Original Article

Accuracy of aortic annulus measurements by three-dimensional transesophageal echocardiography and predictive value for thoracic aorta aneurysm in patients with aortic regurgitation

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Background: Accurate assessment of the aortic annulus (AA) dimension and judgment of thoracic aorta aneurysm is crucial for patients with aortic regurgitation (AR) before surgery. The aim of this study was to evaluate the accuracy and reproducibility of three-dimensional transesophageal echocardiography (3D-TEE) methods for AA measurement and explore the predictive value of the AA dimensions obtained by 3D-TEE for high-risk thoracic aorta aneurysms using the gold standard of multi-slice computed tomography (MSCT).

Methods: 3D-TEE was performed on 111 patients with pure moderate-to-severe AR, and MSCT examination was conducted simultaneously. AA dimensions were obtained using reconstruction software for these two imaging techniques. Thoracic aortic diameters at standard anatomic landmarks were also measured by MSCT. All patients were divided into two groups depending on the presence of high-risk thoracic aorta aneurysms.

Results: Compared to MSCT, 3D-TEE overestimated all AA parameters. However, no statistically significant differences were found in the average bias between methods (minimum diameter: 26.07±3.57 *vs.* 25.88±3.68 mm, P=0.52; maximum diameter: 32.30±2.68 *vs.* 31.78±4.06 mm, P=0.11; area: 669.76±155.19 *vs.* 660.05±168.28 mm^2, P=0.44; perimeter: 93.52±10.42 *vs.* 92.26±11.71 mm, P=0.12). 3D-TEE demonstrated good correlations with MSCT measurement for AA minimum diameter, maximum diameter, area, and perimeter (r=0.63, 0.64, 0.74, 0.69, P<0.05 for all). According to the multivariate logistic regression analysis, the AA minimum diameter obtained by 3D-TEE was the best predictor for the presence of high-risk thoracic aorta aneurysms. The sensitivity and specificity for prediction were 84.6% and 63.9%, respectively, for an AA minimum diameter ≥25.74 mm (AUC: 0.759, 95% CI: 0.668–0.850).

Conclusions: AA measurements obtained by the 3D-TEE method are feasible and reliable for patients with pure AR. The AA minimum diameter measured by 3D-TEE can effectively predict the presence of high-risk thoracic aorta aneurysms.

Keywords: Three-dimensional transesophageal echocardiography (3D-TEE); aortic regurgitation (AR); aortic annulus (AA); thoracic aorta aneurysm

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Introduction

Aortic regurgitation (AR) is a common form of valvular disease. The prevalence of AR has also gradually increased as the average human lifespan has lengthened (1). Consequently, more patients undergo aortic valve replacement/valvuloplasty due to severe AR. Meanwhile, for high-risk or inoperable patients, transcatheter aortic valve implantation may be considered for selected patients with AR in experienced centers (2,3). An accurate preoperative evaluation of the aortic annulus (AA) is of critical importance to reduce the occurrence of complications, regardless of the type of surgery. Currently, multi-slice computed tomography (MSCT) is a highly valuable tool for the workup of patients with aortic valve disease and can accurately evaluate AA dimensions (4). Three-dimensional transesophageal echocardiography (3D-TEE) has also been widely applied as a routine preoperative and intraoperative evaluation for aortic valve surgery. However, relevant studies primarily focused on patients with aortic stenosis. Thus, the first purpose of the present study is to explore whether 3D-TEE can accurately measure AA dimensions in patients with AR, with MSCT as a standard approach.

