Title

Ascending thoracic aortic aneurysm elongation occurs in parallel with dilatation in a nonsurgical population

Journal
European Journal of Cardio-Thoracic Surgery, 63(6)

ISSN
1010-7940

Authors
Gulati, Arushi
Zamirpour, Siavash
Leach, Joseph
et al.

Publication Date
2023-06-01

DOI
10.1093/ejcts/ezad241

Peer reviewed

European Journal of Cardio-Thoracic Surgery 2023, 63(6), ezad241
https://doi.org/10.1093/ejcts/ezad241 Advance Access publication 24 June 2023

ORIGINAL ARTICLE

CONVENTIONAL AORTIC SURGERY

Cite this article as: Gulati A, Zamirpour S, Leach J, Khan A, Wang Z, Xuan Y *et al.* Ascending thoracic aortic aneurysm elongation occurs in parallel with dilatation in a nonsurgical population. Eur J Cardiothorac Surg 2023; doi:10.1093/ejcts/ezad241.

Ascending thoracic aortic aneurysm elongation occurs in parallel with dilatation in a nonsurgical population

Arushi Gulati[a], Siavash Zamirpour[a], Joseph Leach[b], Amir Khan[a], Zhongjie Wang [a], Yue Xuan[a], Michael D. Hope[b], David A. Saloner[b], Julius M. Guccione[a], Liang Ge[a] and Elaine E. Tseng [a,*]

[a] Department of Surgery, University of California San Francisco (UCSF) and San Francisco VA Medical Center, San Francisco, CA, USA
[b] Department of Radiology, University of California San Francisco (UCSF) and San Francisco VA Medical Center, San Francisco, CA, USA

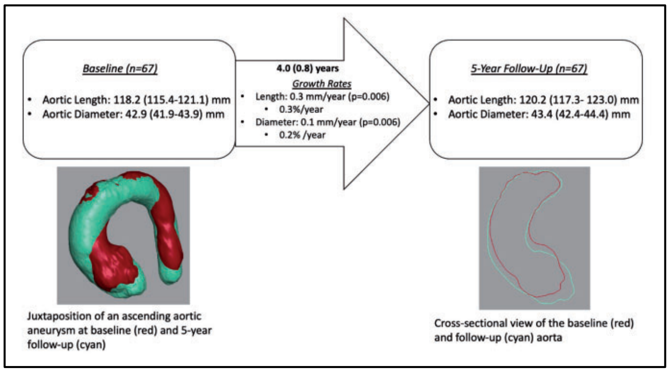
* Corresponding author. Division of Cardiothoracic Surgery, University of California San Francisco and San Francisco VA Medical Center, 500 Parnassus Ave., Suite 405W, San Francisco, CA 94143, USA. Tel: +1-415-221-4810x23452; e-mail: elaine.tseng@ucsf.edu (E.E. Tseng).

Received 16 June 2022; received in revised form 9 April 2023

Ascending Thoracic Aortic Aneurysm Elongation and Dilatation Occur in Parallel at Low Rates in a Nonsurgical Population

Summary

Population: Veteran patients with nonsyndromic, nonsurgical ascending thoracic aortic aneurysms at diameters <5.5 cm
Study Design: Retrospective cohort with analysis of serial computed tomography angiography imaging for up to 5 years
Outcome: Rates of aortic elongation and dilatation



Legend: Figure depicts changes in length and diameter distributions. Values are written as mean (95% confidence interval).

Abstract

OBJECTIVES: Rapid diameter growth is a criterion for ascending thoracic aortic aneurysm repair; however, there are sparse data on aneurysm elongation rate. The purpose of this study was to assess aortic elongation rates in nonsyndromic, nonsurgical aneurysms to understand length dynamics and correlate with aortic diameter over time.

METHODS: Patients with <5.5-cm aneurysms and computed tomography angiography imaging at baseline and 3–5 years follow-up underwent patient-specific three-dimensional aneurysm reconstruction using MeVisLab. Aortic length was measured along the vessel centreline between the annulus and aortic arch. Maximum aneurysm diameter was determined from imaging in a plane normal to the vessel centreline. Average rates of aneurysm growth were evaluated using the longest available follow-up.

RESULTS: Over the follow-up period, the mean aortic length for 67 identified patients increased from 118.2 (95% confidence interval: 115.4–121.1) mm to 120.2 (117.3–123.0) mm ($P = 0.02$) and 15 patients (22%) experienced a change in length of ≥5% from baseline. The mean annual growth rate for length [0.38 (95% confidence interval: 0.11–0.65) mm/year] was correlated with annual growth rate for diameter [0.1 (0.03–0.2) mm/year] (rho = 0.30, $P = 0.01$). Additionally, annual percentage change in length [0.3 (0.1–0.5)%/year] was similar to percentage change in diameter [0.2 (0.007–0.4)%/year, $P = 0.95$].

CONCLUSIONS: Aortic length increases in parallel with aortic diameter at a similar percentage rate. Further work is needed to identify whether elongation rate is associated with dissection risk. Such studies may provide insight into why patients with aortic diameters smaller than surgical guidelines continue to experience dissection events.

Keywords: Aortic aneurysms • Type A dissection • Aortic elongation • Aortic diameter

ABBREVIATIONS

aTAA	Ascending thoracic aortic aneurysm
ATAD	Acute type A aortic dissection
CI	Confidence interval
CT	Computed tomography
CTA	Computed tomography angiography
3D	Three-dimensional
SD	Standard deviation
TAVR	Transcatheter aortic valve replacement

INTRODUCTION

Acute type A aortic dissection (ATAD) is a rare but highly fatal phenomenon, with an incidence of 2.0 per 100 000 persons but a total hospital mortality rate as high as 53% [1, 2]. The risk of ATAD is much higher in patients with existing ascending thoracic aortic aneurysms (aTAAs), with nearly 90% of ATAD events occurring in patients with aortic diameters >4.0 cm [3]. Therefore, current European Society of Cardiology guidelines recommend regular computed tomography (CT) imaging of aTAA patients at annual or semi-annual intervals, depending on aortic size, to assess need for prophylactic surgical repair [4].

