Engineering analysis of aortic wall stress and root dilatation in the V-shape surgery for treatment of ascending aortic aneurysms

Hai Dong, Minliang Liu, Tongran Qin, Liang Liang, Bulat Ziganshin, Hesham Ellauzi, Mohammad Zafar, Sophie Jang, John Elefteriades and Wei Sun

Tissue Mechanics Laboratory, The Wallace H. Coulter Department of Biomedical Engineering, Georgia Institute of Technology and Emory University, Atlanta, GA, USA

Department of Computer Science, University of Miami, Coral Gables, FL, USA

Aortic Institute at Yale New Haven Hospital, Yale University School of Medicine, New Haven, CT, USA

Corresponding author. Tissue Mechanics Laboratory, The Wallace H. Coulter Department of Biomedical Engineering, Georgia Institute of Technology and Emory University, Technology Enterprise Park, Room 206 387 Technology Circle, Atlanta, GA 30313-2412, USA. Tel: (404)-385-1245; e-mail: wei.sun@bme.gatech.edu (W. Sun).

Received 8 September 2021; received in revised form 11 December 2021; accepted 17 December 2021

Abstract

OBJECTIVES: The study objective was to evaluate the aortic wall stress and root dilatation before and after the novel V-shape surgery for the treatment of ascending aortic aneurysms and root ectasia.

METHODS: Clinical cardiac computed tomography images were obtained for 14 patients [median age, 65 years (range, 33–78); 10 (71%) males] who underwent the V-shape surgery. For 10 of the 14 patients, the computed tomography images of the whole aorta pre- and post-surgery were available, and finite element simulations were performed to obtain the stress distributions of the aortic wall at pre- and post-surgery states. For 6 of the 14 patients, the computed tomography images of the aortic root were available at 2 follow-up time points post-surgery (Post 1, within 4 months after surgery and Post 2, about 20–52 months from Post 1). We analysed the root dilatation post-surgery using change of the effective diameter of the root at the two time points and investigated the relationship between root wall stress and root dilatation.

© The Author(s) 2022. Published by Oxford University Press on behalf of the European Association for Cardio-Thoracic Surgery. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted reuse, distribution, and reproduction in any medium, provided the original work is properly cited.
RESULTS: The mean and peak max-principal stresses of the aortic root exhibit a significant reduction, \( P = 0.002 \) between pre- and post-surgery for both root mean stress (median among the 10 patients presurgery, 285.46 kPa; post-surgery, 199.46 kPa) and root peak stress (median presurgery, 466.66 kPa; post-surgery, 342.40 kPa). The mean and peak max-principal stresses of the ascending aorta also decrease significantly from pre- to post-surgery, with \( P = 0.004 \) for the mean value (median presurgery, 296.48 kPa; post-surgery, 183.87 kPa), and \( P = 0.002 \) for the peak value (median presurgery, 449.73 kPa; post-surgery, 282.89 kPa), respectively. The aortic root diameter after the surgery has an average dilatation of 5.01% in total and 2.15%/year. Larger root stress results in larger root dilatation.

CONCLUSIONS: This study marks the first biomechanical analysis of the novel V-shape surgery. The study has demonstrated significant reduction in wall stress of the aortic root repaired by the surgery. The root was able to dilate mildly post-surgery. Wall stress could be a critical factor for the dilatation since larger root stress results in larger root dilatation. The dilated aortic root within 4 years after surgery is still much smaller than that of presurgery.

Keywords: V-shape surgery • Ascending aneurysm • Aortic root • Wall stress • Finite element analysis

ABBREVIATIONS

3D Three-dimensional
CT Computed tomography
FE Finite element
MP Max-principal
STJ Sinotubular junction

INTRODUCTION

Ascending aortic aneurysms often include dilatation of the sinotubular junction (STJ) and extend proximally into the root portion of the aorta. In the root zone, it is the non-coronary sinus that dilates earliest and most severely (thought due to lack of structural support by any coronary ostium) [1, 2], which often leads to aortic insufficiency [3, 4]. Root pathology can be eradicated by traditional surgeries such as full aortic root replacement or valve-sparing aortic root replacement. However, this magnitude of surgical procedure may represent excessive surgical intervention for infirm or elderly patients. We recently [5] reported a simpler V-shape resection technique of the non-coronary sinus, which could reduce the diameter and cross-sectional area of the aortic root aneurysm.