Meanwhile, the etiology of AR is complex and multifactorial, and most patients have concomitant different degrees of aortic dilatation. Preoperative imaging evaluation of severe AR should focus not only on the accurate measurement of AA but also on the detection of high-risk thoracic aorta aneurysms, which is important for the selection of surgical protocols and postoperative follow-up observation. At the anatomical level, the thoracic aorta and the aortic root, including the sinotubular junction, sinus of Valsalva, and AA, are continuous integral structures. A previous study pointed out that aortic annuloplasty can efficiently reduce the annulus and the rate of reoperation in patients with ascending aorta aneurysms, which may be associated with preventing further dilation of the aorta (5). In contrast, postoperative dilation of the AA may lead to the early or late recurrence of AR and aortic aneurysms (6). Thus, we hypothesized that AA dimensions may have predictive value in the existence of thoracic aorta aneurysms. The second purpose of the present study is to explore whether AA dimensions can predict the occurrence of thoracic aorta aneurysm detected by MSCT scan, based on the foundation of accurate measurement of AA dimensions by 3D-TEE. We present the following article in accordance with the GRRAS reporting checklist (available at https://qims.amegroups.com/article/view/10.21037/qims-22-341/rc).

Methods

Study population

From August 2018 to December 2020, 160 patients indicated for aortic valve replacement/valvuloplasty due to pure moderate-to-severe AR undergoing intraoperative 3D-TEE and preprocedural MSCT examination at our institution were consecutively enrolled in this cross-sectional study. The two examinations were performed no more than one week apart. The exclusion criteria were evidence of aortic valve stenosis (n=18), aortic acute or chronic dissection (n=10), aortic coarctation and/or other forms of congenital heart disease (n=7), Marfan syndrome or a family history of Marfan syndrome (n=3), and previous surgery or intervention (n=3). In addition, patients with poor imaging quality were also excluded from the study (n=8). Eventually, 111 patients were included in this study. Clinical characteristics were prospectively collected from the hospital information system and retrospectively analyzed. This study was conducted following the Declaration of Helsinki (as revised in 2013). The protocol was approved by the Institutional Ethics Committee of Fuwai Hospital (No. 2019-1201), and informed consent was obtained from all individual participants.

MSCT acquisition protocol and AA measurements

MSCT data sets were obtained using a second-generation dual source CT system (SOMATOM Definition Flash, Siemens Healthcare, Germany). The data acquisition protocol was described previously in the published article of our research group (7). The imaging volume extended from the aortic arch to the level of the diaphragm in a craniocaudal direction. For assessment of AA dimensions, MSCT images were transferred to an offline post-processing workstation (Leonardo Workstation, Siemens Healthcare, Forchheim, Germany). MSCT measurements were performed by one experienced radiologist. The concept of a basal annular plane comprises a virtual plane connecting the three lowest insertion points of aortic valve cusps in each of the three sinuses. Multiplanar reconstructions were manually oriented to display AA (8). After creating an oblique multiplanar reconstruction exactly aligned with the AA plane, the following dimensions of AA were measured: minimum diameter, maximum diameter, area, and perimeter (*Figure 1*). All examinations were analyzed between 35–45% R-R intervals, when the annulus was in the systolic period, and the clearest image was selected. In addition, the

