortic root dimensions and effective height correlated with body surface area (r = 0.72–0.77, p < 0.001; Fig. 2), body weight (r = 0.7–0.76, p < 0.001) and body height (r = 0.69–0.75, p < 0.001). In the controls, all of whom had normal body mass index, root dimensions correlated better with body surface area (r = 0.72–0.77, p < 0.001; Fig. 2) than with weight (r = 0.7–0.76, p < 0.001) or body height (r = 0.69–0.75, p < 0.001).

Effective height showed a strong correlation with aortoventricular, sinus and sinutubular junction diameter (r = 0.67–0.763, p < 0.001). The best correlation was observed between effective height and sinus diameter (Fig. 3). Moreover, a strong correlation was found between effective height and body surface area (r = 0.81, p < 0.001; Fig. 4), body weight (r = 0.78, p < 0.001), body height (r = 0.77, p < 0.001) and age (r = 0.61, p < 0.001). Thus, for adult individuals with a body surface area ranging from 1.6 m² to 2.1 m², the normal effective height ranged from 7 mm to 12 mm (mean: 9.3 ± 2.4 mm).

No early postoperative aortic insufficiency was detected in 235 patients, mild aortic insufficiency in 370, moderate in 43 and severe in three patients at the follow-up study.
Effective height was the highest in patients without residual aortic valve insufficiency (9.8 ± 0.9 mm) and decreased with increasing grade of residual aortic valve insufficiency. The mean of effective height was in the group with mild insufficiency 9.4 ± 1.1 mm, in the group with moderate insufficiency 7.9 ± 1.4 mm and in severely regurgitant valves 6 ± 1 mm.

The difference in mean effective height between no and mild (p = 0.012) or more (no vs moderate p < 0.0005, no vs severe p < 0.0005) was significant. Significant differences in mean effective height were detected between mild and moderate (p < 0.005) or severe aortic insufficiency (p < 0.005), respectively. No significance could be detected for the difference between moderate and severe aortic insufficiency (p = 0.178).

Of 497 AVR patients with an effective height ≥9 mm, 309 had no or trivial aortic valve insufficiency, 186 mild aortic valve insufficiency and only two moderate aortic valve insufficiency. The grade of aortic insufficiency over time showed hardly any increase in these patients, although of these 497 patients, six patients had to be re-operated on due to severe residual aortic insufficiency. In five of these six patients, the valve was replaced; only in one patient could the valve be successfully re-repaired.

In the remaining 154 patients with an effective height <9 mm, 25 had no or trivial aortic valve insufficiency, 85 had mild aortic valve insufficiency, 41 had moderate aortic valve insufficiency and three had severe aortic valve insufficiency. Furthermore, 10 of these 41 patients with a moderate aortic valve insufficiency show a slow, but obvious increase in the amount of residual aortic regurgitation over a varying time period ranging from 2 to 10 years. The remaining patients with an effective height <9 mm showed a stable haemodynamic result. The ROC curve analysis demonstrated that an effective height ≥9 mm was an excellent predictor (area under the curve (AUC) 0.94) for a good haemodynamic outcome (residual aortic insufficiency moderate or less). In this group, redo surgery was necessary in 11 patients. In opposition to the patients with an effective height ≥9 mm, it was possible to successfully re-repair the valve in eight cases by increasing the effective height. In addition, one patient was re-operated on due to endocarditis or suture dehiscence, respectively. Three patients were re-operated on in other institutions due to severe residual insufficiency, but the underlying mechanism remains unknown.

4. Discussion

AVR remains difficult because different mechanisms contribute to aortic valve insufficiency. Root dilatation is a frequent mechanism and it may be associated with cusp pathologies such as perforation, prolapse and retraction. Root dilatation as an underlying factor can be easily detected by echocardiography or direct intra-operative measurement. While some cusp pathologies, for example, perforation or fenestration, can simply be recognised by intra-operative inspection, evaluation of cusp prolapse, however, remains difficult.

