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QUANTITATIVE MRI MEASURES OF 3D AORTIC MORPHOLOGY IN HEALTHY AGING AND HYPERTENSION

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests

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Authors' contributions

AR, NK and TD designed the study. AGa, AR, EM, GS, NP and SB carried out the data acquisition. SHGS, TD and UG carried out the experiments. AGi, AR, NK and TD interpreted the results. NK and TD drafted the manuscript. All authors edited and revised the manuscript. All authors read and approved the final manuscript.

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Running title

3D aortic morphology from MRI in healthy aging and hypertension

Quantitative MRI measures of 3D aortic morphology in healthy aging and hypertension

ABSTRACT

Background: Automated segmentation of 3D aortic MRI renders possible a retrospective selection of any location to perform quantification of aortic caliber perpendicular to its centerline and provides regional and global 3D biomarkers such as length, diameter or volume. However, normative age-related values of such measures are still lacking.

Purpose: To provide normal values for 3D aortic morphological measures and investigate their changes in aging and hypertension.

Study type: Retrospective

Population: 119 healthy controls (HC:48±14years, 61 men) and 82 hypertensive patients (HT:60±14years, 43 men).

Field strength/Sequence: 1.5 and 3T / 3D SSFP or SPGR

Assessment: Automated 3D aortic segmentation provided aortic length, diameter, volume for the ascending (AAo) and descending aorta (DAo), along with cross-sectional diameters at 3 aortic landmarks.

Age, sex, body surface area (BSA), smoking and blood pressures were recorded. Both groups were divided into 2 subgroups (≤ 50 years, > 50 years).

Statistical Tests: Linear regression for age-related normal values and confidence intervals, Wilcoxon rank sum test for differences between groups (HC or HT), Multivariate analysis to identify main determinants of aortic morphological changes.

Results: In HC, linear regression revealed an increase in the AAo(respectively DAo) length by 2.84mm(7.78mm), maximal diameter by 1.36mm(1.29mm) and volume by 4.28mL(8.71mL) per decade. AAo morphological measures were higher in HT patients

than HC both ≤ 50 years but did not reach statistical significance (length:+2mm, $p=0.531$; diameter:+1.4mm $p=0.2936$; volume:+6.8mL $p=0.1857$). However, length (+6mm, $p=0.003$), maximal diameter (+4mm, $p<0.001$) and volume (+12mL, $p<0.001$) were significantly higher in HT patients than HC, both >50 years. In a multivariate analysis, age, sex and BSA were the major determinants of aortic morphology, irrespective of the presence of hypertension.

Data Conclusion: Global and segmental aortic length, volume and diameters at specific landmarks were automatically measured from 3D MRI to serve as normative measures of 3D aortic morphology. Such indices increased significantly with age and hypertension among the elderly subjects.

KEYWORDS

MRI, aorta, normal values, 3D morphology

INTRODUCTION

One of the critical features of aortic syndromes is their silent progression until a potentially lethal complication occurs (1, 2). Imaging, providing comprehensive coverage and high-resolution evaluation of the aorta, plays a central role in aortic disease detection, follow-up and prognostic evaluation.

Three-dimensional renderings of CT and MRI aortic angiograms are commonly used in clinical routine to identify aortic (coarctation, aneurysms, etc.) and aortic valve (regurgitation, stenosis, bicuspid aortic valve, etc.) abnormalities. Despite outstanding 3D visualization, quantitative measures for clinical decisions have been limited to local measurements of diameters at specific locations (3, 4). Aortic dilation in healthy aging (5, 6), in the general population (7–9) or in specific disease conditions (10–16) has been reported and aortic elongation has also been studied in both CT (9, 14, 17–19) and MRI (7, 20) using such manual or semi-automated methods.

Furthermore, technical advances have been made allowing for automated 3D aortic segmentation and extraction of aortic length or diameters at specific locations from CT (21, 22) and MR (23, 24) images. Automated 3D segmentation has two main advantages: first, it avoids errors due to the potential obliquity of imaging planes when measuring diameters, since cross-sections can be automatically placed perpendicular to the centerline at any desired location within the 3D segmented aorta; second, it is able to provide additional morphological indices, such as volume which combines both diameter and length information, and thus might be more sensitive to subtle changes in aortic morphology.

Three-dimensional aortic MRI is ionizing radiation free and has the potential to be the imaging modality of choice for patients requiring multiple scans for follow-up. While reference 2D measures of aortic morphology have been summarized by Kawel-Boehm et al. (25), there is a lack of normative values of segmental aortic lengths and volumes

as measured by 3D MRI. Accordingly, 3D morphological indices of the thoracic aorta, including maximal diameter, volume, length, curvature and tortuosity were extracted from MR images (24) to: 1/ provide age-related normal values and 95% confidence interval of these indices, 2/ describe morphological changes in healthy aging and in hypertension, as the two main drivers of aortic remodeling, and 3/ identify the main determinants of aortic morphological changes.

MATERIALS AND METHODS

MRI data used in this study are part of local protocols including healthy volunteers and hypertensive subjects, with a focus on associations either between aortic stiffness and microvascular remodeling or on the non-invasive evaluation by ultrafast echo of myocardial stiffness as compared to MRI. Accordingly, the present ancillary work objectives are independent from the primary goals of these protocols.

All participants gave their written informed consent for the initial protocol and ancillary use of their data. The study protocol was approved by the local ethics committee.

Study Population

We retrospectively evaluated 201 individuals: 119 healthy controls (HCs; mean age: 48 ± 14 years, 61 men) and 82 patients with essential hypertension (HT; 60 ± 14 years, 43 men). Age, sex, height, weight, body surface area (BSA), body-mass index (BMI) and current smoking were collected prior to the MRI exam. Inclusion criteria for hypertensives were: absence of secondary causes of hypertension, absence of personal history of cardiovascular disease and stable regimen of antihypertensive treatment. Patients with diabetes were not included. Healthy controls were asymptomatic and free of overt cardiovascular disease defined as a clinical history of hypertension, diabetes mellitus, dyslipidemia, renal disease, known inflammatory conditions and malignancy. The median age of our population was 52 years; thus, a cut-off of 50 years was used to divide both groups into 2 subgroups (≤ 50 years, > 50 years) to study the effect of age. All subjects underwent a cardiac MRI exam at either 3T (site 1, $n = 61$: Discovery MR750w, GE Healthcare, Chicago; site 2, $n = 31$: Prisma, Siemens Healthineers, Erlangen) or 1.5T ($n = 109$, site 3: Aera, Siemens Healthineers, Erlangen). For sites 1 and 3, gadolinium-based contrast agent was typically injected (0.1 to 0.2 mmol/kg) during aortic acquisitions. 3D data were acquired during free breathing with electrocardiographic (diastasis) and respiratory (expiration) gating in a sagittal oblique

