Increased aortic wall stress in aortic insufficiency: clinical
data and computer model

Carsten J. Beller, Michel R. Labrosse, Mano J. Thubrikar, Gabor Szabo, Francis Robicsek, Siegfried Hagl

Abstract

Objective: The study was aimed at determining which cardiac pathologies are associated with increased longitudinal stress in the aorta and therefore may be responsible for the intimal transverse tears seen in aortic dissections. Methods: Aortic root contrast injections were analyzed in 90 cardiac patients to measure the downward motion of the annulus during a cardiac cycle. A finite element model of the pressurized aortic root, arch and supra-aortic vessels was created to assess the influence of the aortic root motion on the aortic wall stress. Results: The axial displacement of the aortic root ranged from 0 to 14 mm. A multivariate analysis showed that aortic insufficiency (AI) grade, hypokinesis of the left ventricle (HKI), and myocardial hypertrophy (HTR) were 3 independent variables which correlated with the axial displacement of the aortic root (DISP), such that ARM (mm) = 5.379 + 1.186 × AI grade (P = 0.0016) − 1.611 × HKI (P = 0.0078) − 1.399 × HTR (P = 0.0355) with R² = 0.23. The major finding of the stress analysis was that in the ascending aorta, at approximately 2 cm above the sino-tubular junction, the longitudinal stress due to aortic root motion was 32% higher in patients with AI than in patients without AI, thereby increasing the risk of transverse intimal rupture. Conclusions: Cardiac patients with AI are likely to experience enhanced longitudinal stress in the ascending aorta due to increased aortic root motion. Thus, these patients should be targeted and their aortic root movement monitored because it may be an important risk factor for aortic dissection.

Keywords: Aortic root motion; Aortic insufficiency; Mechanical stress; Aortic dissection

1. Introduction

The downward displacement of the aortic root during systole is a well-known phenomenon, studied with cinematography and contrast injections in the past [1,2]. Average 8.9 mm axial downward motion and six-degree clockwise axial twist of the aortic root during systole were reported from cine-MRI studies in healthy volunteers [3,4]. However, the possible relationship between the magnitude of the forces acting on the aortic wall and the different cardiac conditions has not been studied so far.

Using a parametric analysis of a representative three-dimensional finite element model of the aortic root, aortic arch and supra-aortic vessels, we recently showed that the deformations of the aortic root have a direct impact on the mechanical stresses present in the aortic wall. In particular, the longitudinal stress in the ascending aorta was found to increase critically above the sino-tubular junction. The functional displacement of the aortic root was revealed to be equal to hypertension as a stress enhancer in the aortic wall. Therefore aortic root motion was highlighted as an additional risk factor in patients at risk of aortic dissection [5].

In our preliminary study of aortic root motion in cardiac patients [5], aortic insufficiency was found to be univariately associated with an increased aortic root motion. The goal of the present study was to determine from a larger series of cardiac patients whether or not aortic insufficiency is an independent risk factor to increase the mechanical (longitudinal) stress in the aortic wall. The finite element model established previously [5] was used to weigh the impact of aortic root motion on the wall stress compared to aortic dilation often found in patients with aortic insufficiency.
2. Materials and methods

2.1. Measurement of aortic root motion in patients

2.1.1. Patient group one
Aortic root contrast injections were analyzed in 90 patients with coronary artery and/or aortic valvular disease (43-88 years old; mean age 68 years). The severity of aortic insufficiency and stenosis were graded from I to IV (trivial to severe) by means of echocardiographic and angiograms.

The patients’ characteristics were the following (Table 1): 36 patients had left-ventricular hypokinesis, 23 had myocardial hypertrophy, 13 had undergone coronary artery bypass grafting (CABG), 15 had aortic insufficiency (AI) and 25 had aortic stenosis (AS). None of the patients had aortic dissection, one patient had a bicuspid aortic valve. Twenty-six patients were examined for elective CABG and showed none of the above conditions. The data from patient group one were used for multivariate analysis.

2.1.2. Patient group two
Based on the findings of the multivariate analysis, the aortic root motion was measured in 17 patients with severe aortic insufficiency (32-76 years old; mean age 59 years) and related information was used for the stress analysis.