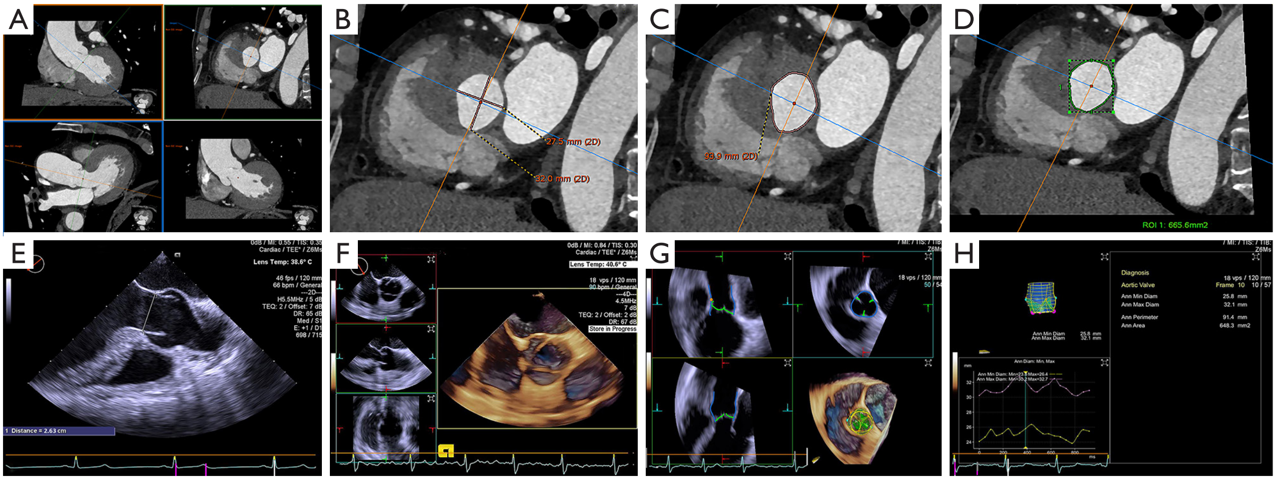

Figure 1 Illustration of aortic annular measurement methods. (A-D) Measurement of aortic annulus dimensions by MSCT. The basal annular plane is defined as a plane perpendicular to the curved axis that touches the lowest points of the valves. After tracing the border of the annulus by placing plots at the blood-tissue interface, the AA maximum, minimum diameter, area, and perimeter were calculated. (E) Measurement of aortic annulus diameter by 2D-TEE in the mid-esophageal position long-axis view during mid-systole. (F-H) Measurement of the aortic annulus by 3D-TEE analytical software. A model of the aortic annulus is created on the basis of detected landmarks automatically, and observers can manually correct the landmarks from different views at different levels. Eventually, quantitative annular parameters in a whole cardiac cycle are exported. MSCT, multi-slice computed tomography; AA, aortic annulus; 2D-TEE, two-dimensional transesophageal echocardiography; 3D-TEE, three-dimensional transesophageal echocardiography.

measurement of thoracic aortic dimensions at standard anatomic landmarks and the definition of aortic dilatation were performed according to the guidelines of the American College of Radiology (9).

Transthoracic and transesophageal echocardiography measurements

Two-dimensional transthoracic echocardiography (2D-TTE) was performed as a part of preoperative evaluation within 1 week before surgery using a Philips EPIQ 7C ultrasound device (Philips Medical Systems, Andover, MA, USA). The left ventricular end-diastolic diameter and end-systolic diameter were obtained from the left parasternal long-axis view. The left ventricular ejection fraction was assessed by the biplane Simpson method. The vena contracta width of the AR jet was also measured according to the American Society of Echocardiography guidelines (10).

TEE was performed using a Siemens ACUSON SC2000 ultrasound system (Siemens Medical Systems, Mountainview, CA) equipped with the transesophageal Z6Ms True Volume transducer. For 2D-TEE evaluation of AA, measurements were taken at the point of the insertion of the valve cusps in the mid-esophageal long axis view with scanning plans from 115–160°. 3D-TEE images for subsequent reconstruction were acquired in the same position using ZOOM mode of the aortic valve apparatus after adjustment of lateral and elevation width to optimize the frame rate (range, 16–25 fps). Three beat, ECG-gated, and full-volume images were used for data analysis.

Online semiautomated 3D measurements were conducted using eSie Valve analytical software (Siemens Medical Systems, Mountainview, CA) that could model the annulus automatically. Observers could verify the landmarks of the automated model and manually correct them from a long axis view of the 3D image shown in different long planes and a short axis view at different levels. Finally, the cyclic changes in the parameters were displayed as a graph (*Figure 1*). The available parameters also included the AA minimum diameter (AA_{min}), maximum diameter (AA_{max}), area (AA_{area}), and perimeter (AA_{peri}). The mid-systolic frame was selected for this analysis. The circularity of AA was indicated by the eccentricity index (maximum diameter/ minimum diameter). All measurements (MSCT and TEE) were measured three times by the same operator based on the same image, and the results shown were averaged. The results were blinded to the different methods of measurement (MSCT and 3D-TEE).

