International Journal of Cardiology 228 (2017) 654–660

Contents lists available at ScienceDirect

International Journal of Cardiology

journal homepage: www.elsevier.com/locate/ijcard

Age-related changes of thoracic aorta geometry used to predict the risk for acute type B dissection

Damian Craiem [a,b,c,d,*], Salma El Batti [e], Mariano E. Casciaro [a], Elie Mousseaux [c,d,f], Marie-Emmanuelle Sirieix [b,d], Alain Simon [b,c,d], Jean-Marc Alsac [c,d,e]

[a] Instituto de Medicina Traslacional, Trasplante y Bioingeniería (IMeTTyB), Universidad Favaloro-CONICET, Argentina
[b] Centre de Médecine Préventive Cardiovasculaire, APHP, Hôpital Européen Georges Pompidou, Paris, France
[c] INSERM U970, APHP, Hôpital Européen Georges Pompidou, Paris, France
[d] Université Paris-Descartes, Paris-Centre de Recherche Cardiovasculaire, Hôpital Européen Georges Pompidou, Paris, France
[e] Service de Chirurgie Cardiaque et Vasculaire, APHP, Hôpital Européen Georges Pompidou, Paris, France
[f] Service d'Imagerie Cardiovasculaire, APHP, Hôpital Européen Georges Pompidou, Paris, France

ARTICLE INFO

Article history:
Received 12 July 2016
Received in revised form 4 November 2016
Accepted 6 November 2016
Available online 09 November 2016

Keywords:
Geometric deformable model
True lumen volume
Aortic arch diameter
Aortic length
Aging

ABSTRACT

Aims: Risk models that use a single aortic diameter threshold have failed to successfully predict acute type B aortic dissection (TBAD). We sought to identify meaningful age-indexed anatomical variables to predict TBAD risk.
Methods and results: A geometric deformable model, consisting of virtual elastic balloons that inflate inside a vessel lumen, was developed to quantify thoracic aorta geometry. In the presence of TBAD, true and total artery lumen morphology were assessed. A stepwise logistic model was built to predict TBAD risk. Initial covariates included age, gender, body mass index and all anatomic variables not directly related to the dissected segment. Patients with acute TBAD ($n = 34$, 62 ± 12 years old, 57% male gender) were compared with subjects with symptoms of dissection, but with a subsequent negative diagnosis ($n = 51$, 62 ± 12 years old, 76% male gender). Patient risk factors did not differ between groups. Most aortic anatomical variables were age-dependent. Aortic size was larger in every segment of the dissected with respect to non-dissected aortas ($p < 0.001$). Variables entering the TBAD risk prediction model were aortic arch diameter, thoracic aorta length and age (predictability = 0.9764, $r = 0.85$), confirmed by a bootstrap internal validation. In dissected aortas, the true lumen volume was correlated to age ($r = 0.72$).
Conclusions: TBAD probability increases with a larger aortic arch diameter and a longer thoracic aorta, whereas threshold values increase with age. The aortic morphology was age-dependent. After dissection, true lumen volume correlated to age. The use of threshold values indexed to age should be encouraged to better prevent and eventually treat TBAD.

1. Introduction

Acute aortic dissection is currently an increasingly common cause of surgical aortic emergencies with an estimated incidence rate of 3 to 6 per 100,000 persons per year [1]. Dissection can occur at any age, mostly in adults aged between 50 and 80 years, and is more frequent in hypertensive males [2]. One third of all aortic dissections are classified as type B (i.e., concerning only the descending aorta) [3]. Despite advances in medical and surgical treatments, the mortality of aortic dissection remains high [4]. Since a relatively small percentage of hypertensive patients develop aortic dissections, novel characteristics other than the traditional risk factors are required to detect and prevent them. Previous attempts to predict type B aortic dissection (TBAD) risk based on descending aorta dilatation have not been accurate enough [5]. Although anatomical variables other than diameter have been proposed to improve TBAD prediction [6], the influence of aging on aortic morphometry was systematically neglected from the risk models. This is particularly odd, since the thoracic aorta tends to dilate, lengthen and unfold throughout life [7–9] and setting threshold values for anatomical variables not indexed by age seems illogical. Furthermore, after dissection occurs, aging could also impact true lumen size, conditioning perfusion towards other vessels and the eventual endograft access if thoracic endovascular aortic repair (TEVAR) is required [3].

In this study we sought to identify meaningful anatomical variables associated with higher risk of TBAD and to build a risk model indexed by age. Patients with acute TBAD were compared with control subjects with symptoms evoking aortic dissection, which was discarded after scan images. Automated geometric deformable models were used to accurately assess several anatomic variables, including vessel cross-sectional area, length, tortuosity and volume estimated through the

* Corresponding author at: Favaloro University, FICEN, Solis 453, CP 1078 Ciudad Autónoma de Buenos Aires, Argentina.
E-mail address: damian@craiem.com.ar (D. Craiem).

http://dx.doi.org/10.1016/j.ijcard.2016.11.125
0167-5273/

ascending, the arch and descending segments of the thoracic aorta. Correlations of anatomic variables to age were calculated for these three segments. The volume of the true lumen with respect to age was also analyzed.