The primary criteria for aTAA surgical assessment and risk determination is diameter, with repair recommended at diameters ≥5.5 cm in the absence of rapid growth, clinical symptoms, or underlying connective tissue disorder [5]. These recommendations are based on early data demonstrating a sharp increase in aneurysm dissection and rupture risk at 6.0 cm [6]. An advantage of using this morphologic threshold is that it can readily be determined by guideline-directed surveillance imaging. However, studies of the International Registry of Acute Aortic Dissections have demonstrated that the average diameter at the time of aortic dissection is 5.3 cm, which is below the currently recommended surgical threshold [3]. Furthermore, we and others have demonstrated that aortic diameters may be more stable over time than previously reported in patients with aTAAs that do not meet criteria for surgery [7, 8]. Yet, rapid growth has only been defined by diameter and little is known about growth with regards to aortic length.

Recent observational studies have demonstrated that ascending aortic length may provide more information than diameter alone. For instance, aortic length has been found to be associated with ATAD, independent of pre-dissection diameter [9–11]. Additional risk prediction models including both aortic length and aortic diameter have also been developed and found to be more predictive than single-parameter models [12, 13]. However, data on how length changes over time in aTAA patients that do not meet diameter-based criteria for surgery remain limited. Therefore, the purpose of this study was to evaluate changes in aortic length in nonsyndromic aTAAs that do not meet criteria for surgical repair in a clinically homogenous population, to better understand the dynamics of aortic length and its relationship with aortic diameter over time.

PATIENTS AND METHODS

Ethical statement

This study was approved by the University of California San Francisco and San Francisco Veterans Affairs Medical Center Institutional Review Boards (IRB 13-10932, approved 12 April 2021). Written consent was waived for this retrospective analysis. Study reporting was conducted in accordance with STrengthening the Reporting of OBservational studies in Epidemiology recommendations [14].

Data collection

Patients with nonsurgical aTAAs (defined as aortic diameter ≥4.0 and <5.5 cm) were identified from an institutional database of aTAA patients undergoing regular surveillance from January 2011 to January 2020. Review of the electronic medical record was conducted to identify available computed tomography angiography (CTA) imaging of the chest taken for any indication. Patients with 2 or more CTA exams performed at least 3 years and up to 5 years apart were included in the study population. If >1 follow-up image was available during this interval, then the most recent follow-up scan available was used. Patients with aortic arch or isolated aortic root aneurysms, or underlying connective tissue disorders were excluded, as were patients who experienced aortic events and/or underwent aneurysm repair between baseline and follow-up imaging. For images with available electrocardiogram gating for aneurysm surveillance, images acquired during the diastolic phase of cardiac cycle were selected for review; however, electrocardiogram gating was not required for study inclusion.

Images were downloaded from radiology picture archiving and communication system, de-identified, and reviewed in open-source Digital Imaging and Communications in Medicine viewer Horos (Horosproject.org). Demographic and clinical data were collected from subjects' electronic medical records.

Diameter and length measurements

Aortic diameter measurements were made by a single board-certified radiologist blinded to any additional subject information using a double-oblique technique to measure maximum aortic diameter in plane normal to local vessel centreline [15]. Measurements were made between sinotubular junction and aortic arch at the level of the innominate artery, and only aortic luminal diameter was measured (i.e. aortic wall thickness was excluded). All baseline imaging was reviewed first, followed by all subsequent surveillance imaging such that no one subject's imaging was reviewed sequentially.

To measure length, de-identified CTA images underwent three-dimensional (3D) aTAA reconstruction from left ventricular outflow tract to aortic arch using MeVisLab software (http://www.mevislab.de/home/about-mevislab). Length measurements

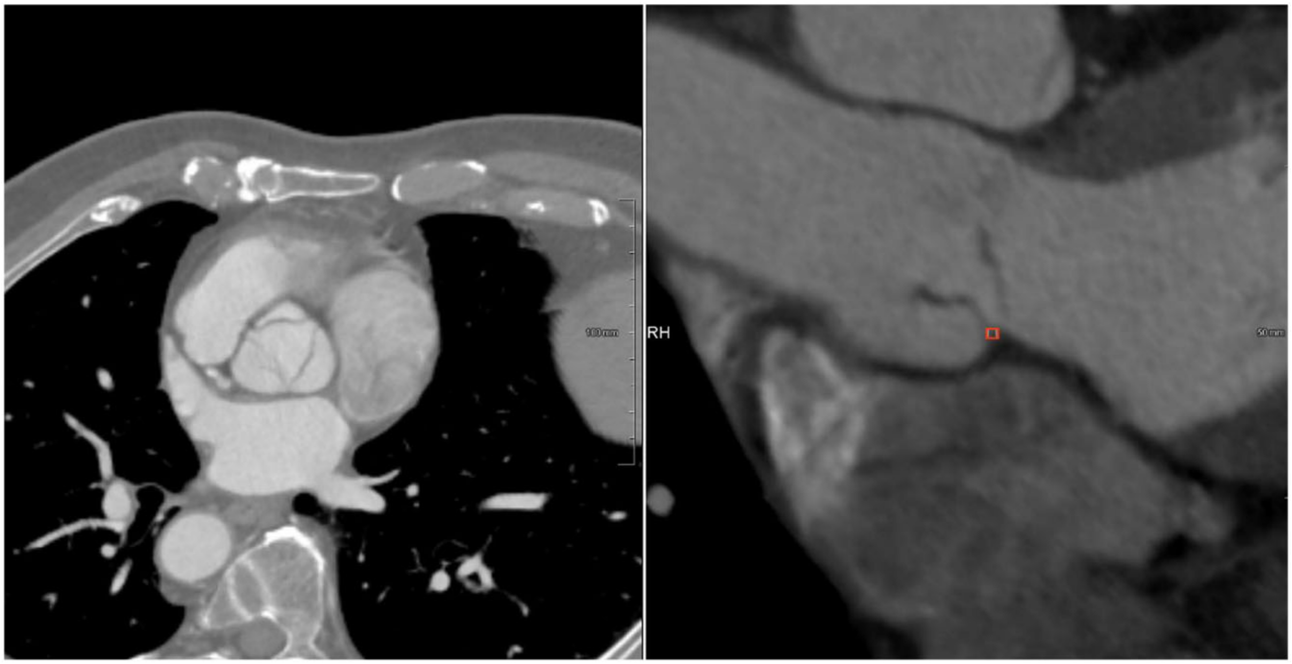


Figure 1: Identification of aortic annulus plane using multiplanar reformatted images of sinuses. Marker in red demonstrates the base of aortic sinuses.