Biomechanical factors such as aortic wall stress play a fundamental role in the natural history of aneurysms [6–8]. Based on engineering principles of material failure [9–16], aneurysm rupture and dissection occur when aortic wall stress exceeds the yield and failure strength criteria of the vessel wall. Moreover, the aortic wall stress is also highly related to the dilatation of aortic aneurysms [17, 18]. Wall stress analysis can clarify the bioengineering impact of V-shaped root resection.

The well-known Laplace’s law is a simple method to calculate the aortic wall stress, which provides a rough estimation. The finite element (FE) method, based on patient-specific geometry, can be applied to obtain more accurate stress values [19–21]. The aim of this study was to assess the morphologic and biomechanical improvements accomplished by the novel V-shape surgery based on the FE analysis.

MATERIALS AND METHODS

Ethics statement

This retrospective chart review study was approved by the Georgia Tech Institutional Review Board (#H20373, 13 October 2020) and Yale University Human Investigation Committee (#2000024367, 12 November 2018). Individual consent was waived.

Study design

We retrospectively collected clinical cardiac computed tomography (CT) images of 14 patients (P1–P14) who underwent V-shape resection of the non-coronary sinus, together with supracoronary ascending aortic replacement, at Yale New Haven Hospital, New Haven, CT, between 2013 and 2018. Patients were selected for this surgery based on their anatomy and other findings in the operating room. Patients with severe enlargement of the aortic root and sinuses of Valsalva underwent full replacement of the aortic root by conventional techniques. Patients with only moderate enlargement of the non-coronary sinus were selected, based on surgeon’s judgement at the operating table, for the V-shape resection procedure. Among those patients, all with suitable imaging studies underwent analysis in the present report. The patients’ inclusion was consecutive per the above criteria. For 10 (P1–P10) of the total 14 patients, the CT images of the thoracic and abdominal aorta pre- and post-surgery were obtained. We used these 10 patients to investigate the impact of the V-shape surgery on the stress distribution of the aortic wall. For 6 (P1, P8, and P11–P14) of the total 14 patients, CT images of the aortic root at 2 follow-up time points post-surgery were available. We used these 6 patients to study the dilatation of the aortic root post-surgery by estimating the temporal evolution of the overall effective diameter of the aortic root.

The V-shape surgery

During the surgery, a deep V-shaped, triangular portion of the non-coronary sinus is resected, from the STJ to just above the aortic annulus (see Fig. 1). The tissue in the resected non-coronary sinus was often thin, but the two-layer closure proved secure in all patients in this small series. This simple, quick V-shape resection addresses the aortic root dilatation without the complexities of full aortic root surgery with coronary button reimplantation. In our practice, choosing the V-shape resection is the exception rather than the rule, being reserved for elderly or infirm patients or those requiring other unrelated concomitant cardiac procedures.

Construction of patient-specific finite element model

For each patient of P1–P10, the three-dimensional (3D) surface geometry (Fig. 2A) of the aorta was reconstructed from the CT
images using 3D Slicer (www.slicer.org). The aortic root, ascending aorta and aortic arch, together with the 3 branches (the brachiocephalic artery, the left common carotid artery and the left subclavian artery), and the proximal descending aorta were obtained (Fig. 2A). The surface geometry was exported from 3D Slicer and imported into Altair HyperMesh 2017 (Altair Engineering, Troy, MI, USA) to generate the FE model for the aorta with trimmed boundaries (Fig. 2B). We first created 4-node quadrilateral shell elements with element size of about 2 mm by 2 mm based on the surface geometry. Four layers of 8-node linear brick elements (C3D8R) were created by offsetting the 4-node quadrilateral shell elements [22]. A total thickness estimate of 1.5 mm was applied to the aortic wall following Liang et al. [23]. Analysis of mesh size independence was performed.