Prolapse appears to be the most frequent cusp pathology in pure aortic insufficiency. This pathology may also co-exist with root dilatation [19]. Most importantly, prolapse may be induced by reduction of root diameters, particularly at the sinutubular level. This can aggravate pre-existing cusp pathology or lead to symmetric prolapse, when cusp dimensions do not correspond to the new root configuration [5,19].

So far, AVR has focussed on the restoration of aortic root dimensions. Over the past 15 years, there has been increasing interest and activities in aortic root repair, and good results have been reported by a number of groups. While there are still arguments regarding details of different operations, the importance of cusp geometry has not been studied systematically. Repair of isolated cusp pathology has been performed less frequently, and results have varied [20,21]. The reasons for suboptimal results remain unclear. One possibility may be that concomitant root pathology was not appreciated [20]. In a four-dimensional study of the aortic root, Lansac et al. demonstrated that during end-diastole aortic root volume re-expanded, but with different dynamics at each level. Basal and commissural areas were re-expanding while at the sinutubular junction and in the ascending aorta, the diameters kept decreasing. This differentiated expansion pattern of each level of the aortic root influences aortic valve’s cusp closure. This highlights the importance of the aortic root for proper aortic valve closure [22].

An alternative explanation may be that assessment of prolapse as yet is not standardised and prolapse or its correction is so far difficult to quantify [23].

Recognition of cusp prolapse mainly depends on surgical judgement. Cusp prolapse can be detected intra-operatively by comparing the height of the free margins relative to each other [23,24]. This method fails, however, if prolapse is not limited to one cusp, since the reference points (the other cusp margins) are also abnormal.

So far, no clear echocardiographic criteria exist for the definition of prolapse. Shapiro et al. suggested protrusion of cusp tissue into the left ventricular outflow tract as the primary criterion for prolapse [4]. This may not always be clearly visible on transthoracic or transoesophageal echocardiography. So far, eccentricity of the regurgitant jet has been used as indirect indicator of prolapse, but this will only
indicate the pathology of one cusp and fail in the presence of prolapse of two or three cusps. To standardise cusp repair, we have sought more objective information on cusp configuration.

Cusp geometry can be defined by intercommissural distance, length of cusp insertion, amount of cusp tissue (geometric height) and length of free margin. Exact cusp dimensions cannot be determined preoperatively, and even intra-operative assessment does not allow exact measurement of these geometrical determinates. We have therefore previously proposed to measure the effective height as the indicator of configuration and geometric height of a cusp as the indicator of sufficient amount of tissue (Fig. 1(B)). Intraoperatively, effective height can be measured by a caliper and this parameter can also be obtained by echocardiography pre-, intra- and postoperatively [16].

Effective height in this study revealed values in healthy adult individuals measured by transthoracic echocardiography in the range of 7—12 mm. In patients with aortic insufficiency preoperatively, we have seen effective height as low as 3—4 mm before cusp repair, indicating marked prolapse. By comparison, in healthy individuals and postoperative patients with competent valves, the effective height ranged from 7 mm to 13 mm. Interestingly, in our patients, effective height decreased with increasing amount of residual valve incompetence, because out of 497 patients with an effective height ≥9 mm, only two patients had moderate aortic insufficiency. By comparison, out of 154 patients with an effective height <9 mm, 41 had moderate and three severe aortic insufficiency (96% of all patients with moderate or more aortic insufficiency). In addition, the ROC curve analysis demonstrated that an effective height ≥9 mm is an excellent predictor for a good haemodynamic outcome (residual aortic insufficiency moderate or less). We are using the naive and not the relativedised effective height in clinical practice, but it should be kept in mind that in individuals at either end of the size spectrum these values may be misleading. This indicates that normalisation of cusp configuration leads to normal valve function.