were then made along vessel centreline between annulus and aortic arch. We first extracted the vessel centrelines using DtfSkeletonization module in MeVisLab. The 3 nadirs (lowest part of sinuses of Valsalva) were manually identified from multiplanar reformatted images of the sinuses to define the aortic annulus plane (Fig. 1). Intercept point of the centreline and aortic annulus plane was considered the proximal end of the ascending aortic centreline. Distal end of the ascending aortic centreline, at the proximal arch, was defined as the point of intersection between the innominate artery centreline and aortic centreline. The curved centreline was then divided into ~50 straight segments and the centreline length was calculated as the summation of these straight segments in an automated program in a 3D method similar to two-dimensional vessel straightening except without flattening into 2D (Fig. 2).

Statistical analysis

Patient demographics and medical history, including aneurysm risk factors, were obtained manually from electronic medical record. Data processing and statistical analysis were performed using Stata Statistical Software (version 16.0; StataCorp LLC, College Station, TX). Body surface area was calculated from height and weight using the method outlined by DuBois and DuBois [16].

The Shapiro–Wilk test was used to assess distributions of continuous variables for normality. Changes in diameter and length distributions over time were calculated using linear mixed-effects models. Diameter and length were dependent variables, and there was a fixed effect for number of years from first scan and a random patient-level intercept. *P*-values were calculated using the *Z*-test. Spearman's rank correlation was used to identify the strength of association between baseline and diameter. A *post hoc* analysis was also conducted using a univariable linear regression model to assess predictors of individual annual elongation rate. A value of $P < 0.05$ was considered to be statistically significant.

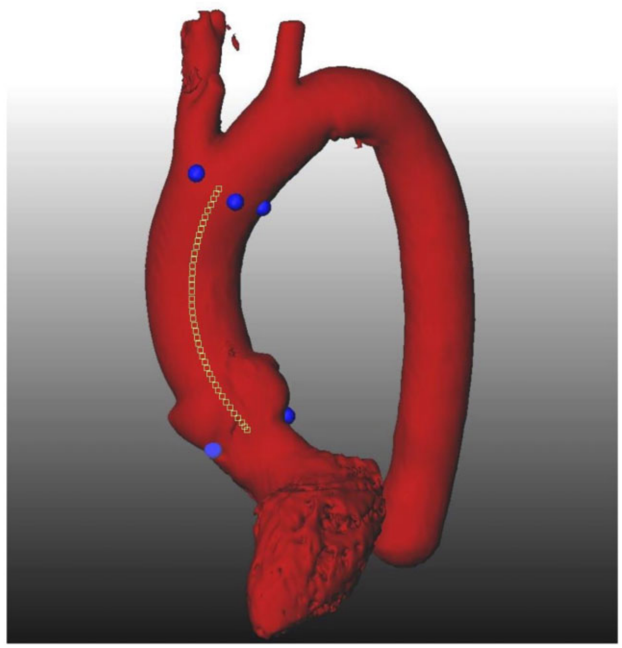


Figure 2: Sample aortic length measurement along three-dimensional centreline. Measurements were taken between the plane of aortic annulus (defined by inferior points) and plane of innominate artery (defined by superior points).

RESULTS

Our veteran cohort included 67 patients with at least 2 CTA scans between 3 and 5 years apart. Of these, 23 patients (34%) had follow-up at 3 years, 26 (39%) had follow-up at 4 years and 18

Table 1: Demographic characteristics of 67 aortic aneurysm patients

Characteristic	Number (%)
Age (years), mean (SD)	66.7 (7.5)
Sex	
Female	1 (1%)
Male	66 (99%)
Height (cm), mean (SD)	179.8 (8.3)
Weight (kg), mean (SD)	97.6 (21.7)
Body mass index (kg/m^2), mean (SD)	30.0 (5.5)
Body surface area (m^2), mean (SD)	1.8 (0.3)
Smoking	
Current smoker	14 (21%)
Former smoker	38 (57%)
Never smoker	15 (22%)
Comorbidities	
Hypertension	48 (72%)
Hyperlipidaemia	49 (73%)
Diabetes mellitus	11 (16%)
Chronic obstructive pulmonary disease	16 (24%)
Valve type	
Bicuspid aortic valve	5 (7%)
Tricuspid aortic valve	62 (93%)
Aortic stenosis	3 (6%)

SD: standard deviation.

(27%) had follow-up at 5 years. The mean [standard deviation (SD)] time between baseline and follow-up was 4.0 (0.8) years. Patients were primarily male ($n = 66$, 99%) with the mean age of 66.7 years and the body mass index of 30.0 kg/m^2 (Table 1). Most patients had a history of hypertension ($n = 48$, 72%) or hyperlipidaemia ($n = 49$, 73%), while 5 (7%) patients had bicuspid aortic valve. All identified aneurysms were noted to be confined to a single aortic segment.

At baseline, patients had a mean aortic length of 118.2 mm [95% confidence interval (CI): 115.4–121.1 mm, $P < 0.001$; median: 120.3 mm (interquartile range: 109.4–126.2 mm)] and a mean aneurysm diameter of 42.9 mm [95% CI: 41.9–43.9 mm, $P < 0.001$; median: 43.00 mm (interquartile range: 41.0–45.5 mm), Table 2]. Baseline length and diameter measurements were significantly correlated (rho = 0.35, $P = 0.003$) (Fig. 3).

Over the 5-year follow-up period, aortic length increased at a mean annual growth rate of 0.38 mm/year (95% CI: 0.11–0.65 mm/year; $P = 0.006$). In addition, 15 patients (22%) experienced a clinically significant change in length, defined as a >5% change from baseline over the total 5-year period. Of these 15 patients, 12 experienced an increase in aortic length while 3 experienced a decrease in length (Fig. 4). Twelve patients who experienced an increase in aortic length had mean (SD) baseline length of 116.8 (12.1) mm and diameter of 43.4 (3.2) mm.