**Stress calculation**

The static determinacy is a property of structures whose internal tension/stress is independent of the material properties (i.e. the tension/stress can be calculated based only on the external force and geometry) [21]. Using Laplace's law to compute the wall hoop stress of a perfect cylindrical tube is one of the most well-known examples of static determinacy [21]. Though the geometry of the aorta is much more complex, it has been shown [20, 21, 24] that the aorta under a pressure loading can also be treated as a structure with static determinacy and that the aortic wall stress is independent of material properties [25–27] and can be calculated directly from the pressure and geometry.

The stress distributions of the aortic wall under systolic pressure were obtained at pre- and post-surgery states, using the FE simulations based on the static determinacy approach [20, 21, 24]. The FE simulation of the aorta was performed by the Abaqus/Standard 2019 (SIMULIA, Providence, RI, USA). The details can be found in the Supplementary Materials.

**Dilatation of the aortic root post-surgery**

For the 6 patients, i.e. P1, P8 and P11–P14, 3D geometries of the aortic root post-surgery at the 2 follow-up time points, Post 1 and Post 2, were reconstructed from the CT images using the same method described in the previous subsection of construction of patient-specific FE model. Figure 3 shows the 3D geometries of the inner surface of the aortic root (aortic annulus to STJ) of a representative patient (P13), with Post 1 (blue) at about 4 months after the surgery and Post 2 (red) at about 20 months from Post 1. The geometries in Fig. 3 indicate that the aortic root dilated minimally after the surgery. We used the effective diameter ($D_e$) of the aortic root at Post 1 and Post 2 for all 6 patients to estimate the overall dilatation of the aortic root post-surgery. The diameter of Post 1 was regarded as the initial diameter of the aortic root after the surgery. The details for calculation of the effective diameter and growth can be found in the Supplementary Materials. In this study, the investigated follow-up period was defined as the time interval between the surgery date and the date of Post 2 (denoting as $\Delta T_{22}$). The potential follow-up period was defined as the time interval between the surgery date and the
study closure date (denoting as $\Delta T_{0c}$). The follow-up index of each patient was calculated based on $\text{FUI} = \Delta T_{02}/\Delta T_{0c}$. We also obtained the stress distribution of the aortic root (from around the aortic annulus to the STJ) based on the FE simulation. A linear regression was performed between the diameter growth (from Post 1 to Post 2) and the mean max-principal (MP) stress of root, with $y = ax + b$, where $x$ is mean MP stress, $y$ is the diameter growth and $(a, b)$ are parameters to fit. The linear regression was performed using the polyfit function in the MATLAB 2018b (Mathworks Inc., Natick, MA, USA).

Statistical analysis

The Wilcoxon signed-rank test was used to compare the stress from different groups (e.g. pre- and post-surgery), with the null hypothesis that the difference of the stress data pre- and post-surgery comes from a distribution with zero median. All analyses were performed with the signrank function in the MATLAB 2018b (Mathworks Inc., Natick, MA, USA). A $P$-value <0.05 was considered to be statistically significant.

RESULTS

Patient data

Patient demographics and CT findings of the 14 patients involved in this study are provided in Table 1. Most patients (11/14, 78.57%) had preoperative aortic insufficiency (AI) (mild in 4, moderate in 5 and severe in 2). The 11 patients who had preoperative AI underwent concomitant aortic valve replacement. None of the patients who underwent a valve-sparing procedure developed AI postoperatively. During the study period, a total of 21 patients had undergone the V-shape surgery, and 14 of them with CT images available are included in this study. For comparison, Dr Elefteriades performed a total of 630 traditional ascending aortic procedures during the same time period. For the 6 patients (P1, P8 and P11–P14) with second follow-up CT used to assess later growth after surgery, the CT of the first time point (Post 1) was obtained within 4 months [median, 2 months (range, 1–4), Table 2] after the surgery. The time interval to the second time point (Post 2) from Post 1 ranged from 20 to 52 months (median, 23.5 months, Table 2). The median follow-up from the surgery date to the Post 2 is 26 months (range, 24–53 months, Table 2) and median follow-up index is 0.79 (range, 0.44–1.0, Table 2). The resolution of the CT images is about 1.2 mm by 1.2 mm by 1.0 mm.