Statistical analysis

Normality of distributions for continuous variables was tested using the Kolmogorov-Smirnov test. Quantitative values are expressed as the mean ± SD, and categorical variables are represented as absolute numbers or proportions. An independent *t*-test was used to compare continuous values between two groups, and categorical variables were compared using the χ^2 test or Fisher's exact test. Pearson correlation coefficients were used to assess the correlation between MSCT and 3D-TEE measurements. Agreement between techniques was plotted using the Bland-Altman method. Predictors of thoracic aorta aneurysms were identified through univariate and multivariate logistic regression models. The cutoff value was determined from the area under the receiver operating characteristic (ROC) curve (AUC) to provide the best sensitivity and specificity for each parameter for prediction. Comparisons of AUCs were performed using the method described by DeLong *et al.* (11). Differences were considered significant at P<0.05. All analyses were performed using SPSS 24.0 (IBM Corp., Armonk, NJ, USA), MedCalc 18.2.1 (MedCalc Software, Ltd., Ostend, Belgium), and GraphPad Prism 8.0.2 (GraphPad Software, San Diego, CA, USA).

Results

Study population

The population consisted of 15 women and 96 men with a mean age of 54.5±12.1 years. Forty-seven patients were judged as having severe AR and 64 had moderate AR. According to the surgical results, all patients in the AR group had tricuspid aortic valves. The etiology of AR was determined via *de novo* review of the intraoperative TEE, surgical direct observation, and pathology reports. The AR mechanisms were categorized as cusp prolapse (n=34, 30.6%), aortic root dilatation (n=35, 31.5%), and cusp restriction/retraction (n=42, 37.9%). In the present study, all patients received aortic valve surgery (aortic valve replacement or valvuloplasty). Concomitant surgical procedures included coronary artery bypass grafting surgery and/or mitral valve annuloplasty. The demographic features and preoperative clinical characteristics of the patients are presented in *Table 1*.

All patients underwent a standard MSCT examination containing the whole thoracic aorta. The diameters of the aorta were measured at eight anatomical landmarks. High-risk thoracic aortic aneurysms requiring surgical intervention were defined as aortic diameters larger than 55 mm at a certain position as measured by MSCT reconstruction. Eventually, the AR group was further divided into Group I (aortic diameter <55 mm, n=71) and Group II (aortic diameter ≥55 mm, n=40). No significant differences were found between Group I and Group II in age, sex, body surface area, medical history, or primary 2D-TTE findings. Compared to Group I, Group II had a significantly larger AA diameter, area, and perimeter (*Table 1*).

Accuracy and reproducibility of AA measurements by 3D-TEE

As reported in *Table 2* and *Figure 2*, AA parameters derived from 3D-TEE had moderate to high correlation with the MSCT reference values (AA_{min}: r=0.63; AA_{max}: r=0.64; AA_{area}: r=0.74; AA_{peri}: r=0.69, P<0.05 for all). Good agreement between 3D-TEE and MSCT measurements was also observed. Bland-Altman comparison demonstrated a mean difference of 0.19 mm between 3D-TEE and MSCT for AA_{min} with a 95% CI of −0.40 to 0.78 for this bias, 0.51 mm for AA_{max} with a 95% CI of −0.10 to 1.13, 9.71 mm^2 for AAarea with a 95% CI of −12.22 to 31.64, and 1.25 mm for AA_{peri} with a 95% CI of −0.40 to 2.90, respectively. No differences were found in average bias between methods (P>0.05). On average, the 3D-TEE method overestimated all AA parameters compared to MSCT.

Meanwhile, to assess the reproducibility of 3D-TEE measurements, 50 subjects were randomly selected. All echocardiography findings were evaluated independently by two experienced echocardiographers. For intraobserver variability, the same operator performed a second measurement after the initial analysis. For interobserver variability, measurements were taken by a second operator. The second investigator was blinded to the initial results. Through Bland-Altman analysis, the intraclass correlation coefficient for intraobserver variability ranged from 0.77 to 0.90, and interobserver variability ranged from 0.75 to 0.88 (*Table 3*). The results showed that AA measurements performed by 3D-TEE had good reproducibility.