While there was also an increase in aneurysm luminal diameter over the study period at a rate of 0.11 mm/year (95% CI: 0.03–0.18; $P = 0.0057$), this difference was likely not clinically significant over the 5-year period due to inability to resolve sub-millimeter changes in imaging. Mean individual % growth rates for length [0.3%/year (SD: 1.0%/year)] correlated with diameter growth rates [0.2%/year (SD: 0.9%/year), rho = 0.30, $P = 0.01$; Fig. 4]. A total of 5 patients (7%) experienced a clinically significant change in diameter over 5 years, 4 of whom experienced an increase and 1 of whom experienced a decrease in diameter. Of these 5 patients, only 1 experienced a corresponding change in length that was >5%.

On univariate analysis, individual aortic elongation rate did not differ based on history of smoking, diabetes or hypertension, or by bicuspid versus tricuspid aortic valve type (Table 3). Elongation rate was also not significantly associated with age, body mass index or baseline diameter (Table 3), although patients with a higher body surface area were more likely to have a more rapid elongation rate ($\beta = 0.98$, $P = 0.048$).

DISCUSSION

While current guidelines for aTAA repair rely on aortic diameter for risk stratification, multiple large cohort studies in the last several years have demonstrated that diameter alone is not a sensitive enough measure of dissection risk [3, 17]. Therefore, there is a need to understand morphologic components of the aorta that may be more strongly associated with dissection risk. One such morphologic component is aortic length, which differs between aTAA patients and healthy controls [9]. Prior studies have also shown length to be independently associated with risk of ATAD, even after adjusting for age, size, and comorbid conditions [9] and that aortic length greater than 12.0 cm may provide an independently increased risk of ATAD or rupture, regardless of aTAA diameter [13, 18]. Furthermore, ATAD risk stratification models that incorporate length perform better than those with diameter alone [10, 12, 19]. However, rates of length and diameter change over time have not yet been well established in a nonsurgical aTAA population and information regarding the relative stability of these 2 metrics can provide further insight for future risk assessment models. Our findings further suggest a weak correlation between aortic length and diameter change, suggesting that both may provide valuable contributions to dissection risk calculation.

In our study population, a median aortic length at baseline when measured from aortic annulus to aortic arch (118.2 mm) was consistent with median values previously reported in aneurysm patients, which range from 91.0 to 120 mm [13, 18–22]. Nevertheless, it is important to note differences in methodology between this and prior studies, including use of two-dimensional multiplanar reformation for length measurement compared to 3D centreline measurement. 3D reconstruction has been used extensively by our group for the reconstruction of aortic geometry, and we felt that this was more likely to represent true aortic length than that given by multiplanar reconstruction, which flattens 3 dimensions to 2D and may compress the length slightly. In doing so, we divided the curved aortic length into straight-line segments at small enough intervals to follow the aortic curvature with high fidelity, and we feel that doing so may have resulted in a more conservative estimate of the true difference between our results and those previously published. Additionally, a subset of prior studies have measured length to the beginning of innominate artery takeoff rather than the centre [13, 19–22]. In contrast, we selected the intersection of the aortic centreline and centreline of the innominate artery as the distal boundary for measurement as it was a more reproducible landmark in 3 dimensions. Furthermore, our length measurements were nearly exclusively for a male population (99%) while prior literature has ranged from 27% to 36% female [13, 18–22]. The aorta is likely longer in males than females both with and without aTAAs [20, 21], and our results may reflect differences in aortic elongation rate between sexes that should be further clarified. Future studies should

Table 2: Comparison of changes in diameter and length over time

	Baseline, mean (95% CI)	5-Year follow-up, mean (95% CI)	Annual growth rate (mm/year) (95% CI)	Significance[a]	Percent annual growth (95% CI)	Significance[a]
Luminal diameter (mm)	42.9 (41.9–43.9)	43.4 (42.4–44.4)	0.11 (0.03–0.2)	**0.006**	0.2 (0.007–0.4)	$P = 0.95$
Length (mm)	118.2 (115.4–121.1)	120.2 (117.3–123.0)	0.38 (0.11–0.65)	**0.006**	0.3 (0.09–0.5)	

[a]Values with $P < 0.05$ are bolded.
CI: confidence interval.

separate men and women with regards to both diameter and length measurements to more accurately reflect risks of adverse outcomes, since women have been shown to have worse outcomes with surgery than men despite similarly sized aneurysms [23, 24].

Our diameter growth rate (0.1 mm/year) in nonsyndromic patients was similar to that observed in longitudinal studies of both healthy adults and aneurysm patients (0.1–0.2 mm/year) [25–28], and our mean annual elongation rate of 0.4 mm/year in this population was comparable to the expected 0.6 mm/year and 0.3%/year elongation rate reported by Redheuil *et al.* [29] in a population of healthy subjects. However, a subgroup of patients experienced clinically significant (i.e. >5%) elongation at a mean rate of 2.0 mm/year, which is similar to the 1.8-mm/year rate reported by Wu *et al.* [13] in a higher-risk aneurysm population, despite having a lower mean baseline length than our overall study population. Thus, further work is needed to identify whether a greater rate of elongation is associated with a higher risk of ATAD or adverse aortic events, rather than a higher baseline length alone. If so, this may explain why patients with aortic diameters smaller than surgical guidelines continue to experience ATAD events.

In contrast to the diameter growth rate, which has been shown to differ between bicuspid and tricuspid aortic valve patients, aortic elongation was stable between the 2 groups, though the small numbers of bicuspid patients require larger sample size and further study. Additionally, patients with smaller baseline aortic diameters often experienced greater aortic elongation, suggesting that further work is needed to understand the aetiology of rapid aortic elongation as those risk factors may differ from risk factors for circumferential aortic dilatation [7, 8].