2. Methods

2.1. Study subjects and image acquisition

Since 2009, the Hôpital Européen Georges Pompidou (Paris, France) runs a program called "SOS Aorte", which gathers information about all patients with aortic emergencies treated in the hospital and stores it into a database. For this study, patients with an acute TBAD were retrospectively reviewed until September 2015. The institutional review committee approved this study and waived the need for individual patient consent. Subjects were excluded if i) the dissection was due to a traumatic event or ii) it was a type A aortic dissection (i.e. concerning the ascending aorta), or iii) evidences of congenital or connective tissue disease were found. A total of 34 patients were included in this study and hereafter called the "dissection group". These patients were compared with a "control group" of 51 subjects with a suspected dissection, but whose scans examination and outcomes revealed their aortas were not dissected. Symptoms included sharp chest, abdominal or back pain. Patients with cancer or any other aortic disease were excluded from this study. All patients were studied on the same 64-slice scanner (Light-speed VCT; GE Health care, Milwaukee, Wisconsin, USA) using an ECG-gated computed tomography angiography (CTA) procedure. The thoracic aorta was visualized using an injection of 100 to 120 ml of contrast and the following configuration: 80 HU threshold within the aorta before starting the volumetric acquisition; 330 ms rotation speed; 64 × 0.6 mm collimation; pitch of 0.2; voltage of 140 kV and current between 500 and 850 mAs.

2.2. Thoracic aorta segmentation

2.2.1. Geometric deformable model (GDM)

A novel algorithm based on deformable surface models was used in this study to fully describe the three-dimensional (3D) morphometry of the thoracic aorta. Accurate measurements of aortic dimensions and shape, including true and total (i.e., true plus false) artery lumen centerline and volume, were automated to reduce user intervention. The proposed algorithm was developed by our group to assess the geometry of abdominal aortic aneurysms before and after endograft implantation [10] and was adapted for the thoracic aorta geometry in this study. A geometric deformable model (GDM) was developed based on the publications by Park, Miller and Terzopoulos et al. [11–13] to mimic a virtual elastic balloon that inflates inside the aortic lumen to measure its volume. The GDM initial shape is a closed spheroidal balloon composed by vertexes connected with elastic edges that form triangular faces. The position of each vertex is dynamically calculated using internal and external forces. Internal forces consist of stretching, bending and dissipative forces. The only external force applied to this model is an inflation pressure that pushes each vertex of the mesh perpendicularly to the surface. The inflation process simulates the application of an internal pressure on the inner surface (i.e. an expansive force), and an external pressure exerted by the vessel walls or other structures in the scan images that oppose to the advance of the GMD (i.e. a compressive force). When equilibrium between forces is reached and no significant changes in the GDM volume are detected, the 3D mesh can be used to describe geometrically the vessel that contains it.

2.2.2. Semi-automatic measurement

In order to quantify the thoracic aorta geometry, seven virtual spherical balloons were "implanted" inside the thoracic aorta lumen as shown in Fig. 1.

Nine points inside the aortic lumen were set manually: two in the axial section at the level of the pulmonary artery (CA and CD), three at oblique planes 45°, 90° and 135°, another two at the sinotubular junction (SJ) level and one at the diaphragm (DIA) level. Finally, a last point at mid distance between SJ and DIA. Virtual balloons of 10 mm diameter were then implanted in the seven intermediate points linking SJ to DIA. A preliminary centerline was calculated interpolating a spline. Nine invisible orthogonal planes were placed between the seed points in order to constrain the growth of the adjacent meshes and avoid mesh superposition.

In the presence of a TBAD, the user was asked to always position the seed points inside the true lumen (TL). Instead of separately segmenting the false lumen, the five points positioned by the user between the LSA and DIA were duplicated and manually placed on the dissection flap. When these balloons were inflated, their expansion covered the entire lumen (i.e. both the true and false lumens), called hereafter total artery lumen (TAL). In order to avoid the undesired growth of the GMD through the lumen of supra aortic arteries nor through flap tears, a "patch tool" was implemented as shown in Fig. 2. Before inflating the balloons, the user was able to place these patches to block the mesh expansion. Once all of the meshes were inflated until equilibrium, two independent centerlines were calculated: one for the TL and another for the TAL as shown in Fig. 2.

A slow motion video showing the balloons growing inside the true aortic lumen in a representative patient with TBAD is provided in the supplemental material.

2.2.3. Geometrical variables

All voxels inside the meshes were painted as to calculate a volume and refine the centerlines estimations. The user was finally asked to indicate the positions of the brachiocephalic and the left subclavian arteries (BSA and LSA, respectively) in order to separate ascending, arch and descending segments. The following geometrical variables were then automatically calculated for patients in both groups:

- Mean diameter, length and volume of each segment;
- Aortic arch width as the distance between CA and CD, and the distances from the aortic arch midpoint to C45°, C90° (arch height) and C135°;
- The tortuosity of the ascending portion, which includes the aortic arch (from SJ to LSA) and of the entire thoracic aorta (from SJ to DIA). Tortuosity was defined as the curvilinear length of a centerline divided by the linear distance between its ends.

In patients with TBAD, separate measurements were made for TL and TAL centerlines.

2.3. Statistical analysis

Groups were compared using unpaired *t*-student tests for continuous variables and chi-square tests for categorical variables. Geometrical comparisons were restricted to the ascending aorta and aortic arch proximal to LSA because the presence of a TBAD could interfere in certain measurements of the descending aorta. Within the dissection group, paired *t*-tests were used to compare true and total artery lumen variables.

The effect of aging on aortic geometry was analyzed calculating linear correlations of anatomic variables to age, after adjusting for body mass index (BMI) and gender. Correlations were restricted, once again, to anatomical variables not affected by the dissection. For patients in the dissection group, correlations between descending aorta TL volume and age before and after normalization to TAL volume were calculated and plotted separately.