An interesting finding was the close correlation of effective height and aortic root dimensions as well as size of the individual. This indicates that probably the configuration of the normal aortic valve and root follows a consistent pattern. The dimensions of the aortic root found in our study are in accord with former measurements [13,25]. Moreover, our data and further studies imply again that the dimensions of the aortic root follow a consistent pattern and root dimensions affect cusp geometry [1,14]. In contrast to previous data, we observed that the diameter of the aortoventricular junction was smaller than the sinutubular junction diameter in every individual [1,14,22]. This discrepancy may depend on the different modes of measurement (pressurised vs non-pressurised). Another factor influencing the aortic root dimension may be the explantation of the aortic root for in vitro measurements [1,14]. Swanson and Clark measured aortic root dimensions in pressurised explanted aortic roots [14]. By contrast, Kunzelmann et al. studied aortic root dimensions by measuring non-pressurised explanted human homografts [1]. Only Lansac et al. measured aortic root dimensions in vivo. These measurements were performed using sonomicrometry in sheep immediately after implantation using cardioplegic arrest during cardiopulmonary bypass. Interestingly, the basal areas appear as the largest areas in the aortic root during diastole, even larger than the sinus diameter. This finding again shows that further investigation with high-resolution devices is necessary to finally resolve the problem of time-dependent aortic root excursion in vivo in humans during the cardiac cycle [22].

A comparison between the aortic root dimensions of our study and previous studies based on echocardiographic and angiocardiographic data indicates that our results are in accord with these findings in humans [13,25].

The limitations of our study are related to the use of transthoracic echocardiography, which does not always yield ideal resolution and has an examiner-related variability. Aortic root dynamics are asymmetric in respect of the location and the point in time during the cardiac cycle. Therefore, it is crucial to exactly define the point in time of the measurement in relation to the cardiac cycle. Both the dimensions of the aortic root and the valve’s cusps vary enormously during mid- and end-diastole [26].

The measurement of effective height in the parasternal long-axis view may not always be accurate, because the exact perpendicular axis can be missed. In addition, this view only allows judgement of the right and non-coronary cusps.

Nevertheless, the data of the control group show excellent correlation despite these physical limitations. In the control group, the interobserver variability was accounted for by a single person performing all examinations. The postoperative echocardiograms were performed by an experienced and instructed team. The effective height can be reduced in insufficient aortic valves either by prolapse or by cusp retraction. This should be considered intraoperatively, when the surgeon can measure both effective height and geometrical height.

5. Conclusion

Parameters of aortic root dimensions follow a seemingly consistent pattern in humans of different sizes. Effective height has a constant relationship to root dimensions and body size. In AVR, normalisation of effective height leads to a high probability of normal or near-normal aortic valve function. Effective height can easily be determined pre- and postoperatively by echocardiography and intra-operatively by direct caliper measurement. These tools allow further standardisation of AVR by supporting the surgeon in his assessment of cusp prolapse.

References

Appendix A. Conference discussion

**Dr G. El Khoury** (Brussels, Belgium): The Homburg group has made a big contribution in the field of aortic valve repair. It is a big job and a lot of work reviewing more than 800 echos with 4 or 5 parameters on each echo.

When I finished reading your paper, I had two surprises. The first is really personal, and I was pleased to see the ratio between the effective height and the height of the sinuses, about 0.5. I used to say that the effective height is at the midway of the sinuses. It gives us an idea of the difference between the Mediterranean approach and this Homburg approach to this problem. So this was the first surprise and I was really pleased.

The second one, I didn’t find anywhere the term ‘coaptation’. In any valve repair, including aortic valve repair, coaptation is what we want to have at the end of the operation and it’s very important. Effective height is efficient if we have coaptation. We must have all three effective heights identical to have good coaptation. And I didn’t find the term coaptation in your article.

I have one more comment and then one more question. The ratio of effective height in the normal population is 0.5; what about in repaired groups? I don’t know if you have looked for that, because I think it can give us an idea about the coaptation. The more we go towards this ratio of 0.5, the more efficient and durable will be our repair.

My question is: When you look at the repaired valves, which has correct height, what is the proportion of this effective height that plays a role in the coaptation? In other words, what is the coaptation with regard to this effective height? This is the only question.

**Dr Bierbach**: We haven’t looked at this ratio at first, but as far as I understood you, you point to another direction. If we correct the valve, we achieve something that is different from before in all dimensions, because everything is interrelated. And what you want to know is the coaptation length, as far as I understood it. This is what you also measured in your last paper on that topic.