Lastly, a subgroup of patients included in our study experienced spontaneous regression of aortic length and/or diameter. This finding is actually consistent with that of a prior study of nonsyndromic aTAAs by Adriaans *et al.* demonstrating no or negative growth in 40.6% of patients. To mitigate measurement error as well as bias, a single board-certified radiologist specialized in aneurysm assessment and vascular disease who was blinded to the study patient performed diameter measurements to reduce interobserver error. Length measurements were performed in a standardized fashion using a computerized program. There are 2 likely explanations for this decrease in size, both reflecting the high rates of anti-hypertensive medication use and blood pressure control within our patient population. Prior murine models of Marfan's syndrome and abdominal aortic aneurysms have demonstrated reduction in diameter and growth rate with angiotensin II receptor blocker or beta-blocker use, although clinical trials in humans have had more mixed results [30–33]. Use of these medications may have in select patients resulted in aneurysm size reduction. Second, blood pressure was not necessarily the same at the various time points of the scans, and the scans were not required to be electrocardiogram (ECG)-gated. It is well known in transcatheter aortic valve replacement (TAVR) that size measurements in systole are larger than in diastole, which directly reflects the blood pressure. Some patients who may have initially had uncontrolled hypertension may experience reduction in aneurysm size by tight control of blood pressure at subsequent scans. Lastly, we have previously demonstrated that aTAAs had similar circumferential and longitudinal stiffness and lower longitudinal than circumferential stresses [34, 35]. While no studies to date have used aortic length as an end point, controlling hypertension could decrease length longitudinally in select patients with stable aneurysm diameter but significant blood pressure reduction.

Ultimately, our results demonstrate slow growth rates in both aortic length and diameter over time in a high-risk population for aortic dissection utilizing a novel measurement technique. If corroborated by future studies, this information may have a wide-ranging impact on how we approach aortic surveillance in nonsyndromic patients. Currently, European Society of Cardiology guidelines recommend regular CT imaging of aTAAs at intervals of 6 months to 1 year [4]. However, our data add to prior literature demonstrating stability or regression in a large percentage of patients, with rapid growth in a small subset that is not yet well characterized [28]. This suggests that current trials in development by our group and others to randomize overall populations of aTAA patients to longer surveillance intervals may actually prove more cost-effective and reduce healthcare burden, while not significantly increasing the risk of missing important physiologic changes to aortic dimensions.

Limitations

First, it is important to note that this is a retrospective study that is limited in sample size due to difficulty in obtaining longitudinal CTA imaging, since contrasted CT and particularly ECG-gating were popularized only after TAVR approval by the US Food and Drug Administration in 2011, and thus a minority of patients reached a 5-year timepoint (27%). Additionally, the patient population treated at our centre is primarily male, with a high prevalence of aTAA risk factors. Thus, it is possible that the aortic dynamics described here do not reflect the broader population of aTAA patients, limiting the generalizability of our results, particularly to women, and highlighting a need for broader, larger-scale subject recruitment. This study followed a nonsurgical population without adverse aortic events, and so evaluation of the relationship of aortic elongation to ATAD risk was outside the

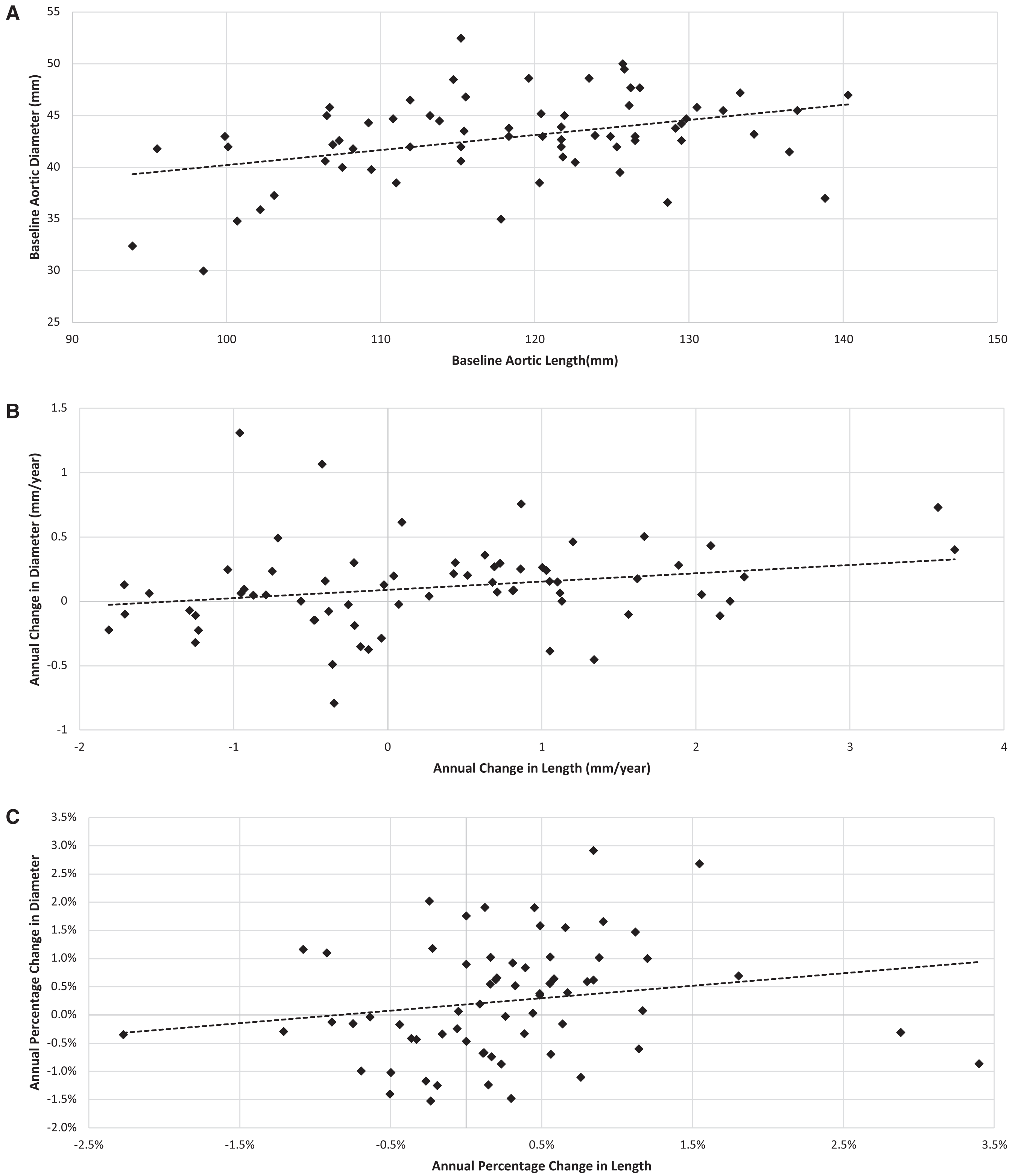


Figure 3: Correlations between baseline aortic length and diameter and between length and diameter annual growth.