Predictors of high-risk thoracic aorta aneurysm and ROC curve analysis

In the univariate logistic regression analysis, 2D-TEE AA diameter, 3D-TEE AA_{min}, 3D-TEE AA_{max}, 3D-TEE AA_{area}, and 3D-TEE AA_{peri} correlated with high-risk thoracic aorta aneurysm. Due to significant correlations between these

Table 1 Clinical data and echocardiographic findings

Variables	All patients (n=111)	Group I (n=71)	Group II (n=40)	P value (Group I *vs*. Group II)
Demographic features				
Age (years)	54.5±12.1	55.4±11.1	52.9±13.8	0.31
Sex (M/F)	96/15	63/8	33/7	0.19
Weight (kg)	73.6±17.0	73.9±19.7	72.9±10.8	0.76
Height (cm)	168.9±15.2	167.0±17.7	172.4±7.7	0.07
BSA (m^2)	1.8±0.2	1.8±0.2	1.8±0.2	0.59
Clinical characteristics, n (%)				
NYHA functional class III–IV	36 (32.43)	24 (33.80)	12 (30.00)	0.18
Smoking	53 (47.75)	35 (49.30)	18 (45.00)	0.81
Hypertension	51 (45.95)	44 (61.97)	17 (42.50)	0.08
Peripheral vascular disease	3 (2.70)	1 (1.41)	2 (5.00)	0.28
Previous cardiac surgery	7 (6.31)	3 (4.23)	4 (10.00)	0.21
2D Transthoracic echocardiography findings				
Mitral regurgitation, n (%)	69 (62.16)	50 (70.42)	19 (47.50)	0.03*
AR vena contracta width (mm)	6.5±2.0	6.6±1.7	6.3±2.5	0.46
LV end-diastolic diameter (mm)	62.7±9.7	63.4±8.5	61.5±11.6	0.35
LV end-systolic diameter (mm)	41.3±10.1	42.2±8.8	39.6±12.1	0.24
LV ejection fraction (%)	59.7±6.8	59.39±6.8	60.3±6.9	0.50
Transesophageal echocardiography parameters				
2D-Aortic annulus diameter (mm)	25.95±2.72	25.51±2.79	26.78±2.41	0.02*
3D-Aortic annulus min diameter (mm)	26.07±3.57	25.27±3.53	27.53±3.19	<0.01*
3D-Aortic annulus max diameter (mm)	32.30±2.68	31.65±3.66	33.50±3.44	0.01*
3D-Aortic annulus area (mm^2)	669.76±155.19	643.73±161.39	717.83±131.89	0.02*
3D-Aortic annulus perimeter (mm)	93.52±10.42	91.40±10.56	97.43±9.02	<0.01*
Ellipticity index	1.25±0.12	1.26±0.12	1.22±0.11	0.11

Data are presented as mean ± standard deviation or number (frequency). *, P<0.05 for independent-sample *t* tests. BSA, body surface area; NYHA, New York Heart Association; AR, aortic regurgitation; LV, left ventricle.

Table 2 Correlations and agreement between 3D-TEE and MSCT for the measurement of the aortic annulus dimensions

	3D-TEE measurement	MSCT measurement	r	Mean bias (95% CI)	95% LOA
Aortic annulus min diameter (mm)	26.07±3.57	25.88±3.68	0.63*	0.19 (–0.40 to 0.78)	–5.95 to 6.32
Aortic annulus max diameter (mm)	32.30±2.68	31.78±4.06	0.64*	0.51 (–0.10 to 1.13)	–5.91 to 6.94
Aortic annulus area (mm^2)	669.76±155.19	660.05±168.28	0.74*	9.71 (–12.22 to 31.64)	–218.78 to 238.20
Aortic annulus perimeter (mm)	93.52±10.42	92.26±11.71	0.69*	1.25 (–0.40 to 2.90)	–15.96 to 18.47

Data are presented as mean ± standard. *, P<0.05 for Pearson correlation analysis. 3D-TEE, three-dimensional transesophageal echocardiography; MSCT, multi-slice computed tomography; CI, confidence interval; LOA, limits of agreement.