volume encompassing the thoracic aorta with the following typical scan parameters: (site 1) spoiled gradient echo (SPGR), voxel size = $0.67 \times 0.67 \times 3.19 \text{ mm}^3$, echo time = 1.3ms, repetition time = 3.1ms and flip angle = 24° ; (site 2) steady state free precession (SSFP), voxel size = $0.98 \times 0.98 \times 1 \text{ mm}^3$, echo time = 1.3ms, repetition time = 311ms and flip angle = 19° ; and (site 3) SSFP, voxel size = $0.66 \times 0.66 \times 1.13 \text{ mm}^3$, echo time = 1.5ms, repetition time = 283ms and flip angle = 90° .

Central blood pressures were recorded using the SphygmoCor Xcel device (AtCor Medical, Sydney) simultaneous to MRI aortic acquisitions at all sites. Three measurements were recorded during the MRI exam and their average provided central systolic (SBP) and diastolic (DBP) blood pressure as well as pulse pressure (PP), calculated as the difference between SBP and DBP.

Assessment of Aortic Morphology

The aorta was segmented using a previously described custom software (Mimosa, Sorbonne Université) (24). Briefly, six anatomical landmarks were manually placed by an experienced operator (5 years) from the sino-tubular junction to the diaphragm and used to automatically initialize the aortic centerline and delimit aortic segments. The aortic lumen was then segmented using a 3D active contour (26) and a final centerline was calculated. The segmented aorta was automatically divided into 3 segments using the given landmarks (Fig.1) according to the European Society of Cardiology guidelines (27): the ascending aorta, defined as the segment between the sino-tubular junction and the brachiocephalic trunk, the aortic arch, defined as the segment comprising the supra-aortic trunks and the descending thoracic aorta, defined as the segment between the left subclavian artery and the diaphragm.

For each aortic segment, 5 morphological indices were automatically extracted: the centerline length, the maximal diameter, the volume, the total curvature (28, 29) and the tortuosity. Tortuosity was computed as $\frac{L_s - L_d}{L_d}$, where L_s is the true segment length

along the centerline and L_d is the direct length between the segment ends. Total

curvature was defined as $\frac{1}{L_s} \int_0^{L_s} \frac{\|\dot{s} \wedge \ddot{s}\|}{\|\dot{s}\|^3} dS$ where \dot{s} and \ddot{s} are the first and second

derivatives of s , the 3D coordinates of the centerline, respectively. Total curvature was normalized by L_s to account for segment length (29).

In-plane diameters were measured at 3 specific locations (ascending aorta at the pulmonary artery level, proximal descending aorta at the pulmonary artery level and distal descending aorta at the diaphragm) to enable comparison with values commonly provided in the literature (4).

A standard computer (Intel Xeon Silver 4110 CPU, 2.1GHz and 32Go RAM) was used for the data analysis.

Statistical Analysis

All measurements were provided as median and interquartile range (IQR) as some measurement distributions were not normally distributed according to a Shapiro-Wilk normality test. To highlight effects of age and hypertension, while minimizing their confounding effect when necessary, non-parametric Wilcoxon tests were performed for continuous subjects characteristics as well as for all MRI quantitative parameters 1) between $HC_{\leq 50}$ and $HC_{>50}$ to characterize the effect of aging on thoracic aorta, and 2) between the two groups of hypertensive patients (≤ 50 and > 50 years) and the corresponding healthy control groups (≤ 50 and > 50 years, respectively) to characterize the effect of hypertension. Allometric indices such as aortic length, maximal diameter and volume were indexed to BSA to account for the effect of body size. Of note, since total curvature and tortuosity were already normalized by aortic segments length, these indices were not indexed to BSA.

Linear regression and Spearman correlation coefficients between aortic measurements of the HC population and age were calculated and age-related normal values were

considered as measurements within the 95% confidence interval for the individual response which was computed as

$$CI_{95\%}(x) = -1.65 \sigma_y \sqrt{1 + \frac{1}{n} + \frac{(x - \bar{x})^2}{(n-1)\sigma_x^2}}$$

where σ_y is the standard deviation of the prediction error and \bar{x} and σ_x are respectively the mean and standard deviation of x . In this equation, x represents age. Changes per decade correspond to 10 times the slope of the linear regression and are provided to enable comparison with values provided in the literature. The relationship of aortic morphology with age, sex, BSA, hypertension, current smoking and central SBP was studied using a multivariate regression model. A p value < 0.05 was considered as significant.

RESULTS

The whole 3D segmentation process, including data loading and results recording, took less than 5 minutes per subject. Figure 2 shows examples within each group of segmented aortas of male subjects with similar height and BSA in order to illustrate aortic morphological changes in aging and hypertension. Supplementary Figure 1 illustrates examples of aortic images obtained from the 3 acquisition sites and scanners.

Patient Characteristics

Patient characteristics, blood pressures and specific landmarks in plane aortic diameters are summarized in Table 1 for each group: healthy controls ($HC_{\leq 50}$ and $HC_{>50}$) as well as hypertensives ($HT_{\leq 50}$ and $HT_{>50}$). Central SBP and PP were significantly higher in the hypertensive groups compared to their age equivalent controls (SBP: $HT_{\leq 50}$ (127mmHg) vs $HC_{\leq 50}$ (109mmHg), $p < 0.0001$; $HT_{>50}$ (126mmHg) vs $HC_{>50}$ (116mmHg), $p < 0.0001$; PP: $HT_{\leq 50}$ (35mmHg) vs $HC_{\leq 50}$ (31mmHg), $p = 0.0005$; $HT_{>50}$ (44 mmHg) vs $HC_{>50}$ (36mmHg), $p = 0.0006$) and in the older healthy individuals compared to younger healthy controls (SBP: $HC_{>50}$ vs $HC_{\leq 50}$, $p = 0.01$; PP: $HC_{>50}$ vs $HC_{\leq 50}$, $p < 0.0001$). $HT_{\leq 50}$ patients also had a significantly higher central DBP ($p < 0.0001$) and BMI ($p = 0.0061$), as compared to $HC_{\leq 50}$. A significant difference in age ($p=0.0012$) was also observed in $HT_{>50}$ patients (median age: 66 years) as compared to $HC_{>50}$ (median age: 60 years).