Most aortograms were done in left anterior oblique projection, some in right anterior oblique view. The aortograms were analyzed frame by frame, and the aortic root outlines in the most upward and downward positions were traced on a transparency. The base of two sinuses and the sino-tubular junction (STJ) were marked. The diameter of the angiocatheter (2 mm) present in the field was also traced and used for distance calibration. After digitizing the transparencies, the distances between the marked points were determined using image analysis software (Image-Pro, Media Cybernetics). The actual-size downward motion (axial displacement) of the aortic root perpendicular to the plane of the sino-tubular junction was measured in millimeters.

Table 1: Measured aortic root axial displacement in patients and listed cardiac conditions

<table>
<thead>
<tr>
<th>DISPa (mm)</th>
<th>Patient count</th>
<th>AIb count</th>
<th>HKIc count</th>
<th>HTRd count</th>
<th>CABGe count</th>
<th>ASf count</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1</td>
<td>9</td>
<td>1</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>2-3</td>
<td>28</td>
<td>2</td>
<td>11</td>
<td>10</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>4-5</td>
<td>23</td>
<td>2</td>
<td>13</td>
<td>6</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>6-7</td>
<td>13</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>8-9</td>
<td>8</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>10-11</td>
<td>7</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>12-13</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>14-15</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>90</td>
<td>15</td>
<td>36</td>
<td>23</td>
<td>13</td>
<td>25</td>
</tr>
</tbody>
</table>

a: DISP: axial displacement of the aortic root. 
b: AI: aortic insufficiency. 
c: HKI: left-ventricular hypokinesis. 
d: HTR: myocardial hypertrophy. 
e: CABG: previous coronary artery bypass grafting. 
f: AS: aortic stenosis.

2.2. Statistical analysis
To determine the presence of which cardiac conditions influenced aortic root motion the Wilcoxon rank test was used. A linear multivariate model was then established based on the conditions associated with a trend or a significant difference in the aortic root motion. The graded values of AS and AI were examined using Spearman’s correlation coefficient. Values at the significance level of 0.05 were considered.

2.3. Stress analysis
To illustrate the mechanical stress associated with different levels of aortic root displacements, we used a finite element model of the human aortic root, aortic arch and supra-aortic vessels (Fig. 1). The model was thoroughly described and validated elsewhere [5]. It was specially constructed to study the effects of aortic root motion, blood pressure, and aortic wall stiffness. The model was based on anatomical data although the geometry was kept general rather than patient-specific. It was discretized into brick elements with homogeneous, nearly incompressible, linear elastic and isotropic material properties (Young’s modulus of 3 MPa and a Poisson’s ratio of 0.49). The distal ends of the supra-aortic vessels and the aorta were fixed in all directions to allow physiological deformation of the model.

In the present study, the twist of the aortic root base was not included because it was shown to have a minor influence on the stress experienced by the aortic wall [5]. A luminal pressure of 120 mmHg was applied in combination with axial displacement of the aortic root. In different analyses, the displacement was given average values as determined from the statistical analysis of the measurements done in the patients with and without aortic insufficiency, and the stress results in both groups were compared. Additional stress analyses were carried out to determine the relative influence of aortic root motion and aortic dilation on the mechanical stress in the aortic wall. To this aim, the diameter of the aortic root was enlarged to the average diameter of the sino-tubular junction found in the patients with severe aortic insufficiency. The geometry of the ascending aorta between the dilated aortic root and the proximal origin of the brachiocephalic trunk was built as a tapering cylinder. The aortic wall thickness was kept the same as in the non-dilated model, thereby accounting for the tissue remodeling that usually accompanies aortic dilatation, as observed in abdominal aortic aneurysms [6].

3. Results

3.1. Effect of cardiac pathology on magnitude of aortic root movement
The downward axial displacement of the aortic root during the cardiac cycle ranged between 0 and 14 mm with a mean of 4.8 mm. It was between 0 and 7 mm in the majority (81%) of the 90 patients (Table 1).
The aortic root movement was significantly reduced in patients with left ventricular hypokinesis (3.7 versus 5.5 mm in patients without hypokinesis, \( P < 0.014 \)). Reduced ventricular traction is likely to entail reduced aortic root motion in these patients (Table 2).