In order to identify significant predictors of TBAD, stepwise logistic regression analysis was used. All of the significant anatomical variables in the group comparisons, together with age, gender and BMI, were considered as covariates in the initial model. Odds ratios and 95% confidence intervals (95% C.I.) were reported for unit increment of each identified covariate. The area under the receiver-operating curve (ROC) was adopted as the apparent

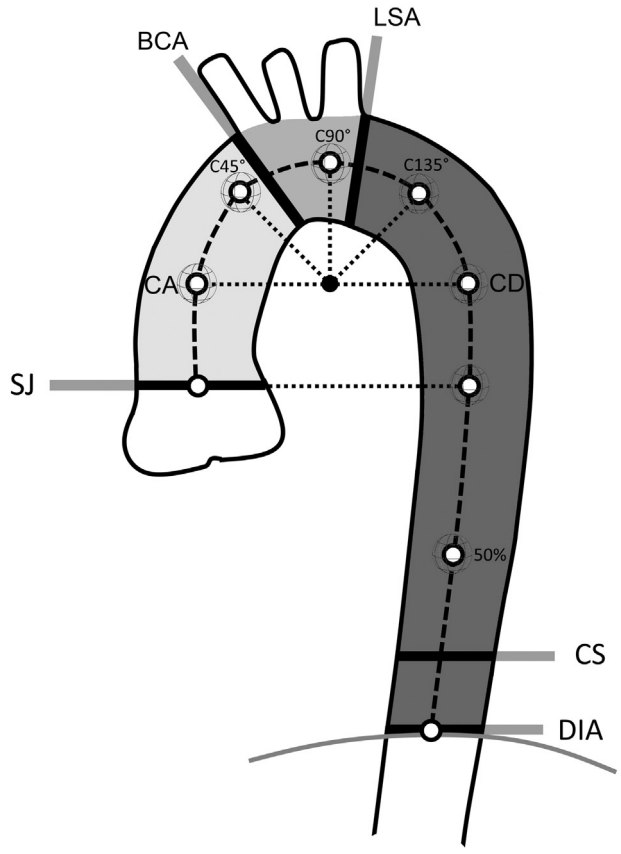

Fig. 1. Illustration of the 9 points required by the user to start the automated segmentation method of the thoracic aorta. Seven deformable spheroids were inflated inside the thoracic aorta lumen. BCA = brachiocephalic artery, CS = coronary sinus, DIA = diaphragm, LSA = left subclavian artery, SJ = sinotubular junction.

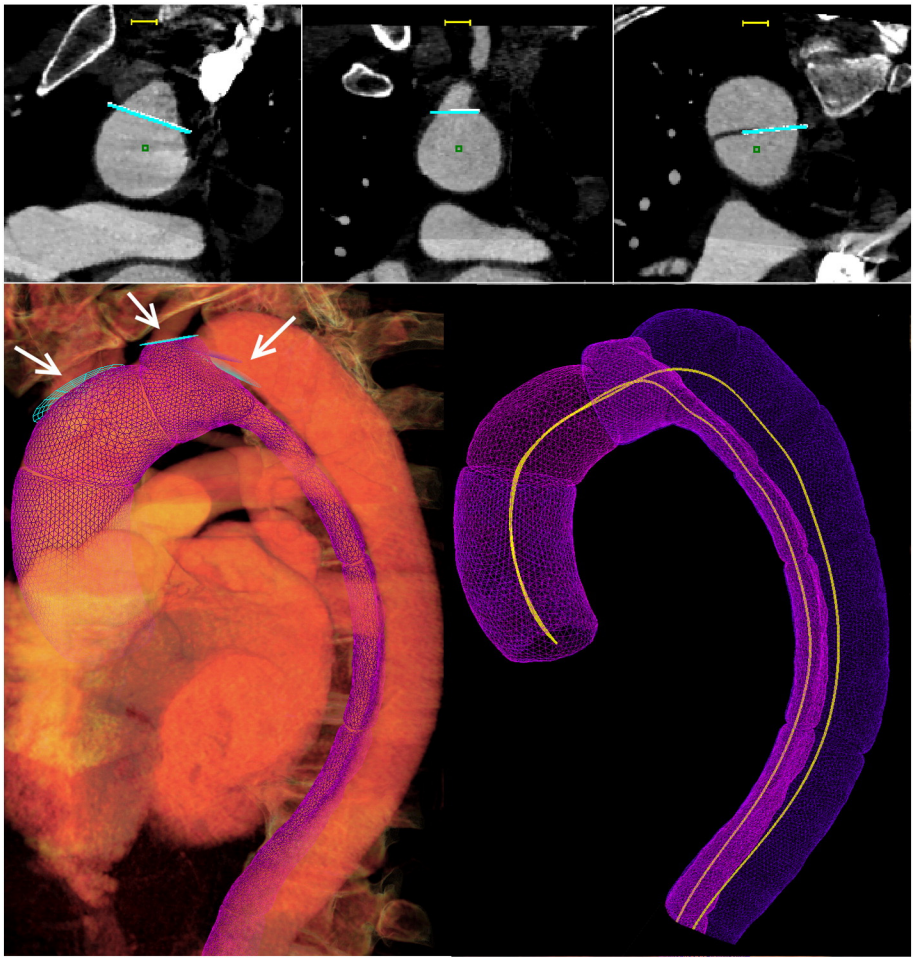

Fig. 2. Top: three virtual patches positioned at the brachiocephalic artery, left subclavian artery and at the main entry tear to restrain the deformable surfaces expansion. Bottom: the true lumen segmentation with arrows pointing the patches (left) together with true and total artery lumens centerlines (right).

performance of the fitted risk model for TBAD prediction. A bootstrap method was used for the internal validation of the selection of model variables and performance [14]. One-thousand samples were bootstrapped with replacement repeating the same stepwise procedure. Finally, we counted the number of times each variable entered the model to evaluate its consistency. The optimism in the apparent performance was calculated as the averaged difference between the performance in each bootstrap sample and the performance of using the model as estimated for each sample in the original sample [14]. All statistical analyses were performed using JMP (SAS, NC, USA) and Matlab (Mathworks, MA, USA) for bootstrap validation.

3. Results

The control and dissection groups are described in Table 1. No significant differences were observed in age, gender, BMI or traditional risk factors between groups.