Morphological Changes in Aging & Normal Values

Table 1 shows the median and IQR for the cross-sectional aortic diameters measured at three specific landmarks (ascending aorta, proximal and distal descending aorta). The diameters were significantly higher in $HC_{>50}$ than in $HC_{\leq 50}$ (ascending aorta: +2.4mm, $p = 0.0019$; proximal descending aorta: +2.3mm, $p < 0.0001$; and distal descending aorta: +2.5mm, $p < 0.0001$). These increases remained significant after diameters

indexation to BSA (ascending aorta: $+1.8\text{mm}\cdot\text{m}^{-2}$, $p < 0.0001$; proximal descending aorta: $+2.1\text{mm}\cdot\text{m}^{-2}$, $p < 0.0001$; and distal descending aorta: $+1.8\text{mm}\cdot\text{m}^{-2}$, $p < 0.0001$). Quantitative 3D-derived measurements in the thoracic aorta (TAo), ascending aorta (AAo), aortic arch (Arch) and descending aorta (DAo) are provided in Table 2 and illustrated in Figure 3 as well as Supplementary Figure 2 for BSA-indexed measures. A significant increase in aortic length (thoracic aorta: $+21.3\text{mm}$, $p < 0.0001$; ascending aorta: $+4.3\text{mm}$, $p = 0.0041$; aortic arch: $+3.2\text{mm}$, $p = 0.0069$; and descending aorta: $+15.1\text{mm}$, $p < 0.0001$) and maximal diameter (thoracic aorta: $+2.7\text{mm}$, $p = 0.0009$; ascending aorta: $+2.7\text{mm}$, $p = 0.001$; aortic arch: $+2.7\text{mm}$, $p = 0.0002$; and descending aorta: $+2.4\text{mm}$, $p < 0.0001$) was observed in $\text{HC}_{>50}$ individuals as compared to $\text{HC}_{\leq 50}$, independently of the considered aortic segment. A significant increase in volume was also observed in all aortic segments between the two age groups (TAo: $+29.7\text{mL}$, $p < 0.0001$; AAo: $+8.2\text{mL}$, $p = 0.0004$; Arch: $+5.6\text{mL}$, $p < 0.0001$; and DAo: $+16.5\text{mL}$, $p < 0.0001$). Significant decreases in AAo (-0.0032mm^{-1} , $p = 0.0024$) and Arch (-0.0096mm^{-1} , $p < 0.0001$) curvatures between the two age groups were observed, while DAo curvature increased ($+0.0018\text{mm}^{-1}$, $p = 0.0011$), and TAo curvature was unchanged ($+9.0 \cdot 10^{-4}\text{mm}^{-1}$, $p = 0.1382$). Significant changes in tortuosity between the two age groups ($\text{HC}_{>50}$ vs $\text{HC}_{\leq 50}$) were also observed in the Arch (-0.025 , $p < 0.0001$), DAo ($+0.068$, $p < 0.0001$) and TAo ($+0.39$, $p < 0.0001$). After indexation to BSA (Supplementary Table 1), all the above changes remained significant ($p < 0.05$).

Linear regressions between all MRI aortic measurements and age were summarized in Table 3 revealing significant ($p < 0.0001$) age-related associations for all indices except for TAo curvature ($p = 0.283$) and AAo tortuosity ($p = 0.389$). Associations between age and volume (TAo: $\rho = 0.605$; AAo: $\rho = 0.526$; Arch: $\rho = 0.536$; DAo: $\rho = 0.602$) were stronger than those with maximal diameter (TAo: $\rho = 0.485$; AAo: $\rho = 0.478$; Arch: $\rho = 0.528$; DAo: $\rho = 0.571$) or length (TAo: $\rho = 0.542$; AAo: $\rho = 0.431$; Arch: ρ

= 0.335; DAo: $\rho = 0.462$) in all aortic regions. The slopes of the linear regression summarized in Table 3 revealed an increase per decade in aortic length (TAo: +12.4mm/decade; AAo: +2.8mm/decade; Arch: +1.7mm/decade; DAo: +7.8mm/decade), maximal diameter (TAo: +1.4mm/decade; AAo: +1.4mm/decade; Arch: +1.4mm/decade; DAo: +1.3mm/decade) and volume (TAo: +15.6mL/decade; AAo: +4.3mL/decade; Arch: +2.6mL/decade; DAo: +8.7mL/decade).

Linear regressions with age for the aortic measures including length, maximal diameter, volume, total curvature and tortuosity are illustrated in Figure 4 for the AAo and DAo, along with 95% confidence intervals highlighting normal ranges. Linear regression corresponding to BSA-indexed indices are illustrated in Supplementary Figure 3.

Morphological Changes in Hypertension

Aortic morphological indices for hypertensive patients ($HT_{\leq 50}$ and $HT_{>50}$) are also provided in Tables 1 and 2. No significant difference in cross-sectional diameters was found at the three anatomical landmarks between $HT_{\leq 50}$ and $HC_{\leq 50}$. DAo was found to be significantly shorter (-10.9mm, $p = 0.0117$), more tortuous (+0.035, $p = 0.0057$) and to have a significantly higher curvature (+0.0012 mm^{-1} , $p = 0.0153$) in $HT_{\leq 50}$ as compared to $HC_{\leq 50}$. TAO curvature was also significantly higher in $HT_{\leq 50}$ compared to $HC_{\leq 50}$ (+0.0018 mm^{-1} , $p = 0.0226$).

A significant increase in cross-sectional diameter was found at the three locations between $HT_{>50}$ and $HC_{>50}$. Length, maximal diameter and volume were significantly higher in $HT_{>50}$ as compared to $HC_{>50}$ for AAo (length: +4.2mm, $p = 0.0033$; diameter: +2.8mm, $p = 0.0002$; volume: +10.5mL, $p = 0.0002$) and Arch (length: +3.5mm, $p = 0.0141$; diameter: +2.1mm, $p = 0.0009$; volume: +3.4mL, $p = 0.0061$). DAo length was significantly lower in $HT_{>50}$ as compared to $HC_{>50}$ (-5.7mm, $p = 0.0199$), while DAo maximal diameter was significantly higher (+2.8mm, $p = 0.0060$).