**Dr El Khoury**: Yes.

**Dr Bierbach**: And these are two different aspects. The effective height is a sum parameter of the root and the complete geometry of the cusps. Even in the case of a completely normal coaptation height, the effective height might be near 0 mm. So these are two different things. That is the reason why we did not look for the coaptation height.

**Dr T. David** (Toronto, Ontario, Canada): But he also has a point; you can have a cusp way inside the root, but the cusps barely touch each other, because you shortened the free margin too much. So you have a very high coaptation height, effective height as you call it, but you may not have good coaptation and the valve is going to leak.

**Dr Bierbach**: This is correct and probably we should measure this dimension as well. Therefore we measure the second dimension, which we term geometric height; this reflects the mass of leaflet tissue available. If you stretch it upward by too much, maybe by plication, then you reduce the coaptation height and you have high effective height; but in addition you have in proportion too little geometric height.

**Dr Schäfers**: Just as an explanation to the last question. We’ve systematically looked for effective height. We have not so systematically looked for coaptation height. This is why we focused on this parameter primarily in this analysis. Most patients, almost all patients in the study, if I recall all the intra-operative TEEs, had a coaptation height of 5 mm or more.

**Dr David**: But can you agree that you can have a very high valve inside the root and the cusps not touching each other because the free margin is too short for the size of the graft?

**Dr Schäfers**: Absolutely, Tirone, and this is why I think the question is important and this is why I wanted to add the information. So coaptation height was not as systematically studied as effective height, number one. Number two, coaptation height in some patients is very difficult to get exactly by transthoracic echocardiography. And this was a methodological reason why we did not include it. Nevertheless, the results, we had a coaptation height of 5 mm or more in most patients when we had sufficient coaptation height. And these findings are similar to those published by the Brussels group. I fully agree that it’s a second important parameter.

**Dr David**: I think both Dr El Khoury and Dr Schäfers have made very important points. You cannot have a valve repair with a cusp inside the ventricle at the end of the procedure. The cusps have to be inside the aortic root. The higher you go, likely better, but if they are too high, they may not coapt well. They have to be inside the aortic root and coapting well.

I have always used what Dr El Khoury has mentioned, coaptation height, more by intuition than knowledge. I have no data to tell you how high is too
high, or how low is too low, but I have always tried to make sure that the coaptation area is above the level of the aortic annulus. Professor Schäfers has now given us a numerical value to base ourselves. I use a 4 to 5 mm minimum amount of coaptation by transoesophageal echocardiography. Dr Schäfers is also right in saying it’s very difficult to measure coaptation height by transthoracic echocardiography. But by transoesophageal, usually it is possible to see the belly of the cusp and the upper part of the coaptation level.

Dr A. Moritz (Frankfurt, Germany): We are also puzzled by the problem of the coaptation height, because it’s obvious that with a higher coaptation, at least at reasonable dimensions, you increase the safety or long-term durability of a repair. The problem with the echo is that, at least in our hands, frequently you see the total height of these leaflets in geometric touch, but you don’t see if one is higher than the other. So the effective coaptation is very difficult to see. Sometimes, and maybe that is the problem, you see one leaflet’s height and both leaflets’ bases, and the distance between could be called coaptation height, but you don’t know if they’re really touching over all this length. This is, at least in our hands, the problem that you don’t really know where you are after repair. If those valves leak, you still don’t know what happened.

Dr David: It is a very good point. New echo programs for 3D reconstruction may actually show all 3 cusps, their belly and the free margin where they coapt. Not all programs for aortic valve 3D visualization are as good as for the mitral valve, but I am sure this issue will be resolved in the near future. We should be able to get the images in the operative theatre as soon as we come off bypass. You can alter the loading condition, blood pressure, and see what happens to the geometry of the valve. As Anton Moritz mentioned, you may see only 2 cusps at a time by 2D echo, another very good point.
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Eur J Cardiothorac Surg 2010;38:400-406
DOI: 10.1016/j.ejcts.2010.01.060

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