The aortic anatomical variables of both groups are shown in Table 2, and an equivalent lumen diameter at different positions of the thoracic aorta is shown in Fig. 3. Significant anatomical variables in the group comparisons were considered as initial covariates in the subsequent stepwise logistic regression process. The average diameter, lumen volume and centerline length of ascending aorta and arch segments were larger in the dissection group with respect to the control group ($p < 0.001$). Ascending aortic tortuosity (including the aortic arch) did not differ between groups, whereas vectors C90° (aortic height) and C45° were longer in patients with TBAD ($p < 0.001$). In the last two columns of Table 2, a comparison between TL and TAL of patients with TBAD is shown to depict and quantify the severity of the TL shrinkage (see Fig. 3). The average diameter of the TL in the descending aorta was halved with respect to TAL ($p < 0.001$), lumen volume was reduced by 71% ($p < 0.001$), centerline length shortened by 8% ($p < 0.001$) and tortuosity decreased 3% ($p < 0.001$). The length of the entire thoracic aorta centerline path was 6% shorter in the TL with respect to TAL ($p < 0.001$) and 2% less tortuous ($p < 0.05$), respectively. The TL centerline path was closer to the aortic arch center, as evidenced by a shorter aortic arch width (−8%, $p < 0.001$) and C135° vector length (−10%, $p < 0.001$) with respect to TAL.

Changes of anatomical variables per decades of life after adjustment for gender and BMI are shown in Table 3. Anatomical variables were positively associated with age both in subjects with and without

Table 1
Demographics in patients with and without acute type B aortic dissection.

	Control group	Dissection group	p value
Number of patients	51	34	
Age, yrs. (range)	62 ± 14 (34–88)	62 ± 12 (40–88)	0.95
Male gender, n (%)	29 (57)	26 (76)	0.06
Body mass index, kg/m^2 (range)	27.9 ± 6.1 (17–46)	27.6 ± 5.8 (18–43)	0.83
Hypertension, n (%)	28 (55)	24 (71)	0.14
Hypertension treatment, n (%)	26 (51)	14 (41)	0.37
Current or past smoker, n (%)	13 (26)	15 (44)	0.09
Diabetes, n (%)	6 (12)	2 (6)	0.35

Values expressed as mean ± standard deviation or percentages.

Table 2
Anatomical variables.

Aortic measurements	Control group	Dissection group		
		Ascending + aortic arch	Descending TAL	Descending TL
Average diameter, cm				
Ascending	2.98 ± 0.37	3.47 ± 0.46 (+16%)*		
Arch	2.61 ± 0.29	3.30 ± 0.42 (+26%)*		
Descending	2.27 ± 0.28		3.45 ± 0.46*	1.81 ± 0.48 (−48%)‡
Lumen volume, cm^3				
Ascending	43 ± 15	71 ± 29 (+65%)*		
Arch	22 ± 8	39 ± 14 (+77%)*		
Descending	69 ± 23		198 ± 71*	58 ± 31 (−71%)‡
Length, cm				
Ascending + aortic arch	9.79 ± 1.37	11.42 ± 1.58 (+17%)*		
Descending	16.95 ± 2.53		21.69 ± 3.10*	19.93 ± 3.61 (−8%)‡
Thoracic aorta	26.73 ± 3.21		33.11 ± 3.72*	31.10 ± 4.38 (−6%)‡
Tortuosity				
Ascending + aortic arch	1.29 ± 0.08	1.26 ± 0.07		
Descending	1.18 ± 0.09		1.32 ± 0.15*	1.28 ± 0.15 (−3%)‡
Thoracic aorta	2.75 ± 0.44		3.30 ± 0.31*	3.22 ± 0.70 (−2%)†
Aortic arch shape, cm				
Height	4.2 ± 0.9	5.2 ± 0.7 (+24%)*		
C45° vector	4.1 ± 0.6	4.9 ± 0.7 (+20%)*		
Width	8.3 ± 1.3		10.3 ± 1.9*	9.5 ± 1.9 (−8%)‡
C135° vector	4.3 ± 0.8		5.2 ± 0.9*	4.7 ± 0.9 (−10%)‡

TL = true lumen. TAL = total arterial lumen.
* $p < 0.001$ with respect to control group values (unpaired *t*-test).
† $p < 0.05$, ‡ $p < 0.001$; with respect to TAL (paired *t*-test).

TBAD. In the control group, correlations to age were stronger for ascending and aortic arch size ($p < 0.001$ and $p < 0.01$ respectively), entire thoracic aorta tortuosity ($p < 0.01$) and C45° vector length ($p < 0.01$). In the dissection group, variables that showed stronger correlations to age were ascending aorta volume ($p < 0.01$), ascending + aortic arch length ($p < 0.01$), total thoracic aorta length ($p < 0.001$), aortic arch height ($p < 0.001$) and C45° vector length ($p < 0.01$. When patients in the dissection group were analyzed separately, the descending TL volume was