Wall stress of the aorta pre- and post-surgery

The wall stress of the aorta of the 10 patients (P1–P10) pre- and post-surgery was obtained from the FE simulation. Figure 4 shows the MP stress field of the aorta of a representative patient (P1) pre- and post-surgery. We extracted the MP stress field of 4 ring bands of the aorta from each patient, with band-1 at the repaired aortic root (from around the sinus to STJ), band-2 at the ascending aneurysm with the maximum diameter presurgery, band-3 at the ascending aorta just proximal to the brachiocephalic artery (essentially, above the graft), which might be slightly affected by the surgery and band-4 at the position just distal to the aortic arch. The presurgery ascending aneurysm of band-2 was surgically replaced by an ascending aortic graft as shown post-surgery. Band-1, band-3 and band-4 post-surgery represent native aortic tissue. The longitudinal height of each ring band presurgery is approximately the same as that post-surgery.

Figure 5 shows the mean (first row) and peak (second row) MP stresses of the 4 ring bands between pre- and post-surgery for the 10 patients. There is a significant reduction for the mean and peak MP stresses of band-1, with $P = 0.002$ (Fig. 5A and B). The mean and peak MP stresses of band-2 (Fig. 5A and E) were also reduced significantly, with $P = 0.004$ (Fig. 5B) and $P = 0.002$. 

Figure 3: Three-dimensional geometries of the aortic root of a representative patient (P13) post-surgery at 2 follow-up time points. Post 1 (blue): about 4 months after the surgery; Post 2 (red): 20 months later from Post 1. Note minimal growth of the aortic root between time points.
The mean MP stress of band-3 and band-4 has a significant reduction from pre- to post-surgery, with $P = 0.020$ (Fig. 5C) and $P = 0.027$ (Fig. 5D), respectively, while there is no statistical difference between the pre- and post-surgery for the peak MP stress of band-3 (Fig. 5G; $P = 0.359$) and band-4 (Fig. 5H, $P = 0.027$).

**DISCUSSION**

We obtained the static stress distribution of the aortic wall under patient-specific systolic pressure. The cyclic loading and unloading were not considered. Based on the principles of biomechanics, larger pressure loading would induce larger stress in the aortic wall. The wall stress under systolic pressure is expected to be maximum; and further, the corresponding risk is also the maximum, during a cardiac cycle. Thus, we only considered the state of systolic pressure.

Detailed stress distribution of the aortic wall from band-1 to band-4 can be compared between pre- and post-surgery states, using our patient-specific stress analysis. The V-shape surgery significantly reduced the mean and peak MP stress of band-1 (corresponding to the repaired aortic root; Fig. 5A and E). If the rupture strength of the root wall is assumed to be unchanged post-surgery, the rupture risk will be expected to decrease in concert with the decreased wall stress \[10-12\]. The major portion of the ascending aneurysm (band-2 in Fig. 4A) was replaced by an ascending aortic graft (band-2 in Fig. 4B). The diameter of the graft is much smaller than that of the ascending aneurysm pre-surgery and the stress of band-2 was significantly reduced by the surgery (Fig. 5B and F). Although the polymeric graft has no rupture issue, the reduction of the diameter of band-2 may

**Table 1:** Demographics of the patients involved in this study

| Demographics           | Value                                      |
|------------------------|--------------------------------------------|
| Total patient number   | 14                                         |
| Age/years, mean ± SD (range) | 62.57 ± 12.43 (33-78)                     |
| Male, n (%)            | 10 (71.43%)                                |
| Max ascending aortic size/cm, mean ± SD (range) | 4.41 ± 0.45 (3.50-5.45)                  |
| Max aortic root size/cm, mean ± SD (range) | 4.53 ± 0.34 (4.00-5.05)                  |
| Preoperative aortic insufficiency (AI), n (%) | 11 (78.57%); 4 mild, 5 moderate, 2 severe |