Relationship Between Aortic Morphology and Clinical Features

In multivariate analysis (Table 4) on the entire study population, age was found to be the main determinant of all aortic morphological indices except the AAo curvature and Arch tortuosity. Besides, sex and BSA were the second most common independent correlates. When indexed to BSA, aortic volumes did not vary significantly between males and females in both age groups (Figure 5, Supplementary Table 2), while there were significant differences in terms of indexed aortic length and maximal diameters. Hypertension was the only determinant of AAo total curvature while current smoking was the only determinant of Arch tortuosity, though the model regression coefficients were low ($r^2 = 0.067$ and $r^2 = 0.109$, respectively). Regression coefficients of the volume model were higher than those of other morphological indices (Table 4).

DISCUSSION

In this study, 3D aortic MRI images of 119 healthy controls and 82 hypertensive patients were automatically segmented providing segmental and global indices of aortic morphology. Cross-sectional aortic diameters at predefined anatomical landmarks as well as normal values and confidence intervals of 3D aortic measurements including length, maximal diameters, volumes, curvature and tortuosity were reported. Significant increase in length and maximal diameters was found between young and elderly healthy controls for all aortic segments leading to a 3 to 4 times higher increase in volume between the two groups. While no marked differences were found in aortic morphology indices between hypertensives and healthy controls in the young age, we found higher diameters, length and volumes in elderly hypertensives as compared to elderly controls. Of note, younger and elderly subjects were defined according to a cut-off of 50 years which was close to the median age in this study (52 years) and was chosen according to previous aortic pathophysiology knowledge (30). A multivariate regression analysis revealed that age, sex and BSA were the major determinants of aortic morphology, irrespective of the presence of hypertension.

Median values of cross-sectional aortic diameters in the AAo at the level of the pulmonary artery (PA) as well as in the proximal DAo at the level of the PA and distal DAo at the level of diaphragm were 26.2mm (28.4mm), 19.6mm (21.9mm) and 17.4mm (19.9mm) for healthy subjects \leq 50 years (healthy subjects $>$ 50 years). These measures are in the same range than those of other studies on healthy individuals (5, 6) with mean age of 49 ± 17 y (AAo: 31 ± 4 mm, proximal DAo: 23 ± 3 mm, distal DAo: 21 ± 3 mm (5)) or a mean age of 37 ± 12 y (AAo: 26.7 ± 7 mm, proximal DAo: 20.6 ± 6 mm, distal DAo: 17.6 ± 5 mm (6)) and slightly lower than those of general population studies (7, 8, 31) which included patients with risk factors that are known to have an effect on the aorta.

Regarding the association of the 3D MRI-derived measures with age, a significant increase in aortic length and diameter were observed, in both ascending and descending aorta, resulting in a marked age-related increase in their volumes. These values were similar in range with those reported in other studies (5–7, 17), though a direct comparison was not possible due to differences in measurement methods (2D vs 3D), imaging modalities (CT vs. MRI), and patients cardiovascular risk.

In the ascending aorta and aortic arch, the observed increase in length and decrease in total curvature with aging suggested an unfolding of the proximal aorta, probably due to the mechanical constraints perpetually exerted on the aorta by the left ventricle combined with the subsequent and inherent aortic tissue elastic alteration (7, 32). In the descending aorta, the elongation and increased total curvature and tortuosity reflected the transition from a straight to a more tortuous segment. This is consistent with the unbound nature of the ascending aorta within the anterior mediastinum whereas the descending aorta is tied to the spine through the posterior thoracic arteries. Our findings also indicated the gradual transition from a roundish aortic arch to an unfolded shape, which has been previously described (7, 17, 33, 34). Of note, these significant decreases in AAO and Arch curvatures and increase in DAo curvature with age resulted in an overall unchanged TAo curvature.

While no marked differences in aortic morphological measures could be observed between healthy subjects and hypertensive patients considering subjects ≤ 50 years, significant length, maximal diameter and volume increases at the level of the ascending aorta and aortic arch were observed between hypertensive patients over 50 years compared to their matched healthy controls. Indeed, as they comprehensively assess the aortic morphology, these 3D indices could provide a better means of detecting subclinical changes than local cross-sectional diameter measurements since they overcome most of the 2D-measures drawbacks such as the subjective positioning in the

most dilated or narrow section as well as possible slice obliquity. Furthermore, differences in aortic morphology under the effect of hypertension in the older individuals and their absence in younger groups might reflect the aggravating and integrative effects of hypertension through a lifespan, rather than acute effects on aortic morphology. Indeed, it is well known that higher-pressure conditions within the aorta in hypertensive subjects progressively damage the elastin fibers of the aortic wall inducing a higher stiffness (32, 35). This increased stiffness can be associated with an aortic dilation to reduce the blood pressure and consequently the load exerted on the left ventricle. The differences in aortic morphology measures found in our elderly hypertensive patients as compared to the healthy controls reflects this geometrical remodeling of the aorta as it adapts to the higher blood pressure regimen. This aortic remodeling remains however within normal range as no diameter > 40mm have been measured.

The multivariate analysis performed on the entire study group revealed that age, sex and BSA were the major determinants of aortic morphology as previously reported (6, 8). Although women had smaller aorta than men in terms of length, diameter and volume, they had similar tortuosity and curvature. Moreover, after indexation to BSA, no significant differences in volumes were observed between men and women.

Limitations

One limitation of our study is the unbalanced and relatively small samples especially in the elderly healthy controls and young hypertensives groups. However, one might emphasize that our distributions are consistent with those in the general population as elderly healthy subjects without cardiovascular comorbidities were difficult to enroll and prevalence of hypertension is known to considerably increase with age (36). Furthermore, a large proportion of our data were acquired after contrast agent injection during a standardized clinical procedure. This ultimately enhances the signal to noise

ratio in the resulting aortic images but might limit the usefulness in patients with counterindication to contrast agents. However, one might note that our segmentation technique was shown to be robust to low image quality, as it was able to reliably segment 4D flow MRI-derived aortic angiograms (37, 38), which are known to have lower signal to noise ratio than conventional anatomical images. Our MRI data were acquired from three different sites using different field strengths (1.5T and 3T) and sequences (SPGR and SSFP). This might have slightly altered the distribution of our normal values but reflects the real-life conditions with multi-center inclusions. Finally, our study population did not include patients with a higher risk of aortic dissection to fully demonstrate the clinical usefulness of the 3D measures against a 2D measure of diameters. However, such studies would need normative values of the 3D morphology which was the primary objective of the present study. Besides, we believe that a 3D rendering of the aorta with precise and local geometric measures, resulting from our segmentation, may help in the planning of aortic surgery especially in complex, tortuous geometry or excessive dilation where the aortic pathway would not be easy to track.