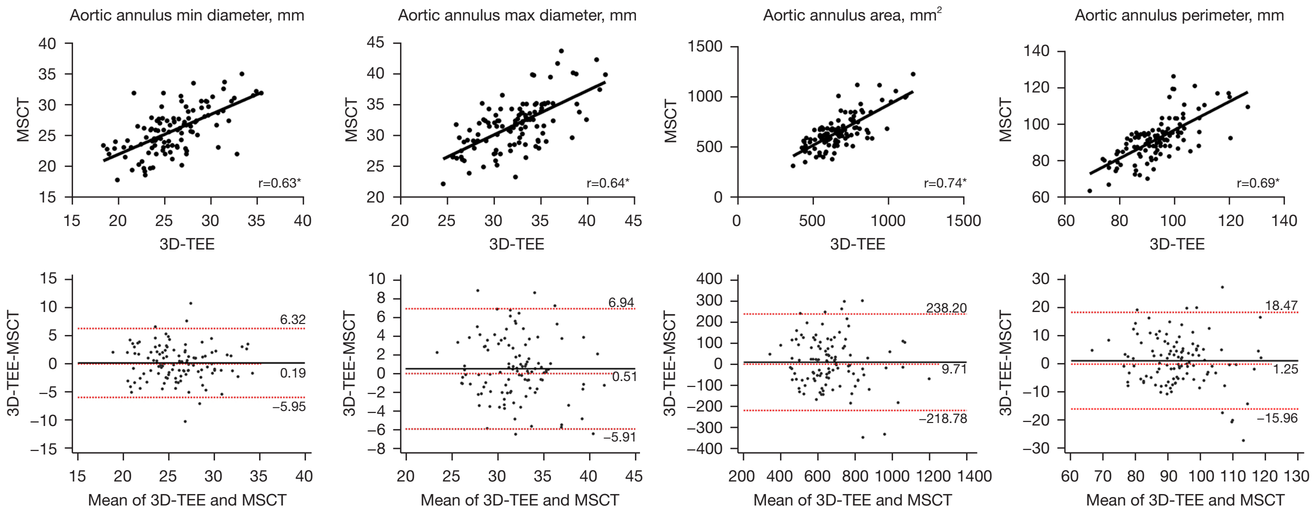

Figure 2 Correlations and agreement between 3D-TEE and MSCT measurements for aortic annulus dimensions. *, P<0.05 for Pearson correlation analysis. 3D-TEE, three-dimensional transesophageal echocardiography; MSCT, multi-slice computed tomography.

Table 3 Intra- and interobserver variabilities for measurement of the aortic annulus by 3-dimensional transesophageal echocardiography

	Intraobserver		Interobserver	
	Intraclass correlation coefficient	95% CI	Intraclass correlation coefficient	95% CI
Aortic annulus min diameter (mm)	0.83*	0.71–0.90	0.75*	0.56–0.86
Aortic annulus max diameter (mm)	0.77*	0.63–0.87	0.76*	0.61–0.86
Aortic annulus area (mm^2)	0.90*	0.83–0.94	0.88*	0.79–0.93
Aortic annulus perimeter (mm)	0.86*	0.77–0.92	0.80*	0.68–0.88

*, P<0.05 for Bland–Altman analysis. CI, confidence interval.

parameters, multivariate logistic regression analysis was performed separately to determine independent variables of AA parameters associated with thoracic aorta aneurysm in patients with AR. After multivariate adjustment for traditional risk factors, including age, sex and BSA (12), all of these parameters remained independent (*Table 4*).

ROC curves were generated to determine the accuracy of the AA parameters most associated with high-risk thoracic aorta aneurysm. As presented in *Figure 3*, AA_{min} measured by 3D-TEE had the largest AUC (AUC: 0.759, 95% CI: 0.668–0.850, P<0.05), and it was used to calculate optimal cutoff values for prediction. A cutoff value of 25.74 mm for 3D-TEE AA_{min} provided a sensitivity of 84.6% and a specificity of 63.9%. Comparisons of AUCs showed that the AUC of 3D-TEE AA_{min} was superior to the AA diameter measured by 2D-TEE and AA_{max} (0.759 *vs.* 0.642, and 0.759 *vs.* 0.676; P<0.05). The AUC of 3D-TEE AA_{min} was similar to the aortic annular parameters obtained by 3D-TEE (AA_{area}, 0.696, and AA_{peri}, 0.709; all P>0.05).