**Table 2:** Effective diameter of the aortic root of Post 1 and Post 2 for 6 patients

|       | P1  | P8  | P11 | P12 | P13 | P14 |
|-------|-----|-----|-----|-----|-----|-----|
| Post 1 (cm) | 2.86 | 3.23 | 3.63 | 3.47 | 3.19 | 3.52 |
| Post 2 (cm) | 2.99 | 3.42 | 3.79 | 3.62 | 3.33 | 3.75 |
| Chg (cm) | 0.13 | 0.19 | 0.16 | 0.15 | 0.14 | 0.23 |
| Chg/year (cm) | 0.07 | 0.10 | 0.04 | 0.08 | 0.08 | 0.05 |
| $g_1$ (%) | 4.55 | 5.88 | 4.41 | 4.32 | 4.39 | 6.53 |
| $g_2$ (%) | 2.35 | 2.90 | 1.21 | 2.33 | 2.61 | 1.47 |
| $\Delta T_{01}$ (month) | 3 | 2 | 2 | 2 | 4 | 1 |
| $\Delta T_{02}$ (month) | 23 | 24 | 43 | 22 | 20 | 52 |
| $\Delta T_{0c}$ (month) | 26 | 26 | 45 | 24 | 24 | 53 |
| FUI | 1.0 | 0.81 | 0.82 | 0.77 | 0.44 | 0.64 |

Chg: diameter growth from Post 1 to Post 2; Chg/year: annual diameter growth during Post 1 and Post 2; $g_1$: total percentage growth of root effective diameter from Post 1 to Post 2; $g_2$: annual percentage growth of root effective diameter during Post 1 and Post 2; $\Delta T_{01}$: time interval between the surgery date and Post 1; $\Delta T_{02}$: time interval between Post 1 and Post 2; $\Delta T_{0c}$: time interval between the surgery date and Post 2; FUI: follow-up index.

Dilatation of the aortic root post-surgery

The effective diameter of the aortic root at Post 1 and Post 2 for the 6 patients (P1, P8 and P11–P14) is presented in Table 2, which showed a minimum annual growth of 1.21% for P11, a maximum annual growth of 2.90% for P8, and an average growth of 4.55% in total, and 2.15%/year. Linear regression trend lines were obtained, with $R^2 = 0.7414$ and 0.9229, for the relations between the diameter change and the mean MP stresses of the root at Post 1 and Post 2, respectively, shown in Fig. 6.

Supplementary Material, Fig. S1 shows the comparison of the effective diameter of the aortic root at 3 time points of presurgery (Pre), Post 1 and Post 2, for 4 patients (P1, P8, P11 and P14) whose the CT images of the aortic root are available for all the 3 time points. The effective diameter of the aortic root of Post 2 within 4 years after the surgery is smaller than that of presurgery for all four patients.

AI: aortic insufficiency; SD: standard deviation.
contribute to the stress reduction (Fig. 5C) of the adjacent band-3 which is native aortic tissue. The average value for the 10 patients of the mean and peak MP stress of band-4 (Fig. 5D and H) also decreases after the surgery, but there is no statistical difference ($P > 0.05$) between the pre- and post-surgery for the stress of band-4.

It has been shown by Elefteriades et al. [5] that the mean wall tension of the aortic root decreased post-surgery with the reduced root diameter, simply based on the Laplace's law. However, the change of the wall stress, especially the peak wall stress, of the aortic root may not have a similar simple relation with the reduced diameter, since the wall stress field is usually inhomogeneous and depends not only on the diameter but also on other shape features including the centreline and surface curvatures, as has been shown by Liang et al. [23] and de Galarreta et al. [28]. Thus, a detailed patient-specific biomechanical analysis in this study is essential for a more accurate evaluation for the impact of the novel V-shape surgery on the wall stress of the aortic root.