scope of this study. Lastly, overall growth in 5 years was modest, as the duration of retrospective inclusion was in part limited by the availability of ECG-gated contrast imaging prior to the implementation of TAVR in 2013 within our healthcare system. Thus, while our results further support the dynamic nature of aortic length in a high-risk population, even in the setting of diameter stability, further prospective studies, possibly over longer time periods, are needed to identify risk factors for aortic growth and better interpret its contribution towards aortic dissection.

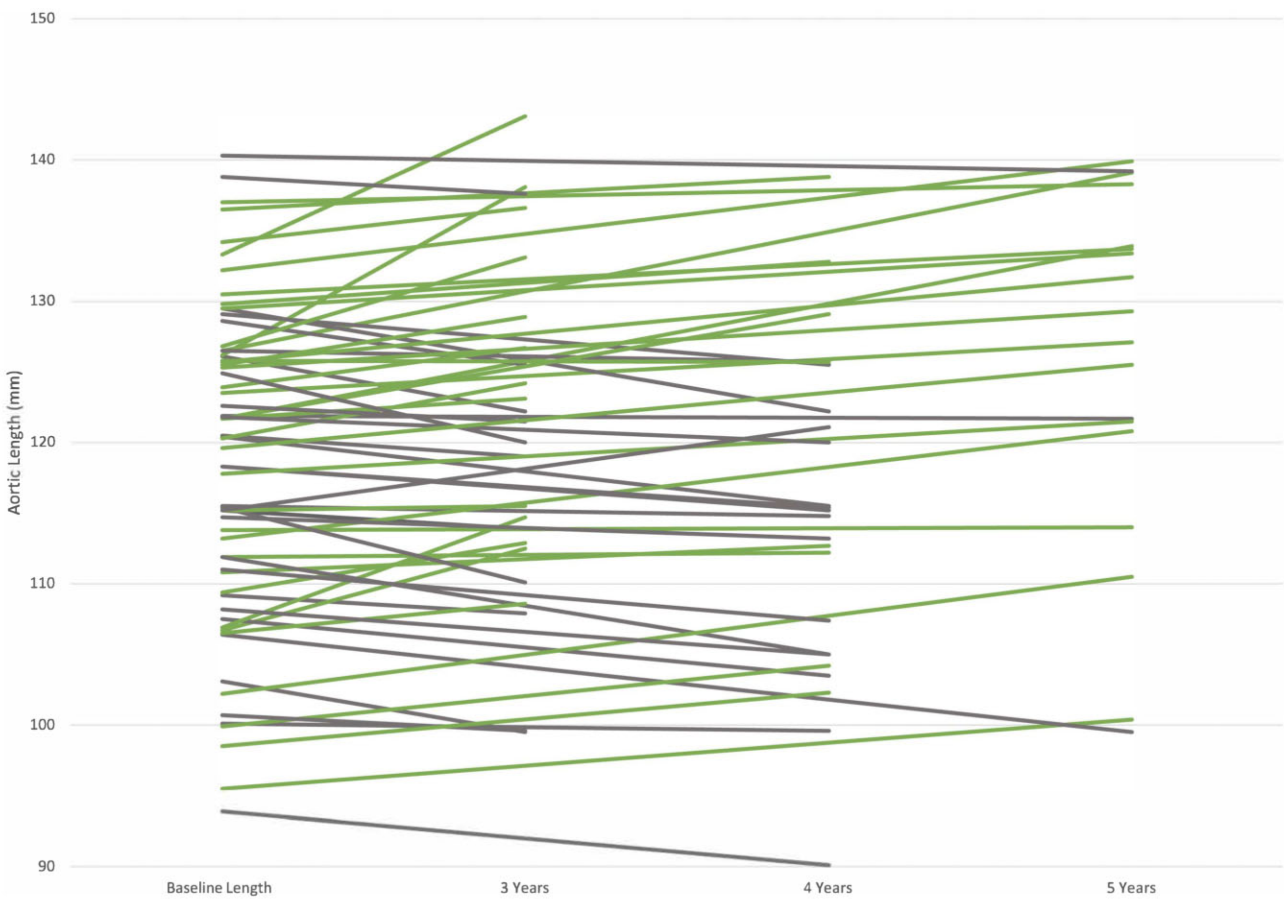


Figure 4: Aortic length at baseline and follow-up time points. Patients with elongation are depicted in green and patients with length decrease are depicted in grey.

Table 3: Association of risk factors with length growth rate on univariate analysis

Independent variable	Coefficient (95% confidence interval)	Significance[a]
Age	-0.01 (-0.05 to 0.03)	0.69
BMI	0.04 (-0.02 to 0.09)	0.19
BSA	0.98 (0.01 to 1.96)	**0.05**
Smoking	-0.16 (-0.61 to 0.30)	0.49
Diabetes mellitus	0.73 (-0.06 to 1.52)	0.07
Hypertension	-0.03 (-0.70 to 0.63)	0.92
ACE inhibitor or ARB use	-0.09 (-0.72 to 0.54)	0.78
Beta blocker use	0.06 (-0.56 to 0.69)	0.84
Hyperlipidaemia	-0.23 (-0.91 to 0.44)	0.49
Valve type	-0.24 (-1.38 to 0.90)	0.68
Aortic stenosis	-0.32 (-1.70 to 1.07)	0.65
Aortic regurgitation	0.10 (-0.20 to 0.41)	0.51
Baseline diameter	0.05 (-0.02 to 0.13)	0.13
Diameter growth rate	0.82 (-0.04 to 1.68)	0.06
Baseline length	0.01 (-0.14 to 0.05)	0.33

[a]Values with $P < 0.05$ are bolded.