Myocardial hypertrophy showed a trend to decrease the aortic root movement compared to patients without hypertrophy (3.8 versus 5.1 mm, \( P = 0.073 \), Table 2).

Previous cardiac operations were not found to play a significant role in the magnitude of aortic root motion, nor was aortic stenosis (Table 2).

In contrast, patients with AI exhibited significantly increased aortic root motion: 7.3 mm as opposed to 4.3 mm in patients without AI (\( P = 0.003 \), Table 2).

### 3.2. Multivariate analysis

A linear multivariate analysis established that AI grade, left ventricular hypokinesis (HKI) and myocardial hypertrophy (HTR) were three independent variables correlating with the magnitude of the aortic root axial displacement (DISP), such that DISP (mm) = 5.379 \( (P < 0.0001) + 1.186 \times \text{AI grade} \ (P = 0.0016) - 1.611 \times \text{HKI} \ (P = 0.0078) - 1.399 \times \text{HTR} \ (P = 0.0355) \) with \( R^2 = 0.23 \).

Between the aortic root motion in patients with AI and those without any of the listed conditions only a trend toward statistical difference was found (\( P = 0.076 \), Table 2). This may point to the important role conditions other than AI may play in reducing the aortic root motion in patients with multiple conditions.

### 3.3. Sub-analysis of patients with severe aortic insufficiency

After aortic insufficiency was identified as an independent risk factor increasing the aortic root movement, a subset of 17 patients with severe aortic insufficiency and no other cardiac condition was examined. The displacement ranged from 0 to 22 mm, with a mean of 7.8 mm. It was above 7 mm in 6 patients out of 17 (35%). The STJ diameter ranged between 24 and 61 mm, with a mean of 42.4 mm.

To better analyze the contribution of AI, it was interesting to determine whether aortic dilation influenced the magnitude of the aortic root motion. The individual STJ diameter found in the 17 patients was measured and sorted into two categories: non-dilated (\( \leq 30 \text{ mm} \)) and dilated (\( > 30 \text{ mm} \)) [7]. The sub-analysis showed no significant difference in aortic root motion between patients with or without dilated aortae. This suggested that AI itself, irrespective of aortic dilation, affects the aortic root axial displacement.

Interestingly, in the subset of patients with severe AI, the axial displacement of the aortic root correlated inversely with the patients’ age \( (R^2 = 0.40, \text{Fig. 2}) \). This is probably due to the presence in the subgroup of younger patients whose aortic wall was more elastic.

### 3.4. Stress analysis

In describing the results from the finite element analysis, the emphasis is placed on the mechanical stress, because...
the deformations of the model were previously shown to be in the physiological range [5]. The magnitude of the deformation due to aortic root motion decreases distally as it affects the ascending aorta, the transverse aortic arch, and the supra-aortic vessels. In Figs. 3–5, the stresses are averaged across the vessel wall thickness, and displayed in the toroidal coordinate system attached to the aortic arch. Therefore, the specification of orientation is only correct in the region of interest including the aortic arch and the ascending aorta.

3.4.1. Stresses with aortic root motion in patients without Al

Fig. 3 shows the results for mechanical stress in the control model subjected to 120 mmHg pressure and 4.3 mm axial displacement of the aortic root. Stress concentrations were present at the ostia of the supra-aortic vessels as expected. Between the brachiocephalic trunk and the left common carotid artery (LCCA), the circumferential stress was approximately 0.44 MPa and the longitudinal stress approximately 0.27 MPa. Above the STJ, the circumferential and longitudinal stresses in the aortic wall were 0.30 and 0.22 MPa, respectively.

3.4.2. Stresses with aortic root motion in patients with Al

At 120 mmHg luminal pressure, the circumferential and longitudinal stresses did not change markedly between the brachiocephalic trunk and the LCCA when 7.3 mm axial displacement was applied to the aortic root. The area where the most significant changes occurred was approximately 2 cm above the STJ. While the circumferential stress was unchanged, the longitudinal stress increased by 32% up to 0.29 MPa (Fig. 4).