Shang et al. [17] investigated the relation between the wall stress and expansion rate in descending thoracic aortic aneurysms without surgery, and they found that larger peak wall stress results in larger aneurysm expansion rate. However, there is currently a lack of studies on the dilatation of aortic wall/root after a surgical operation. Thus, it is also essential to quantitatively estimate the potential aortic root dilatation after the surgery for a comprehensive evaluation of the novel V-shape surgery.

The results of this study indicated that the aortic root manifests only small dilatation post-surgery. The average percentage diameter increase is 5.01% in total, and 2.15%/year, and the average absolute increase of 1.7 mm in total and 0.71 mm/year, which is much smaller than the diameter increase reported in the literature for aortic aneurysms without surgery (e.g. a mean diameter increase of 2.9 mm/year obtained in Shang et al. [17], and 4.2 mm/year in Hirose et al. [29]). The dilatation could be affected by the wall stress since larger root wall stress results in larger root

Figure 4: Max-principal stress field of the aorta of a representative patient (P1): (A) pre- and (B) post-surgery. Four ring bands: band-1 at the repaired aortic root, band-2 at the ascending aorta with the maximum diameter presurgery, band-3 at the ascending aorta just proximal to the brachiocephalic artery (above the graft) and band-4 at the position just distal to the aortic arch.

Figure 5: Mean (first row, A-D) and peak (second row, E and F) max-principal stresses of the band-1 (A, E), band-2 (B, F), band-3 (C, G) and band-4 (D, H). Bar charts represent the median, range and interquartile range (IQR) for the 10 patients. **P-value < 0.05.
dilatation (as shown in Fig. 6). Moreover, the comparison of results in Fig. 6A and B indicates that the impact of wall stress is relatively constant over time.

In addition, it should be noted that, although the effective diameter of the aortic root of Post 2 increases mildly comparing with that of Post 1, the root diameter of Post 2 is still smaller than that of presurgery at current stage (within 4 years after the surgery), which suggests the V-shape surgery effectively reduces the aortic root diameter for a relatively long time period post-surgery.

This advanced engineering analysis adds credence to the V-shaped resection of the non-coronary sinus as a viable procedure. We tend to use the V-shaped resection for aortic roots in the range of 4.0–5.0 cm in patients who are not candidates for full aortic root replacement because of age or frailty or need for extensive, critical other intraoperative procedures (e.g. mitral valve surgery, coronary artery bypass, aortic arch replacement, etc.). We do not use it for aortic roots beyond 5.0 cm. The beneficial findings in this engineering analysis give support for the V-shaped resection as another tool in the surgeon’s armamentarium for the mildly dilated aortic root.

One limitation of this study is that the analyses are based on a relatively small cohort of patients (total n = 14), since the V-shape surgery was the exception rather than the rule and was reserved largely for elderly or infirm patients. However, results were quite consistent among this small group of patients, suggesting that these results would generalize to larger cohorts. For example, the mean and peak values of the root wall stress (band-1) for all 10 patients was reduced by more than -14% after the surgery, which results in very small P-values (Fig. 5A and E) between pre- and post-surgery. Thus, it can be expected that similar results may be obtained with a larger cohort of patients. Finally, a uniform thickness of 1.5 mm for the aortic wall may be obtained based on the method in Elefteriades et al. [30] when both contrast and non-contrast CT scans are available.

CONCLUSIONS

This study marks the first biomechanical analysis of the novel V-shape surgery. The study has demonstrated a significant reduction in aortic wall stress of the aortic root repaired by V-shaped resection of the moderately dilated aortic root at the time of ascending aortic replacement. Wall stress reduction is important in reducing the dilatation process. Indeed, the low redilatation rate (2.15%/year) portends well for the future of the aortic root repaired by V-shaped resection.

SUPPLEMENTARY MATERIAL

Supplementary material is available at ICVTS online.