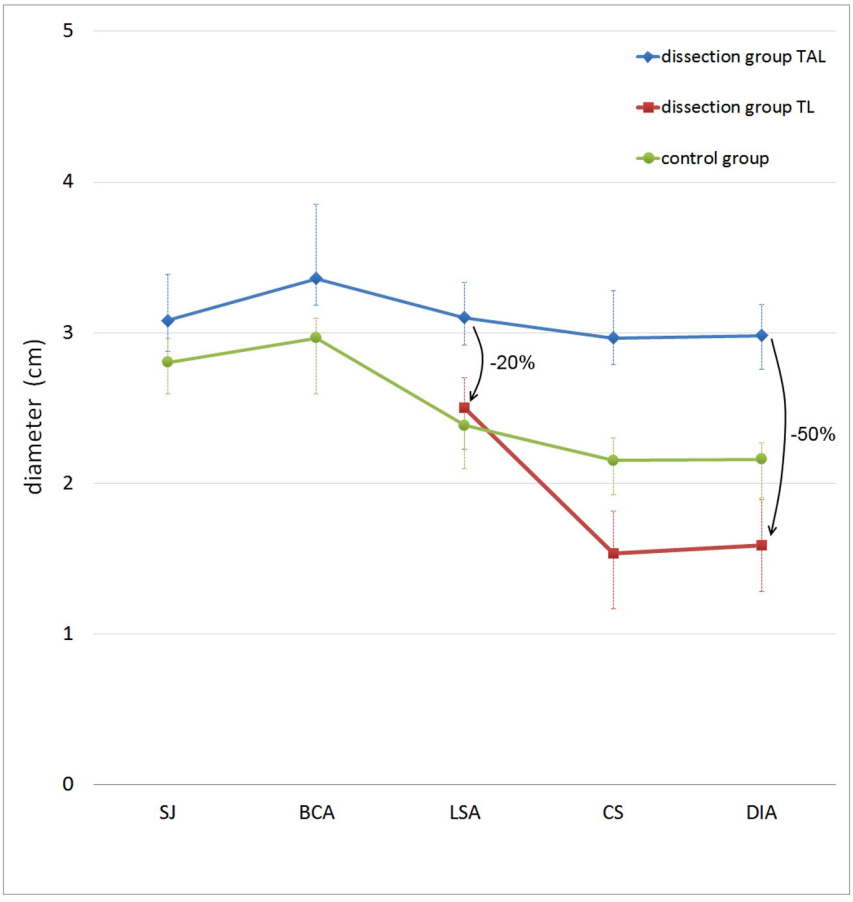

Fig. 3. Equivalent aortic diameter at different levels of the thoracic aorta derived from cross-sectional area measurements. BCA = brachiocephalic artery, CS = coronary sinus, DIA = diaphragm, LSA = left-subclavian artery, SJ = sinotubular junction, TL = true lumen, TAL = total artery lumen.

Table 3
Correlation of anatomical variables with age after adjustment for BMI and gender.

	Control group			Dissection group		
Geometrical variable	β_{age}	p value	Model r	β_{age}	p value	Model r
Average diameter, cm/10-yrs						
Ascending	0.14	<**0.001**	0.69	0.14	**0.022**	0.50
Arch	0.08	**0.002**	0.69	0.04	0.481	0.27
Lumen volume, cm^3/10-yrs						
Ascending	5.7	<**0.001**	0.66	10.7	**0.008**	0.51
Arch	1.8	**0.009**	0.70	2.6	0.209	0.40
Length, cm/10-yrs						
Ascending + aortic arch	0.29	**0.036**	0.57	0.67	**0.002**	0.55
Entire thoracic aorta	0.91	**0.013**	0.50	2.50	<**0.001**	0.73
Tortuosity, 1/10-yrs						
Ascending + aortic arch	0.02	0.054	0.51	0.00	0.973	0.26
Entire thoracic aorta	0.16	**0.001**	0.59	0.25	**0.003**	0.66
Aortic arch shape, cm/10-yrs						
Height	0.22	**0.022**	0.50	0.32	**0.001**	0.60
C45° vector	0.18	**0.009**	0.55	0.31	**0.001**	0.61

TL = true lumen. TAL = total arterial lumen.
p values <0.05 were considered significant and emphasized in bold letters.

strongly correlated to age ($p < 0.001$, $r = 0.72$), even after normalization for TAL volume (Fig. 4).

After a stepwise logistic regression process, only three variables appeared in the risk model to predict TBAD: aortic arch diameter, aortic length and age. Accordingly, the probability of TBAD can be calculated as $\Pr(TBAD) = 1/1 + e^{-y}$, where e is the natural exponential function and y is the linear combination of variables as shown in Table 4. For example, a 60 year-old patient with an aortic arch diameter of 3.2 cm and aortic length of 28 cm yields $y = 0.57092$ and the Pr(TBAD) results 64%. The odds ratio and 95% C.I. for 1 mm increase in aortic arch diameter was 2.12 [1.43–3.76] and for 1 cm increase in aortic length was 2.18 [1.45–4.17]. Assuming a fixed 90% probability of TBAD, the interplay between aortic arch diameter and aortic length values adjusted for age, is shown in Fig. 5. Subjects with anatomical variables above their corresponding age curves are at high risk (probability > 90%) of TBAD. Finally, the consistency in the covariates selection for the model was tested with a bootstrap method and internal validations. Aortic arch diameter, length and age entered in 99%, 96% and 88% of the 1000 bootstrapped repetitions, respectively. The other anatomic variables entered less than 50% of the time. The predictability of the model (evaluated with the area under the ROC) was 0.9764 and the optimism of this apparent performance resulted 0.0162.

4. Discussion

Current image modalities allow for a better understanding of the thoracic aorta development throughout life [7–9]. Age-associated changes of aortic geometry are now unquestionable and should not be excluded from any risk model developed to prevent aortic diseases. Accordingly, in this study we show that the risk of TBAD can be successfully predicted using aortic arch diameter and thoracic aorta length, indexed to age (Table 4). Aging was associated with most of the three-dimensional anatomical variables assessed in patients with and without TBAD. Additionally, after dissection occurs, the true lumen volume was positively correlated to age. These findings, which encourage the calculation of threshold values indexed to age, should help to better prevent and eventually treat TBAD.