Fig. 3. Distribution of circumferential (A) and longitudinal (B) stresses (MPa) in the aortic arch under 120 mmHg luminal pressure (see text). In this control model, the measured average 4.3 mm axial displacement of the aortic root was applied to represent the patients without aortic insufficiency. Expected stress concentrations around the ostia of the supra-aortic vessels were observed.

Fig. 4. Same as Fig. 3, with 7.3 mm axial displacement applied to the aortic root to represent the average measurements in patients with aortic insufficiency. The longitudinal stress in the ascending aorta was increased by 32% compared to the control model.

Fig. 5. Same as Fig. 4, with 7.3 mm axial displacement applied to the aortic root to represent the average measurements in patients with aortic insufficiency, but when dilatation of the aortic root brings the sino-tubular junction to 42.4 mm. The longitudinal stress in the ascending aorta was decreased to the control level, while the circumferential stress increased slightly.
3.4.3. Stresses with aortic root motion in patients with AI and aortic dilatation

When a dilated aortic root (42.4 mm in diameter) replaced the normal geometry (Fig. 5) in the model, again, the circumferential and longitudinal stresses did not change markedly between the brachiocephalic trunk and the LCCA with 7.3 mm axial displacement and 120 mmHg luminal pressure. However, in the region above the STJ, the circumferential stress increased to 0.33 MPa, while the longitudinal stress decreased to 0.23 MPa. Table 3 shows how the dilated aorta experiences significantly (up to 24%) less longitudinal stress than the non-dilated one, while the circumferential stress stays essentially constant when different values of aortic root displacement are applied to the model. It is important to note the more spherical shape assumed by the model with the dilated aorta, compared to the one with the non-dilated aorta.

4. Discussion

4.1. Magnitude of aortic root motion

The fact that our measurements of axial displacement of the aortic annulus (0-14 mm) were in the same range as those reported by Kozerke et al. [3] from 3D MRI (6.4-11.3 mm in healthy subjects) implies that the plane of the aortogram is where most of the 3D displacement of the aortic root occurs. The average 8.9 mm in Kozerke’s healthy subjects may be related to their relative young age (mean age 32, range 26-56) and mostly intact elasticity of their aortae, whereas the 90 patients in our series were older (mean age 68, range 43-88) with an average aortic root displacement of 4.8 mm. Interestingly, Kozerke et al. reported values of aortic root displacement in 4 patients with aortic regurgitation (mean age 60, range 39-73) and found a 6.5 mm average (range 3.4-10.2 mm), which agrees well with our findings. Most importantly, patients with aortic insufficiency and large aortic root displacement (up to 22 mm) may be at a considerable risk of mechanical damage to their aortae through acute (rupture) or chronic (fatigue-related) events.

4.2. Aortic insufficiency and aortic root movement

Aortic insufficiency admittedly leads to increased stroke volume as a compensation mechanism. Our results suggest that aortic insufficiency does also increase the aortic root displacement in its axial direction. Whether increased stroke volume is related to increased or unchanged aortic root motion has been debated based on studies focusing on the aortic displacement in the frontal-dorsal direction using 2D echocardiography [8-11]. However, pulsations of the aorta are well known in severe cases of AI, and can even be transmitted to the patient’s head (nodding or de Musset’s sign). The augmenting influence of AI on the aortic root displacement was already noted in our preliminary study [5] and is confirmed in this series by multivariate analysis.

4.3. Significance of aortic wall stress and surgical implications

The significance of the aortic wall stress as influenced by the aortic root motion, blood pressure and aortic wall stiffness was discussed elsewhere [5], along with the validity of the finite element model used in this study. Although simplifications have been introduced to make the model tractable, it is believed that the results of the stress analysis are meaningful, especially in a comparative sense. A mesh sensitivity analysis was carried out and showed that in the regions of interest, the results for stress varied by less than 7% when the number of elements was doubled. The 32% increase in longitudinal stress in the ascending aorta between patients with AI and without AI shows the significant change accompanying the aortic root motion increase from 4.3 to 7.3 mm. Even more detrimental effects are expected with larger values of displacements found in some patients.