ACKNOWLEDGEMENTS

Hai Dong thanks lab members Courtney Huynh, Samuel Li, Kristen Riess, Pankirt Oggu and Daksha Jadhav for their assistance in image segmentation, mesh creation and finite element simulation.

Funding

This study is in part supported by American Heart Association (AHA) 18TPA34230083.

Conflict of interest: Wei Sun is co-founder and serves as the Chief Scientific Advisor of Dura Biotech. Wei Sun has received compensation and owns equity in the company. John Elefteriades: Principal, CoolSpine; Data & Safety Monitoring Board, Terumo; Consultant, CryoLife.
Data availability statement

All relevant data are within the manuscript and its Supporting Information files.

Author contributions

Hai Dong: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Writing—original draft. Minliang Liu: Investigation; Software; Writing—review & editing. Tongran Qin: Investigation; Software; Writing—review & editing. Liang Liang: Software; Writing—review & editing. Bulat Ziganshinn: Resources; Writing—review & editing. Hesham Ellauzi: Resources; Writing—review & editing. Mohammad Zafar: Resources; Writing—review & editing. Sophie Jang: Resources; Writing—review & editing. John Elefteriades: Conceptualization; Project administration; Resources; Supervision; Writing—review & editing. Wei Sun: Conceptualization; Funding acquisition; Investigation; Project administration; Resources; Supervision; Writing—review & editing.

Reviewer information

Interactive CardioVascular and Thoracic Surgery thanks Roman Gottardi, Tomas Holubec and the other, anonymous reviewer(s) for their contribution to the peer review process of this article.