In the International Registry of Aortic Dissection (IRAD), where 12 international referral centers and more than 4400 patients participate, the mean age was 63 years, 65% were men and 77% had a history of hypertension [2], comparable to demographics in our patients. Using the IRAD database, the attempt to set a threshold value for descending aorta diameter to early recognize TBAD patients had major limitations. For instance, the IRAD reported that 80% of their patients would skip detection using the proposed 5.5 cm threshold for descending aorta diameter [5,15]. The IRAD does not have a control group and thus, aortic dissection prediction was not possible. In the current study, we sought to look beyond the assessment of a single diameter to predict TBAD, including several anatomical variables measured in 3D. The three variables that were kept by the stepwise logistic process to predict TBAD were aortic arch mean diameter, total aortic length and age. The internal validation using a bootstrap method confirmed the final variable selection. The logistic model explained 72% of all the variability. It reached a high predictability value of 0.9764 with an internal optimism estimation of 0.0162. In a recent report, aortic arch diameter and aortic length also appeared as significant anatomic variables to predict TBAD risk, together with the brachiocephalic angle and the entire aorta tortuosity [6]. The angulations of the supra-aortic arteries were not measured in our study because these vessels were excluded from the expansion region of the automated deformable model. Whereas in this previous study tortuosity included the abdominal aorta, our study was limited to the thoracic aorta; this is probably the reason why tortuosity was not yielded as an explanatory variable. On the other hand, age was consistently selected into our model, accounting for 88% of the samples in a 1000 times bootstrap validation. Age-associated changes of anatomic variables in the thoracic aorta have been widely reported [7–9,16,17], with a significant acceleration of aortic enlargement and unfolding in hypertensive patients [18]. In accordance with the literature [9,16,17,19], we found that the mean diameter and length of the ascending and aortic arch

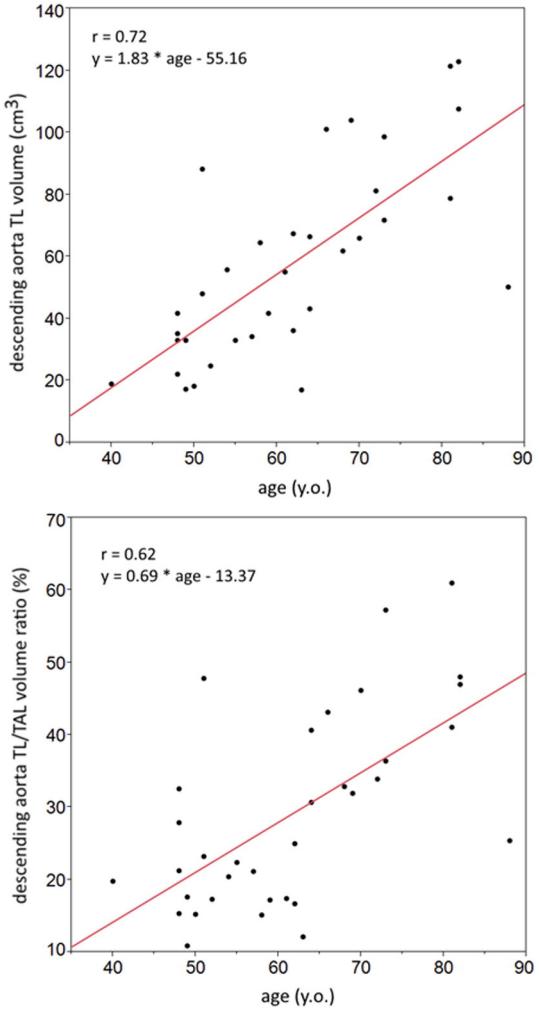

Fig. 4. Correlation between descending aorta TL volume with age before and after normalization by the TAL volume (n = 34). TL = true lumen. TAL = total aortic lumen.

Table 4
Logistic regression model to predict TABD risk.

Predictor	β-coefficient	Standard error	p value	Area under ROC	r
Aortic arch diameter	7.5311	2.3892	**0.002**	0.9764	0.85
Thoracic aorta length	0.7793	0.2599	**0.003**		
Age	−0.1851	0.0653	**0.005**		
Intercept	−34.2420	9.7039	<**0.001**		

ROC = receiver-operating curve.
p values <0.05 were considered significant and were emphasized in bold letters.

segments increased 1 mm and 3 mm per decade of life, respectively (Table 3). Our model suggests that, in order to predict the risk of TBAD, threshold values for anatomical variables should be indexed to age. This is clear in Fig. 5, where the 90% probability of TBAD curves show that elderly patients have longer and larger threshold values for the anatomical predictors. For instance, a 50 year-old patient with a 28 cm thoracic aorta length has an aortic arch diameter threshold of <3 cm to define the high risk of TBAD, whereas in a 70 year-old patient with the same aortic length, the same risk of TBAD is obtained with a < 3.5 cm threshold. This seems logical, since the fact that the aorta enlarges throughout life is undeniable, and expecting a single threshold value for aortic diameter to predict TBAD for all subjects would be inaccurate.

The attempt to use a diameter measured within the aortic damaged segment after aortic dissection has occurred seems initially questionable. Rylski et al. have recently compared the ascending aorta size before and after type A aortic dissection onset [20]. They reported a significant expansion of the ascending aorta (without significant length modifications), both in retrograde and spontaneous cases, showing that aortic size is clearly affected by dissection. Since aortic diameters in most studies have been measured in dissected aortas, published data on aortic dissection prediction should be carefully interpreted. In our study, we decided to exclude from the logistic analysis all anatomical variables directly involved with the aortic regions affected by dissection. Nevertheless, the hypothesis of a proximal aorta expansion due to a distal dissection cannot be completely rejected and should be further explored.

Aortic arch diameter and the length of thoracic aorta, adjusted to age, were found in our study as independent predictors of TBAD development. These two anatomical variables were assessed using a geometrical deformable model. The automation of the procedure aimed at reducing the measurement duration and variability. Regarding the latter objective, the volumetric assessment of the aortic lumen ensured that instead of using a single diameter, measurements were averaged over several diameters to assess each aortic segment dimension. Nevertheless, these measurements are not restricted to our geometric deformable model, as shown in recent reports that incorporated similar morphological descriptors to predict TBAD using plain 3D reconstructions [6]. We are aware that chest computed tomography with contrast material is not a part of screening test for hypertensive patients. However, we have recently shown that 3D aortic geometry can also be assessed using non-contrast cardiac CT scans employed in coronary and thoracic aorta calcium assessments [21]. Accordingly, patients with increased cardiovascular risk that are screened for calcifications could simultaneously benefit from a morphological evaluation of the thoracic aorta to prevent TBAD.