Half to two-thirds of the patients with proximal aortic dissection exhibit aortic insufficiency. In contrast, fewer than 10% of the patients with distal aortic dissection show aortic insufficiency [12,13]. In view of our findings, one may hypothesize that AI perhaps is not always a consequence of aortic dissection; instead, AI may preexist and trigger aortic dissection by significantly increasing the longitudinal stress in the aortic wall.

Concomitant aortic dilatation may or may not increase the mechanical stress in the aorta, depending on the shape taken by the aneurysm. Indeed, under a pressure $P$, the circumferential and longitudinal stresses in a cylinder of thickness $t$ and radius $R$ are $PR/t$ and $PR/2t$, respectively, while they are both $PR/2t$ in a sphere of same thickness and radius [14]. Therefore, the impact of aortic root motion on the aortic wall stress may in some instances be more substantial than that of dilatation. According to the same equations, if the wall thickness were to decrease as the aorta dilates, both the circumferential and the longitudinal stresses would increase and make the risk of aortic dissection more acute.

Finally, due to the direct impact of the magnitude of the aortic root motion on the longitudinal stress in the ascending aorta (and therefore on the risk of aortic dissection and rupture), AI appears to be a most significant cardiac pathology that should be used as an indicator and be part of the rationale to plan surgical correction in susceptible patients.
Acknowledgements

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References


Appendix A. Conference discussion

Dr M. Cotrufo (Naples, Italy): There is now some documentation that in cases such as bicuspid aortic valve or aortic regurgitation or left myocardial hypertrophy the ascending aorta will dilate and degenerate, and often these problems are not circumferential but are asymmetrical. Do you have any data regarding the longitudinal stress on the circumference of the aorta? Is it equal all over or is there maybe some major stress on the convexity of the aorta regarding the concavity?

Dr Beller: I think there are some inhomogeneities of the stress, but at this stage our model is rather general than patient-specific and it would be a future step to model specific cases with specific dilatation and elongation of the aorta, but right now I cannot give you the final answer.

Dr A. Haverich (Hannover, Germany): Did you have a chance to look at patients who actually had Marfan syndrome, dilated aorta and aortic insufficiency, and compare those with patients who had aortic regurgitation and dilatation but no Marfan syndrome?

Dr Beller: That is a very good point for the future. We could not do it so far. But one idea as the next step is to look at the possible remodeling of the aortic root motion in patients who are subjected to aortic valve replacement and then to look postoperatively and see if the aortic root motion reduced parallel to a ventricular remodeling. I think that’s another interesting step.

Dr M. Cotrufo (Naples, Italy): So you would recommend removing the ascending aorta in a patient with aortic regurgitation mostly to prevent dissection?

Dr Beller: Well, I think at this stage it would be too far to propose that, but I truly think that the conventional parameters of hypertension or wall abnormality or increased dilatation only give part of the story, so therefore I think it is important to look at the aortic root motion as a dynamic parameter in the follow-up of patients.

Dr A. Della Corte (Naples, Italy): Do you think that the increased aortic root motion in aortic regurgitation only predisposes to aortic dissection starting from the ascending aorta or also can increase the risk of dilatation of the ascending aorta? We would think that an increased radial stress could predispose to dilatation. In your opinion does longitudinal stress also cause this or not?

Dr Beller: Well, I think the aortic root motion could contribute to consecutive dilatation, but I think it is another scope and we would need the follow-up in patients to finally answer that question.

Dr Della Corte: We usually see root dilatations, more often than dilatations of the ascending tract proper, in association with aortic regurgitation. So do those cases represent primitive aortic root dilatations with secondary aortic regurgitation or do you think it could all begin with the aortic regurgitation and then aortic root dilatation develops due to increased root motion? This could be an interesting question.

Dr Beller: Yes, I agree, but I think at this stage it is hard to derive that from the model.