REFERENCES

[1] Westaby S, Saito S, Anastasiadis K, Moorjani N, Jin X. Aortic root remodeling in atheromatous aneurysms: the role of selected sinus repair. Eur J Cardiothorac Surg 2002;21:459–64.
[2] David TE, Feindel CM, Bos J. Repair of the aortic valve in patients with aortic insufficiency and aortic root aneurysm. J Thorac Cardiovasc Surg 1995;109:345–52.
[3] Stavridis GT, Downey RS, Gerdisch MW, Hughes GC, Jasinski MJ, Rankin JS et al. Aortic valve repair for tri-leaflet aortic insufficiency associated with asymmetric aortic root aneurysms. Ann Cardiothorac Surg 2019;8:426–9.
[4] David TE, Feindel CM, Webb GD, Colman JM, Armstrong S, Maganti M. Long-term of aortic valve-sparing operations for aortic root aneurysm. J Thorac Cardiovasc Surg 2006;132:347–54.
[5] Elefteriades JA, Peterss S, Nezami N, Gluck G, Sun W, Tranquilli M et al. V-shape noncoronary sinus remodeling in ascending aortic aneurysm and aortic root ectasia. J Thorac Cardiovasc Surg 2017;154:72–6.
[6] Humphrey J, Taylor C. Intracranial and abdominal aortic aneurysms: similarities, differences, and needs for a new class of computational models. Annu Rev Biomed Eng 2008;10:221–46.
[7] Vorp DA. Biomechanics of abdominal aortic aneurysm. J Biomech 2007;40:1887–902.
[8] Humphrey JD, Canham PB. Structure, mechanical properties, and mechanics of intracranial saccular aneurysms. J Elast 2000;61:49–81.
[9] Kubicek L, Staffa R, Novotny T, Vlachovsky R, Bursa J, Polzer S et al. Abdominal aortic aneurysm rupture risk prediction based on computer-aided vascular wall stress assessment using finite element method—the future of decision making process. Eur J Vasc Endovasc Surg 2019;58:e306–7.
[10] Duprey A, Trabelsi O, Vola M, Favre J-P, Avril S. Biaxial rupture properties of ascending thoracic aortic aneurysms. Acta Biomech 2016;42:273–85.
[11] Raghavan M, Vorp DA. Toward a biomechanical tool to evaluate rupture potential of abdominal aortic aneurysm: identification of a finite strain constitutive model and evaluation of its applicability. J Biomech 2000;33:475–82.
[12] Liu M, Dong H, Lou X, Iannucci G, Chen EP, Leshnower BG et al. A novel anisotropic failure criterion with dispersed fiber orientations for aortic tissues. J Biomech Eng 2020;142:1–11.
[13] Dong H, Liu M, Martin C, Sun W. A residual stiffness-based model for the fatigue damage of biological soft tissues. J Mech Phys Solids 2020;143:104074.
[14] Dong H, Li Z, Wang J, Karihaloo B. A new fatigue failure theory for multi-directional fiber-reinforced composite laminates with arbitrary stacking sequence. Int J Fatigue 2016;87:294–300.
[15] Dong H, Wang J. A criterion for failure mode prediction of angle-ply composite laminates under in-plane tension. Compos Struct 2015;128:234–40.
[16] Dong H, Wang J, Karihaloo B. An improved Puck’s failure theory for fibre-reinforced composite laminates including in the situ strength effect. Compos Sci Technol 2014;96:86–92.
[17] Dong H, Wang J, Karihaloo B. An inverse problem for prediction of in vivo mechanical properties of the aortic wall. J Mech Behav Biomed Mater 2017;72:148–58.
[18] Speelman L, Hellenthal FA, Pulinx B, Bosboom E, Breeuwer M, Van Sambeek M et al. The influence of wall stress on AAA growth and biomarkers. Eur J Vasc Endovasc Surg 2010;39:410–6.
[19] Qin T, Caballero A, Mao W, Barrett B, Kamioka N, Lerakis S et al. The role of stress concentration in calcified bicuspid aortic valve. J R Soc Interface 2020;17:20190893.
[20] Liu M, Liang L, Sun W. A new inverse method for estimation of in vivo mechanical properties of the aortic wall. J Mech Behav Biomed Mater 2017;72:148–58.
[21] Liu M, Liang L, Liu H, Zhang M, Martin C, Sun W. On the computation of in vivo transmural mean stress of patient-specific aortic wall. Biomech Model Mechanobiol 2019;18:387–98.
[22] Qin T, Caballero A, Hahn RT, McKay R, Sun W. Computational Analysis of Virtual Echocardiographic Assessment of Functional Mitral Regurgitation for Validation of Proximal Isovelocity Surface Area Methods. J Am Soc Echocardiogr 2021;34:1211–23. https://doi.org/10.1016/j.echo.2021.06.011.
[23] Liang L, Liu M, Martin C, Elefteriades JA, Sun W. A machine learning approach to investigate the relationship between shape features and numerically predicted risk of ascending thoracic aneurysm. Biomech Model Mechanobiol 2017;16:1519–33.
[24] Joldes GR, Miller K, Witten A, Doyle B. A simple, effective and clinically applicable method to compute abdominal aortic aneurysm wall stress. J Mech Behav Biomed Mater 2016;58:139–48.
[25] Holzapfel GA, Gasser TC, Ogden RW. A new constitutive framework for arterial wall mechanics and a comparative study of material models. J Elast Phys Soc Solids 2000;61:1–48.
[26] Gasser TC, Ogden RW. Holzapfel GA. Hyperelastic modelling of arterial layers with distributed collagen fibre orientations. J R Soc Interface 2006;3:15–35.
[27] Dong H, Sun W. A novel hyperelastic model for biological tissues with planar distributed collagen fibers and a second kind of Poisson effect. J Mech Phys Solids 2021;151:104377.
[28] de Galarreta SR, Cazon A, Antón R, Finol EA. The relationship between surface curvature and abdominal aortic aneurysm wall stress. J Biomech Eng 2017;139:1–7.
[29] Hirose Y, Hamada S, Takamiya M, Imakita S, Naito H, Nishimura T. Aortic aneurysms: growth rates measured with CT. Radiology 1992;185:249–52.
[30] Elefteriades JA, Mukherjee SK, Mejibian H. Discrepancies in measurement of the thoracic aorta: JACC review topic of the week. J Am Coll Cardiol 2020;76:201–17.