Conclusion

Normal values of global and segmental aortic length, volume, curvature and tortuosity as well as diameters at specific landmarks were automatically measured from 3D MRI to serve as reference measures of 3D aortic morphology. Such 3D aortic indices increased significantly with age and hypertension among the elderly subjects. Further longitudinal studies on larger cohort including patient with cardiovascular diseases are required to evaluate the full benefit of this 3D morphometric analysis.

Availability of Data and Materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing Interests

The authors declare that they have no competing interests

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TABLES

Table 1 – Subject characteristics

	Healthy controls ≤ 50y	Healthy controls > 50y	Hypertensives ≤ 50y	Hypertensives > 50y
N	70	49	21	61
Sex (M / F)	39 / 31	22 / 27	11 / 10	32 / 29
Age (years)	41.5 [32.8; 47.3]	60.0 [53.0; 68.5] *** <i>p</i> < 0.0001	43.0 [31.5; 49.5] <i>p</i> = 0.5554	66.0 [60.5; 72.5] †† <i>p</i> = 0.0012
BSA (m ²)	1.81 [1.62; 1.93]	1.69 [1.56; 1.87] <i>p</i> = 0.0556	1.89 [1.74; 2.08] <i>p</i> = 0.0752	1.76 [1.63; 1.91] <i>p</i> = 0.1181
BMI (kg.m ⁻²)	23.1 [21.5; 25.3]	23.9 [21.8; 26.1] <i>p</i> = 0.3172	25.7 [22.8; 29.8] ** <i>p</i> = 0.0061	25.2 [22.6; 27.2] <i>p</i> = 0.1125
Central SBP (mmHg)	109 [101; 117]	116 [106; 125] ** <i>p</i> = 0.010	127 [118; 148] *** <i>p</i> < 0.0001	126 [118; 131] ††† <i>p</i> < 0.0001
Central DBP (mmHg)	79 [70; 85]	79 [72; 87] <i>p</i> = 0.6181	91 [83; 100] *** <i>p</i> < 0.0001	82 [76; 88] <i>p</i> = 0.1947
Central PP (mmHg)	31 [27; 36]	36 [32; 43] *** <i>p</i> < 0.0001	35 [32; 44] *** <i>p</i> = 0.0005	44 [38; 50] ††† <i>p</i> = 0.0006
Aortic diameters at predefined anatomical landmarks				
AAo at PA (mm)	26.2 [24.1; 28.8]	28.4 [25.8; 30.7] ** <i>p</i> = 0.0019	27.4 [25.2; 29.8] <i>p</i> = 0.1379	30.8 [27.3; 32.6] † <i>p</i> = 0.0203

DAo at PA (mm)	19.6 [17.9; 21.5]	21.9 [20.7; 23.4] *** <i>p</i> < 0.0001	20.8 [18.2; 22.5] <i>p</i> = 0.1765	23.5 [21.0; 25.4] † <i>p</i> = 0.0338
DAo at diaphragm (mm)	17.4 [16.4; 19.6]	19.9 [18.9; 21.4] *** <i>p</i> < 0.0001	19.5 [16.7; 20.2] <i>p</i> = 0.2725	23.2 [19.1; 24.5] †† <i>p</i> = 0.0008
Aortic diameters indexed to BSA at predefined anatomical landmarks				
AAo at PA (mm.m ⁻²)	14.7 [13.4; 16.4]	16.5 [15.5; 18.2] *** <i>p</i> < 0.0001	14.7 [13.2; 16.0] <i>p</i> = 0.7602	16.8 [15.3; 18.8] <i>p</i> = 0.4257
DAo at PA (mm.m ⁻²)	11.0 [10.1; 11.9]	13.1 [11.9; 13.7] *** <i>p</i> < 0.0001	11.1 [9.7; 12.1] <i>p</i> = 0.9696	13.0 [12.0; 14.6] <i>p</i> = 0.440
Diaphragm (mm.m ⁻²)	10.1 [9.2; 10.9]	11.9 [11.1; 12.6] *** <i>p</i> < 0.0001	10.2 [8.7; 10.9] <i>p</i> = 0.7674	12.6 [11.4; 15.2] † <i>p</i> = 0.0118

Pairwise Wilcoxon test: * *p* < 0.05, ** *p* < 0.01, *** *p* < 0.001 for comparisons of healthy controls > 50y or hypertensives ≤ 50y against healthy controls ≤ 50y, † *p* < 0.05, †† *p* < 0.01, ††† *p* < 0.001 for comparisons of hypertensives > 50y against healthy controls > 50y. SBP/DBP: systolic/diastolic blood pressure; PP: pulse pressure; BSA: body surface area; BMI: Body mass index; AAo: ascending aorta; PA: pulmonary artery; DAo: descending aorta.

Table 2 – Global and segmental aortic morphology quantitative measures

	Healthy controls ≤ 50y	Healthy controls > 50y	Hypertensives ≤ 50y	Hypertensives > 50y
Thoracic aorta				
Length (mm)	235.5 [217.0; 254.8]	256.8 [239.1; 276.6] *** <i>p</i> < 0.0001	225.6 [211.6; 238.3] <i>p</i> = 0.1354	256.4 [239.7; 270.3] <i>p</i> = 0.6606
Maximal diameter (mm)	27.3 [24.9; 29.6]	29.9 [27.0; 32.6] *** <i>p</i> = 0.0009	28.7 [25.8; 30.7] <i>p</i> = 0.3068	32.8 [30.2; 35.5] ††† <i>p</i> = 0.0002
Volume (mL)	84.5 [70.8; 111.9]	114.1 [98.1; 134.6] *** <i>p</i> < 0.0001	98.8 [73.3; 113.6] <i>p</i> = 0.6343	139.3 [110.1; 178.2] †† <i>p</i> = 0.0032
Total curvature (mm ⁻¹)	0.023 [0.022; 0.025]	0.023 [0.022; 0.025] <i>p</i> = 0.1382	0.025 [0.023; 0.027] * <i>p</i> = 0.0226	0.025 [0.023; 0.027] †† <i>p</i> = 0.0067
Tortuosity	1.50 [1.28; 1.69]	1.89 [1.68; 2.17] *** <i>p</i> < 0.0001	1.57 [1.46; 1.88] <i>p</i> = 0.0628	2.04 [1.82; 2.37] † <i>p</i> = 0.0299
Ascending aorta				
Length (mm)	51.9 [45.7; 58.8]	56.2 [52.3; 63.3] ** <i>p</i> = 0.0041	53.9 [50.4; 57.4] <i>p</i> = 0.5310	60.4 [55.8; 66.0] †† <i>p</i> = 0.0033
Maximal diameter (mm)	27.3 [24.9; 29.6]	29.9 [26.9; 32.6] *** <i>p</i> = 0.0010	28.7 [25.8; 30.7] <i>p</i> = 0.2936	32.8 [30.2; 35.4] ††† <i>p</i> = 0.0002
Volume (mL)	26.5 [21.4; 34.7]	34.7 [28.5; 43.5] *** <i>p</i> = 0.0004	33.3 [24.4; 36.9] <i>p</i> = 0.1857	45.2 [35.9; 53.2] ††† <i>p</i> = 0.0002
Total curvature (mm ⁻¹)	0.037 [0.032; 0.042]	0.033 [0.030; 0.037] **	0.037 [0.034; 0.039]	0.035 [0.030; 0.038]