ACE: angiotensin converting enzyme; ARB: angiotensin receptor blocker; BMI: body mass index; BSA: body surface area.

CONCLUSION

Aortic length shows promise in providing additional information regarding aortic dissection risk. However, we found that in this population with multiple aneurysm risk factors, aortic length was slightly higher than previously described likely due to the preponderance of men in the study population, although elongation rate was lower. Further large-scale prospective studies are needed to characterize growth rate in the larger civilian population, in men vs. women, and to identify factors associated with aTAA elongation.

Funding

This work was supported by the National Institutes of Health [R01HL119857-01A1 (Tseng/Ge), K25HL150408 (Xuan)]; Veterans Affairs Merit [I01CX002365-01A1 (Tseng/Ge)]; American Heart Association [20POST35211107 (Wang)]; American Association for Thoracic Surgery [Summer Intern Fellowship (Zamirpour)]; and University of California San Francisco [Summer Explore Fellowship (Gulati/Zamirpour)].

Conflict of interest: The authors have no conflicts of interest to disclose.

DATA AVAILABILITY

Data underlying this article cannot be shared publicly for the privacy of individuals that participated in the study. De-identified data will be shared on reasonable request to the corresponding author.

Author contributions

Arushi Gulati: Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Writing—original draft; Writing—review & editing. **Siavash Zamirpour:** Data curation; Formal analysis; Investigation; Writing—review & editing. **Joseph Leach:** Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Resources; Validation; Visualization; Writing—original draft. **Amir Khan:** Data curation; Formal analysis; Investigation; Methodology; Project administration; Software; Validation; Visualization; Writing—original draft; Writing—review & editing. **Zhongjie Wang:** Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Software; Validation; Visualization; Writing—original draft. **Yue Xuan:** Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Software; Validation; Visualization. **Michael D. Hope:** Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Supervision; Validation. **David A. Saloner:** Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Supervision; Validation. **Julius M. Guccione:** Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Supervision. **Liang Ge:** Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Writing—review & editing. **Elaine E. Tseng:** Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing—review & editing.

Reviewer information

European Journal of Cardio-Thoracic Surgery thanks John Elefteriades, Tobias Krüger, Gabriele Piffaretti and the other, anonymous reviewer(s) for their contribution to the peer review process of this article.

REFERENCES

[1] Wundram M, Falk V, Eulert-Grehn JJ, Herbst H, Thurau J, Leidel BA *et al.* Incidence of acute type A aortic dissection in emergency departments. Sci Rep 2020;10:7434.

[2] McClure RS, Brogly SB, Lajkosz K, Payne D, Hall SF, Johnson AP. Epidemiology and management of thoracic aortic dissections and thoracic aortic aneurysms in Ontario, Canada: a population-based study. J Thorac Cardiovasc Surg 2018;155:2254–64.e4.

[3] Pape LA, Tsai TT, Isselbacher EM, Oh JK, O'gara PT, Evangelista A *et al.*; International Registry of Acute Aortic Dissection (IRAD) Investigators. aortic diameter ≥5.5 cm is not a good predictor of type A aortic dissection. Circulation 2007;116:1120–7.

[4] Erbel R, Aboyans V, Boileau C, Bossone E, Di Bartolomeo R, Eggebrecht H *et al.* 2014 ESC Guidelines on the diagnosis and treatment of aortic diseases: document covering acute and chronic aortic diseases of the thoracic and abdominal aorta of the adult. The Task Force for the Diagnosis and Treatment of Aortic Diseases of the European Society of Cardiology (ESC). Eur Heart J 2014;35:2873–926.

[5] Hiratzka LF, Bakris GL, Beckman JA, Bersin RM, Carr VF, Casey DE Jr *et al.* 2010 ACCF/AHA/AATS/ACR/ASA/SCA/SCAI/SIR/STS/SVM guidelines for the diagnosis and management of patients with Thoracic Aortic Disease: a report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines, American Association for Thoracic Surgery, American College of Radiology, American Stroke Association, Society of Cardiovascular Anesthesiologists, Society for Cardiovascular Angiography and Interventions, Society of Interventional Radiology, Society of Thoracic Surgeons, and Society for Vascular Medicine. Circulation 2010;121: e266–369.

[6] Coady MA, Rizzo JA, Hammond GL, Mandapati D, Darr U, Kopf GS *et al.* What is the appropriate size criterion for resection of thoracic aortic aneurysms? J Thorac Cardiovasc Surg 1997;113:476–91.

[7] Gagné-Loranger M, Dumont É, Voisine P, Mohammadi S, Dagenais F. Natural history of 40-50 mm root/ascending aortic aneurysms in the current era of dedicated thoracic aortic clinics. Eur J Cardiothorac Surg 2016;50:562–6.

[8] Gulati A, Leach J, Wang Z, Xuan Y, Hope MD, Saloner DA *et al.* Ascending thoracic aortic aneurysm growth is minimal at sizes that do not meet criteria for surgical repair. Quant Imaging Med Surg 2022;12: 333–40.

[9] Heuts S, Adriaans BP, Gerretsen S, Natour E, Vos R, Cheriex EC *et al.* Aortic elongation part II: the risk of acute type A aortic dissection. Heart 2018;104:1778–82.

[10] Heuts S, Adriaans BP, Rylski B, Mihl C, Bekkers SCAM, Olsthoorn JR *et al.* Evaluating the diagnostic accuracy of maximal aortic diameter, length and volume for prediction of aortic dissection. Heart 2020;106:892–7.

[11] Krüger T, Forkavets O, Veseli K, Lausberg H, Vohringer L, Schneider W et al Ascending aortic elongation and the risk of dissection. Eur J Cardiothorac Surg 2016;50:241–7.

[12] Krüger T, Boburg RS, Hamdoun H, Oikonomou A, Bongers MN, Schlensak C. Development of a multivariable prediction model for patient-adjusted aortic risk morphology. Eur J Cardiothorac Surg 2020; 58:692–9.