We found that the TL volume was correlated to age, even after normalization to TAL (Fig. 5). When dissection occurs, the assessment of the TL size could be of interest because it influences the prognosis of TBAD patients [22,23]. As the false lumen dilates, the TL is contracted, leading to critical limitation of vessel perfusion through the TL [3]. Since the expanded use of endovascular interventions has a growing effect on

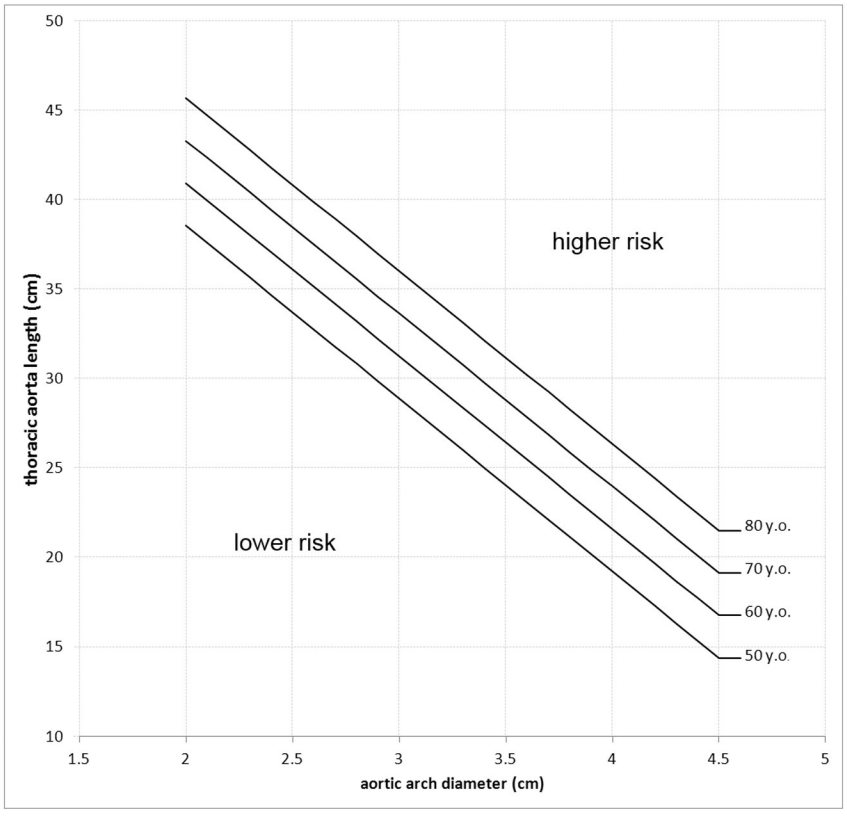

Fig. 5. Risk model of aortic dissection using thoracic aorta length and mean aortic arch diameter as anatomic variables indexed to age ($r^2 = 0.72$, AUC = 0.9764). The 90% probability of AAD curves adjusted for age are shown.

management of TBADs [2], the fact that TL size is age-dependent might be of clinical implications for pre-procedural planning regarding vascular access and for complications as TL collapse or vessel malperfusion.

Some limitations of this study need to be addressed. Our results should be interpreted with caution due to the retrospective nature of our case-control study and the small size of each group. Only the thoracic aorta was measured. Some scans covered the abdominal aorta, but they were more prone to contrast artifacts. The automated algorithm still needs manual interventions. We are currently exploring to gradually incorporate new tools to automatically describe the morphology of entry tears and the false lumen patency. Nevertheless, it seems potentially useful even for other applications like TEVAR planning for dissection patients. The fact that volumes were not helpful contributors into the final risk prediction model does not mean their assessment was redundant because all diameter and length measurements were ultimately based on the volume technique. Finally, the analysis made in this study was essentially structural and not functional. The interaction of aortic dilatation and elasticity with aging would certainly improve TBAD prediction [24], suggesting that structural and functional measurements should be visualized as a future strategy to better understand aortic diseases.

5. Conclusions

In this study we show that the probability of TBAD increases with a larger aortic arch diameter and a longer thoracic aorta, whereas threshold values increase with age. In fact, age was not only associated with most of the three-dimensional anatomical variables assessed in patients with and without TBAD, but also with the true lumen volume after dissection occurs. These findings, which encourage the calculation of threshold values indexed to age to predict TBAD risk, should help to identify vulnerable patients, better prevent and eventually treat TBAD.

Conflicts of interest statement

The authors report no relationships that could be construed as a conflict of interest.

Acknowledgements

The authors thank Eng. Sandra Wray for her invaluable help in the correction of this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ijcard.2016.11.125.