		<i>p</i> = 0.0024	<i>p</i> = 0.7169	<i>p</i> = 0.3210
Tortuosity	0.111 [0.078; 0.137]	0.113 [0.084; 0.149] <i>p</i> = 0.5837	0.122 [0.108; 0.158] <i>p</i> = 0.0683	0.134 [0.088; 0.198] <i>p</i> = 0.0854
Aortic arch				
Length (mm)	32.1 [28.0; 37.2]	35.2 [31.8; 40.9] ** <i>p</i> = 0.0069	34.3 [30.4; 36.6] <i>p</i> = 0.4315	38.8 [34.7; 43.7] † <i>p</i> = 0.0141
Maximal diameter (mm)	25.7 [23.2; 28.1]	28.4 [25.4; 30.8] *** <i>p</i> = 0.0002	25.9 [24.2; 28.5] <i>p</i> = 0.3249	30.5 [27.8; 33.5] †† <i>p</i> = 0.0009
Volume (mL)	13.9 [10.9; 17.7]	19.5 [14.7; 23.0] *** <i>p</i> < 0.0001	15.3 [11.2; 17.9] <i>p</i> = 0.4711	22.9 [17.0; 31.7] †† <i>p</i> = 0.0061
Total curvature (mm ⁻¹)	0.036 [0.031; 0.042]	0.027 [0.025; 0.032] *** <i>p</i> < 0.0001	0.037 [0.033; 0.042] <i>p</i> = 0.8469	0.031 [0.025; 0.034] <i>p</i> = 0.3152
Tortuosity	0.050 [0.031; 0.073]	0.025 [0.016; 0.037] *** <i>p</i> < 0.0001	0.039 [0.029; 0.056] <i>p</i> = 0.1647	0.026 [0.017; 0.045] <i>p</i> = 0.4308
Descending aorta				
Length (mm)	147.6 [137.8; 163.5]	162.7 [150.6; 179.5] *** <i>p</i> < 0.0001	136.7 [122.6; 146.7] * <i>p</i> = 0.0117	157.0 [143.7; 163.7] † <i>p</i> = 0.0199
Maximal diameter (mm)	21.8 [20.0; 23.5]	24.2 [22.8; 26.1] *** <i>p</i> < 0.0001	22.4 [20.1; 24.3] <i>p</i> = 0.3887	27.0 [23.2; 29.7] †† <i>p</i> = 0.0060
Volume (mL)	45.3 [37.0; 56.3]	61.8 [51.8; 72.9] *** <i>p</i> < 0.0001	48.7 [34.7; 56.2] <i>p</i> = 0.9025	70.3 [50.9; 92.3] <i>p</i> = 0.0922

Total curvature (mm ⁻¹)	0.016 [0.014; 0.018]	0.018 [0.015; 0.020] *** <i>p = 0.0011</i>	0.017 [0.017; 0.019] * <i>p = 0.0153</i>	0.019 [0.017; 0.021] † <i>p = 0.0492</i>
Tortuosity	0.096 [0.074; 0.124]	0.164 [0.135; 0.218] *** <i>p < 0.0001</i>	0.131 [0.095; 0.178] ** <i>p = 0.0057</i>	0.193 [0.144; 0.251] <i>p = 0.3832</i>

Pairwise Wilcoxon test: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ for comparisons of healthy controls $> 50y$ and hypertensives $\leq 50y$ against healthy controls $\leq 50y$, † $p < 0.05$, †† $p < 0.01$, ††† $p < 0.001$ for comparisons of hypertensives $> 50y$ against healthy controls $> 50y$.

Table 3 - Association between age and aortic measurements

	ρ	p-value	Slope
Thoracic aorta			
Length (mm)	0.542	< 0.0001	1.238
Maximal diameter (mm)	0.485	< 0.0001	0.1351
Volume (mL)	0.605	< 0.0001	1.556
Total curvature (mm ⁻¹)	-0.154	0.283	-2.10 ⁻⁵
Tortuosity	0.728	< 0.0001	0.0201
Ascending aorta			
Length (mm)	0.431	< 0.0001	0.2840
Maximal diameter (mm)	0.478	< 0.0001	0.1356
Volume (mL)	0.526	< 0.0001	0.4283
Total curvature (mm ⁻¹)	-0.363	< 0.0001	-0.0002
Tortuosity	0.114	0.389	0.0003
Aortic arch			
Length (mm)	0.335	< 0.0001	0.1764
Maximal diameter (mm)	0.528	< 0.0001	0.1424
Volume (mL)	0.536	< 0.0001	0.2564
Total curvature (mm ⁻¹)	-0.568	< 0.0001	-0.0003
Tortuosity	-0.427	< 0.0001	-0.0008
Descending aorta			
Length (mm)	0.462	< 0.0001	0.7776
Maximal diameter (mm)	0.571	< 0.0001	0.1292
Volume (mL)	0.602	< 0.0001	0.8711
Total curvature (mm ⁻¹)	0.346	< 0.0001	0.0001
Tortuosity	0.768	< 0.0001	0.0038

Association between age and aortic measurements for healthy individuals ($n = 119$).

ρ : Spearman correlation coefficient.