[13] Wu J, Zafar MA, Li Y, Saeyeldin A, Huang Y, Zhao R *et al.* Ascending aortic length and risk of aortic adverse events: the neglected dimension. J Am Coll Cardiol 2019;74:1883–94.

[14] von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP; STROBE Initiative. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. J Clin Epidemiol 2008;61:344–9.

[15] Mendoza DD, Kochar M, Devereux RB, Basson CT, Kim JK, Holmes K et al; GenTAC (National Registry of Genetically Triggered Thoracic Aortic Aneurysms and Cardiovascular Conditions) Study Investigators. Impact of image analysis methodology on diagnostic and surgical classification of patients with thoracic aortic aneurysms. Ann Thorac Surg 2011;92: 904–12.

[16] Du Bois D, Du Bois EF. A formula to estimate the approximate surface area if height and weight be known. 1916. Nutrition 1989;5:303–11.

[17] Kim EK, Choi SH, Sung K, Kim WS, Choe YH, Oh JK *et al.* Aortic diameter predicts acute type A aortic dissection in patients with Marfan syndrome but not in patients without Marfan syndrome. J Thorac Cardiovasc Surg 2014;147:1505–10.

[18] Krüger T, Sandoval Boburg R, Lescan M, Oikonomou A, Schneider W, Vohringer L *et al.* Aortic elongation in aortic aneurysm and dissection: the Tübingen Aortic Pathoanatomy (TAIPAN) project. Eur J Cardiothorac Surg 2018;54:26–33.

[19] Sun L, Li X, Wang G, Sun J, Zhang X, Chi H *et al.* Relationship between length and curvature of ascending aorta and type A dissection. Front Cardiovasc Med 2022 ;9:927105.

[20] Saade W, Vinciguerra M, Romiti S, Macrina F, Frati G, Miraldi F *et al.* 3D morphometric analysis of ascending aorta as an adjunctive tool to predict type A acute aortic dissection. J Thorac Dis 2021;13:3443–57.

[21] Eliathamby D, Gutierrez M, Liu A, Ouzounian M, Forbes TL, Tan KT *et al.* Ascending aortic length and its association with type A aortic dissection. J Am Heart Assoc 2021;10:e020140.

[22] Della Corte A, Rubino AS, Montella AP, Bancone C, Lo Presti F, Galbiati D *et al.* Implications of abnormal ascending aorta geometry for risk prediction of acute type A aortic dissection. Eur J Cardiothorac Surg 2021; 60:978–86.

[23] Gasser S, Stastny L, Kofler M, Krapf C, Bonaros N, Grimm M *et al.* Type A aortic dissection is more aggressive in women. Eur J Cardiothorac Surg 2022;62:ezac040.

[24] Flink BJ, Long CA, Duwayri Y, Brewster LP, Veeraswamy R, Gallagher K et al Women undergoing aortic surgery are at higher risk for unplanned readmissions compared with men especially when discharged home. J Vasc Surg 2016;63:1496–504.e1.

[25] Chang HW, Kim SH, Hakim AR, Chung S, Kim DJ, Lee JH *et al.* Diameter and growth rate of the thoracic aorta-analysis based on serial computed tomography scans. J Thorac Dis 2020;12:4002–13.

[26] Kälsch H, Lehmann N, Möhlenkamp S, Becker A, Moebus S, Schmermund A *et al.* Body-surface adjusted aortic reference diameters for improved identification of patients with thoracic aortic aneurysms:

results from the population-based Heinz Nixdorf Recall study. Int J Cardiol 2013;163:72–8.

[27] Kauhanen P, Korpela T, Hedman M. Dilatation of the ascending aorta - Growth rate, risk factors and clinical outcomes in the long-term follow-up. Eur J Radiol 2022;150:110234.

[28] Adriaans BP, Ramaekers MJFG, Heuts S, Crijns HJGM, Bekkers SCAM, Westenberg JJM *et al.* Determining the optimal interval for imaging surveillance of ascending aortic aneurysms. Neth Heart J 2021;29:623–31.

[29] Redheuil A, Yu WC, Mousseaux E, Harouni AA, Kachenoura N, Wu CO et al Age-related changes in aortic arch geometry: relationship with proximal aortic function and left ventricular mass and remodeling. J Am Coll Cardiol 2011;58:1262–70.

[30] Park SM, Hong M-K, Kim SH, Jung S, Kim BK, Choi D. Comparison of efficacy between ramipril and carvedilol on limiting the expansion of abdominal aortic aneurysm in mouse model. J Cardiovasc Pharmacol Ther 2019;24:172–81.

[31] Verbrugghe P, Verhoeven J, Clijsters M, Vervoort D, Schepens J, Meuris B *et al.* The effect of a nonpeptide angiotensin II type 2 receptor agonist, compound 21, on aortic aneurysm growth in a mouse model of Marfan syndrome. J Cardiovasc Pharmacol 2018;71:215–22.

[32] McGee K, Bollache E, Barker AJ, Carr JC, Markl M, Kansal P *et al.* Impact of beta-blocker, ACE inhibitor, and ARB therapy on thoracic aorta wall shear stress in bicuspid aortic valve patients. J Cardiovasc Magn Reson 2016;18:345.

[33] Bicknell CD, Kiru G, Falaschetti E, Powell JT, Poulter NR; AARDVARK Collaborators. An evaluation of the effect of an angiotensin-converting enzyme inhibitor on the growth rate of small abdominal aortic aneurysms: a randomized placebo-controlled trial (AARDVARK). Eur Heart J 2016;37:3213–21.

[34] Azadani AN, Chitsaz S, Mannion A, Mookhoek A, Wisneski A, Guccione JM *et al.* Biomechanical properties of human ascending thoracic aortic aneurysms. Ann Thorac Surg 2013;96:50–8.

[35] Gomez A, Wang Z, Xuan Y, Hope MD, Saloner DA, Guccione JM *et al.* Association of diameter and wall stresses of tricuspid aortic valve ascending thoracic aortic aneurysms. J Thorac Cardiovasc Surg 2022;164:1365–75.