References

[1] R. Erbel, V. Aboyans, C. Boileau, E. Bossone, R.D. Bartolomeo, H. Eggebrecht, 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. 35 (2014) 2873–2926.
[2] L.A. Pape, M. Awais, E.M. Woznicki, T. Suzuki, S. Trimarchi, A. Evangelista, et al., Presentation, diagnosis, and outcomes of acute aortic dissection: 17-year trends from the International Registry of Acute Aortic Dissection, J. Am. Coll. Cardiol. 66 (2015) 350–358.
[3] R. Karmy-Jones, A. Simeone, M. Meissner, B. Granvall, S. Nicholls, Descending thoracic aortic dissections, Surg. Clin. North Am. 87 (2007) 1047–1086 (viii-ix).
[4] P.G. Hagan, C.A. Nienaber, E.M. Isselbacher, D. Bruckman, D.J. Karavite, P.L. Russman, et al., The International Registry of Acute Aortic Dissection (IRAD): new insights into an old disease, JAMA 283 (2000) 897–903.
[5] S. Trimarchi, F.H. Jonker, J.B. Froehlich, G.R. Upchurch, F.L. Moll, B.E. Muhs, et al., Acute type B aortic dissection in the absence of aortic dilatation, J. Vasc. Surg. 56 (2012) 311–316.
[6] A.S. Shirali, M.S. Bischoff, H.M. Lin, I. Oyfe, R. Lookstein, R.B. Griepp, et al., Predicting the risk for acute type B aortic dissection in hypertensive patients using anatomic variables, JACC Cardiovasc. Imaging 6 (2013) 349–357.
[7] D. Craiem, G. Chironi, A. Redheuil, M. Casciaro, E. Mousseaux, A. Simon, et al., Aging impact on thoracic aorta 3D morphometry in intermediate-risk subjects: looking beyond coronary arteries with non-contrast cardiac CT, Ann. Biomed. Eng. 40 (2012) 1028–1038.
[8] A. Redheuil, W.C. Yu, E. Mousseaux, A.A. Harouni, N. Kachenoura, C.O. Wu, et al., Age-related changes in aortic arch geometry: relationship with proximal aortic function and left ventricular mass and remodeling, J. Am. Coll. Cardiol. 58 (2011) 1262–1270.
[9] J. Sugawara, K. Hayashi, T. Yokoi, H. Tanaka, Age-associated elongation of the ascending aorta in adults, j. Am. Coll. Cardiol. Img. 1 (2008) 739–748.
[10] M.E. Casciaro, S. El-Batti, G. Chironi, A. Simon, E. Mousseaux, R.L. Armentano, et al., Deformable surface model for the evaluation of abdominal aortic aneurysms treated with an endovascular sealing system, Ann. Biomed. Eng. (2015).
[11] J.V. Miller, D.E. Breen, W.E. Lorensen, R.M. O'Bara, M.J. Wozny, Geometrically deformed models: a method for extracting closed geometric models form volume data, SIGGRAPH Comput. Graph. 25 (1991) 217–226.
[12] J.-Y. Park, T. McInerney, D. Terzopoulos, M.-H. Kim, A non-self-intersecting adaptive deformable surface for complex boundary extraction from volumetric images, Comput. Graph. 25 (2001) 421–440.
[13] D. Terzopoulos, A. Witkin, M. Kass, Constraints on deformable models: recovering 3D shape and nonrigid motion, Artif. Intell. 36 (1988) 91–123.
[14] E.W. Steyerberg, F.E. Harrell Jr., G.J. Borsboom, M.J. Eijkemans, Y. Vergouwe, J.D. Habbema, Internal validation of predictive models: efficiency of some procedures for logistic regression analysis, J. Clin. Epidemiol. 54 (2001) 774–781.
[15] S. Trimarchi, F.H. Jonker, S. Hutchison, E.M. Isselbacher, L.A. Pape, H.J. Patel, et al., Descending aortic diameter of 5.5 cm or greater is not an accurate predictor of acute type B aortic dissection, J. Thorac. Cardiovasc. Surg. 142 (2011) e101–e107.
[16] B. Rylski, B. Desjardins, W. Moser, J.E. Bavaria, R.K. Milewski, Gender-related changes in aortic geometry throughout life, Eur. J. Cardiothorac. Surg. 45 (2014) 805–811.
[17] A. Wolak, H. Gransar, L.E.J. Thomson, J.D. Friedman, R. Hachamovitch, A. Gutstein, et al., Aortic size assessment by noncontrast cardiac computed tomography: normal limits by age, gender, and body surface area, J. Am. Coll. Cardiol. Img. 1 (2008) 200–209.
[18] D. Craiem, G. Chironi, M.E. Casciaro, A. Redheuil, E. Mousseaux, A. Simon, Three-dimensional evaluation of thoracic aorta enlargement and unfolding in hypertensive men using non-contrast computed tomography, J. Hum. Hypertens. 27 (2013) 504–509.
[19] E.B. Turkbey, A. Jain, C. Johnson, A. Redheuil, A.E. Arai, A.S. Gomes, et al., Determinants and normal values of ascending aortic diameter by age, gender, and race/ethnicity in the Multi-Ethnic Study of Atherosclerosis (MESA), J. Magn. Reson. Imaging 39 (2014) 360–368.
[20] B. Rylski, P. Blanke, F. Beyersdorf, N.D. Desai, R.K. Milewski, M. Siepe, et al., How does the ascending aorta geometry change when it dissects? J. Am. Coll. Cardiol. 63 (2014) 1311–1319.
[21] D. Craiem, J.M. Alsac, M.E. Casciaro, S. El Batti, E. Mousseaux, M.E. Sirieix, et al., Association between thoracic aorta calcium and thoracic aorta geometry in a cohort of asymptomatic participants at increased cardiovascular risk, Rev. Esp. Cardiol. (Engl. Ed.) 69 (2016) 827–835.
[22] I.D. Andacheh, C. Donayre, F. Othman, I. Walot, G. Kopchok, R. White, Patient outcomes and thoracic aortic volume and morphologic changes following thoracic endovascular aortic repair in patients with complicated chronic type B aortic dissection, J. Vasc. Surg. 56 (2012) 644–650 (discussion 50).
[23] J.L. Tolenaar, J.W. van Keulen, F.H. Jonker, J.A. van Herwaarden, H.J. Verhagen, F.L. Moll, et al., Morphologic predictors of aortic dilatation in type B aortic dissection, J. Vasc. Surg. 58 (2013) 1220–1225.
[24] J.L. Cavalcante, J.A. Lima, A. Redheuil, M.H. Al-Mallah, Aortic stiffness: current understanding and future directions, J. Am. Coll. Cardiol. 57 (2011) 1511–1522.