Table 4 - Independent correlates of aortic morphology (n=201)

	r^2	p-value	Significant correlates					
			Age	Sex	BSA	Central SBP	Hypertension	Current smoking
Thoracic aorta								
Length (mm)	0.272	< 0.001	p < 0.0001	p = 0.0080	p = 0.6053	p = 0.2007	p = 0.2739	p = 0.4155
Maximal diameter (mm)	0.369	< 0.001	p < 0.0001	p = 0.0125	p = 0.0411	p = 0.9742	p = 0.1114	p = 0.6443
Volume (mL)	0.495	< 0.001	p < 0.0001	p < 0.0001	p = 0.0519	p = 0.1795	p = 0.1364	p = 0.6124
Total curvature (mm ⁻¹)	0.067	0.0096	p = 0.3290	p = 0.0620	p = 0.5505	p = 0.1866	p = 0.0035	p = 0.4163
Tortuosity	0.448	< 0.001	p < 0.0001	p = 0.8472	p = 0.1054	p = 0.4463	p = 0.1522	p = 0.0216
Ascending aorta								
Length (mm)	0.300	< 0.001	p < 0.0001	p = 0.0400	p = 0.0521	p = 0.6154	p = 0.9364	p = 0.1399
Maximal diameter (mm)	0.364	< 0.001	p < 0.0001	p = 0.0063	p = 0.0679	p = 0.7366	p = 0.1615	p = 0.6154
Volume (mL)	0.384	< 0.001	p < 0.0001	p = 0.0035	p = 0.0429	p = 0.7537	p = 0.2370	p = 0.1890
Total curvature (mm ⁻¹)	0.031	0.090	p = 0.0212	p = 0.3859	p = 0.9243	p = 0.3071	p = 0.5055	p = 0.4611
Tortuosity	0.109	0.005	p = 0.1091	p = 0.3346	p = 0.0764	p = 0.5827	p = 0.0626	p = 0.0304
Aortic arch								

Length (mm)	0.182	< 0.001	p < 0.0001	p = 0.8326	p = 0.0056	p = 0.0230	p = 0.0316	p = 0.9266
Maximal diameter (mm)	0.410	< 0.001	p < 0.0001	p = 0.0009	p = 0.0940	p = 0.4102	p = 0.0516	p = 0.9573
Volume (mL)	0.379	< 0.001	p < 0.0001	p = 0.0437	p = 0.0066	p = 0.0185	p = 0.0257	p = 0.9399
Total curvature (mm ⁻¹)	0.270	< 0.001	p < 0.0001	p = 0.0828	p = 0.0418	p = 0.7076	p = 0.0795	p = 0.2395
Tortuosity	0.136	< 0.001	p < 0.0001	p = 0.1139	p = 0.8974	p = 0.5324	p = 0.6951	p = 0.2312
Descending aorta								
Length (mm)	0.149	< 0.001	p < 0.0001	p = 0.0144	p = 0.2193	p = 0.3101	p = 0.0254	p = 0.7125
Maximal diameter (mm)	0.464	< 0.001	p < 0.0001	p < 0.0001	p = 0.2978	p = 0.0326	p = 0.0243	p = 0.1809
Volume (mL)	0.469	< 0.001	p < 0.0001	p < 0.0001	p = 0.3253	p = 0.0922	p = 0.3459	p = 0.9821
Total curvature (mm ⁻¹)	0.161	< 0.001	p = 0.0006	p = 0.2950	p = 0.2258	p = 0.1879	p = 0.0110	p = 0.2596
Tortuosity	0.396	< 0.001	p < 0.0001	p = 0.0667	p = 0.0184	p = 0.9421	p = 0.1758	p = 0.0925

r^2 : adjusted correlation coefficient; BSA: body surface area; SBP: central systolic blood pressure. Bold values correspond to significant correlates in the multivariate model.

FIGURES

Figure 1

3D aortic segmentation and partition into segments. Green dots: anatomical landmarks; purple line: aortic centerline; red segment: ascending aorta; green segment: aortic arch; blue segment: descending thoracic aorta

Figure 2

Examples of aortic 3D morphology in each group: (a) Healthy control (HC) male ≤ 50 y, (b) Healthy male > 50 y, (c) Hypertensive (HT) male ≤ 50 y and (d) Hypertensive male > 50 y. These subjects had similar height and body surface area with ranges of 173 – 175 cm and 1.78 - 1.87 m², respectively.

Figure 3

Boxplot representation of morphological changes between groups in the ascending aorta (AAo), aortic arch (Arch) and descending aorta (DAo).

Blue shades: healthy controls (HC) \leq and > 50 years, red shades: hypertensives (HT) \leq and > 50 years. Colored dots correspond to outliers in each group. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Figure 4

Normal morphological measures in the ascending aorta (AAo, top row) as well as in the descending aorta (DAo, bottom row).

Red line: linear regression; grey area: 95% confidence interval for the individual response; blue dots: healthy controls. ρ : Spearman correlation coefficient.

Figure 5

Boxplot representation of ascending aorta (AAo), aortic arch (Arch) and descending aorta (DAo) morphological measures indexed to BSA in healthy males and females ≤ 50 years (top) and > 50 years (bottom).

Blue: female subjects, red: male subjects. Colored dots correspond to outliers in each group. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

SUPPLEMENTARY MATERIAL

Supplementary Table 1 – Morphological aortic measures indexed to BSA

	Healthy controls ≤ 50y	Healthy controls > 50y	Hypertensives ≤ 50y	Hypertensives > 50y
Thoracic aorta				
Length (mm .m ⁻²)	134.1 [123.0; 142.0]	153.5 [134.2; 163.8] *** <i>p</i> < 0.0001	116.9 [105.3; 135.3] ** <i>p</i> = 0.0053	142.8 [132.3; 158.0] <i>p</i> = 0.1489
Maximal diameter (mm.m ⁻²)	15.6 [14.3; 17.0]	17.4 [16.3; 19.3] *** <i>p</i> < 0.0001	15.2 [13.7; 16.5] <i>p</i> = 0.3906	18.1 [16.9; 20.4] † <i>p</i> = 0.0305
Volume (mL.m ⁻²)	49.3 [39.9; 59.8]	68.9 [54.7; 82.9] *** <i>p</i> < 0.0001	54.2 [39.1; 57.5] <i>p</i> = 0.9316	78.5 [61.6; 93.2] †† <i>p</i> = 0.0061
Ascending aorta				
Length (mm .m ⁻²)	29.1 [27.2; 33.5]	33.0 [30.0; 36.2] *** <i>p</i> = 0.0001	28.9 [27.8; 31.3] <i>p</i> = 0.6402	34.7 [32.3; 37.3] <i>p</i> = 0.0926
Maximal diameter (mm.m ⁻²)	15.6 [14.3; 17.0]	17.4 [16.2; 19.3] *** <i>p</i> < 0.0001	15.2 [13.7; 16.5] <i>p</i> = 0.4012	18.0 [16.8; 20.4] † <i>p</i> = 0.424
Volume (mL.m ⁻²)	14.8 [12.8; 18.9]	20.8 [16.7; 24.0] *** <i>p</i> < 0.0001	17.1 [13.3; 19.3] <i>p</i> = 0.4454	24.5 [20.2; 29.0] ††† <i>p</i> = 0.0004
Aortic arch				

Length (mm.m ⁻²)	18.1 [15.6; 20.8]	20.3 [18.2; 24.0] ** <i>p</i> = 0.0015	18.0 [15.8; 19.8] <i>p</i> = 0.4862	22.6 [19.3; 25.2] <i>p</i> = 0.0903
Maximal diameter (mm.m ⁻²)	14.5 [13.4; 16.0]	16.4 [15.1; 17.9] *** <i>p</i> < 0.0001	13.6 [12.5; 15.5] <i>p</i> = 0.3853	17.1 [15.8; 19.7] † <i>p</i> = 0.0430
Volume (mL.m ⁻²)	7.9 [6.2; 9.9]	11.1 [7.9; 13.5] *** <i>p</i> < 0.0001	8.4 [6.3; 9.8] <i>p</i> = 0.7099	12.5 [9.9; 18.5] †† <i>p</i> < 0.0001

Descending aorta

Length (mm.m ⁻²)	85.2 [76.6; 91.6]	97.4 [84.6; 106.2] *** <i>p</i> < 0.0001	70.8 [62.4; 84.0] ** <i>p</i> = 0.0025	88.6 [80.9; 97.1] †† <i>p</i> = 0.0054
Maximal diameter (mm.m ⁻²)	12.7 [11.3; 13.2]	14.3 [13.0; 15.4] *** <i>p</i> < 0.0001	12.1 [10.7; 13.5] <i>p</i> = 0.5866	14.9 [13.2; 16.7] <i>p</i> = 0.0772
Volume (mL.m ⁻²)	26.2 [21.5; 31.0]	35.7 [30.0; 42.1] *** <i>p</i> < 0.0001	25.7 [19.2; 29.7] <i>p</i> = 0.4147	39.4 [29.9; 51.3] <i>p</i> = 0.1480

Morphological aortic measures indexed to Body Surface Area (BSA) for each group. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ for comparisons of healthy controls > 50 years or hypertensive patients ≤ 50 years against healthy controls ≤ 50 , † $p < 0.05$, †† $p < 0.01$, ††† $p < 0.001$ for comparisons of hypertensive > 50 years against healthy controls > 50 years.

Supplementary Table 2 – Morphological aortic measures indexed to BSA

	Female ≤ 50y	Male ≤ 50y	Female > 50y	Male > 50y
Ascending aorta				
Length (mm .m ⁻²)	30.4 [27.1; 33.0]	28.8 [27.3; 33.9] <i>p = 0.990</i>	35.7 [32.8; 38.2]	30.2 [27.7; 32.9] ††† <i>p = 0.0002</i>
Maximal diameter (mm.m ⁻²)	16.5 [14.6;17.3]	15.0 [14.0; 16.1] * <i>p < 0.0113</i>	17.8 [16.5; 19.6]	16.8 [15.2; 18.0] <i>p = 0.0572</i>
Volume (mL.m ⁻²)	14.4 [10.2; 18.2]	15.8 [13.2; 21.3] <i>p = 0.0742</i>	20.5 [17.5; 23.6]	21.3 [15.8; 25.1] <i>p = 0.876</i>
Aortic arch				
Length (mm .m ⁻²)	19.7 [16.4; 22.0]	17.3 [14.2;20.3] <i>p = 0.106</i>	20.5 [18.5; 25.3]	19.6 [17.2; 24.0] <i>p = 0.3884</i>
Maximal diameter (mm.m ⁻²)	15.0 [13.7; 16.2]	13.8 [12.8; 15.6] * <i>p = 0.0358</i>	17.2 [15.5; 18.1]	15.9 [14.5; 17.2] <i>p = 0.0943</i>
Volume (mL.m ⁻²)	7.66 [6.49. 9.23]	7.97 [6.10; 10.0] <i>p = 0.6906</i>	11.2 [7.63; 13.1]	11.1 [9.28; 13.8] <i>p = 0.2241</i>
Descending aorta				
Length (mm.m ⁻²)	89.8 [82.4; 94.2]	79.4 [73.4; 88.8] ** <i>p = 0.0034</i>	99.2 [89.6; 112.2]	91.1 [78.0; 102.1] <i>p = 0.0756</i>

Maximal diameter (mm.m ⁻²)	12.7 [11.7; 13.6]	12.1 [11.1; 13.0] <i>p = 0.214</i>	14.9 [13.8; 15.5]	13.9 [12.3; 14.7] † <i>p = 0.0427</i>
Volume (mL.m ⁻²)	24.1 [18.4; 27.6]	26.4 [22.0; 33.2] <i>p = 0.089</i>	34.1 [29.6; 41.5]	38.3 [30.1; 48.8] <i>p = 0.1607</i>

Morphological aortic measures indexed to Body Surface Area (BSA) for healthy subjects of each sex. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ for comparisons of healthy male ≤ 50 years against healthy female ≤ 50 , † $p < 0.05$, †† $p < 0.01$, ††† $p < 0.001$ for comparisons of healthy male > 50 years against healthy female > 50 years.

Supplementary Figure 1

Illustration of images and segmentation quality in representative data from our 3 acquisition sites. Site 1: SPGR sequence acquired at 3T (Discovery MR750w, GE Healthcare, Chicago); site 2: SSFP sequence acquired at 3T (Prisma, Siemens Healthineers, Erlangen); site 3: SSFP sequence acquired at 1.5 T (Aera, Siemens Healthineers, Erlangen).

Supplementary Figure 2

Morphological changes between groups in the ascending aorta (AAo), aortic arch (Arch) and descending aorta (DAo).

Blue shades: healthy controls (HC) \leq and $>$ 50 years, red shades: hypertensives (HT) \leq and $>$ 50 years. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Supplementary Figure 3

Normal morphological measures indexed to BSA in the ascending aorta (AAo, top row) as well as in the descending aorta (DAo, bottom row).

Red line: linear regression; grey area: 95% confidence interval for the individual response; blue dots: healthy controls. ρ : Spearman correlation coefficient.