Discussion

The main findings of the present study are as follows: For patients with pure moderate-to-severe AR, (I) 3D-TEE measurement of AA is feasible, reliable with a good correlation between 3D-TEE and MSCT measurements, and reproducible with a low intraobserver and interobserver variability. (II) The AA minimum diameter obtained by 3D-TEE was a predictive parameter to indicate the presence of high-risk thoracic aorta aneurysm detected by MSCT examination.

Accuracy of AA measurements by 3D-TEE in patients with AR

Accurate AA measurements are essential for the selection

Table 4 Univariate and multivariate logistic regression analyses for predicting thoracic aorta dilatation

Variables	Logistic regression analysis	β	95% CI	P value
2D-TEE Aortic annulus diameter (mm)	Univariate analysis	1.19	1.03–1.39	0.02*
	Adjusted for age, gender, and BSA	1.21	1.02–1.44	0.03*
3D-TEE Aortic annulus min diameter (mm)	Univariate analysis	1.21	1.07–1.37	<0.01*
	Adjusted for age, gender, and BSA	1.23	1.07–1.41	<0.01*
3D-TEE Aortic annulus max diameter (mm)	Univariate analysis	1.16	1.03–1.30	0.01*
	Adjusted for age, gender, and BSA	1.15	1.01–1.31	0.04*
3D-TEE Aortic annulus area (mm^2)	Univariate analysis	1.00	1.00–1.01	0.02*
	Adjusted for age, gender, and BSA	1.00	1.00–1.01	0.04*
3D-TEE Aortic annulus perimeter (mm)	Univariate analysis	1.06	1.02–1.11	<0.01*
	Adjusted for age, gender, and BSA	1.07	1.02–1.12	0.01*
Ellipticity index	Univariate analysis	0.05	0.01–1.96	0.11
	Adjusted for age, gender, and BSA	0.02	0.01–0.77	0.06

*, P<0.05 for logistic regression analysis. 2D-TEE, two-dimensional transesophageal echocardiography; 3D-TEE, three-dimensional transesophageal echocardiography; BSA, body surface area; CI, confidence interval.

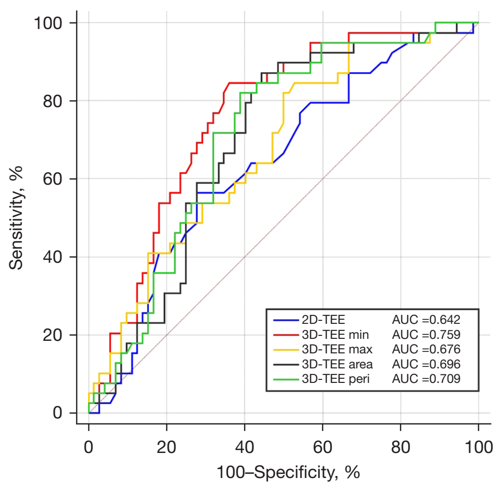

Figure 3 Receiver operating characteristic curve analyses to determine the most predictive aortic annulus parameters associated with high-risk thoracic aorta aneurysm. 2D-TEE, two-dimensional transesophageal echocardiography; 3D-TEE, three-dimensional transesophageal echocardiography; AUC, area under the curve.

of surgical strategies and the sizing of valve prostheses. Previous studies have reported that for patients with severe aortic stenosis, MSCT can provide accurate AA measurements (13-17). However, unlike aortic stenosis, the etiology of AR is complex and multifactorial. Calcification of the aortic valve leaflets and annulus is much less common in AR. Thus, the advantages of CT imaging for identifying calcifications cannot be entirely highlighted. Moreover, in real clinical practice, not all patients with AR undergo preoperative MSCT examination for annulus evaluation. The primary aim of MSCT examination for AR patients is to investigate concomitant diseases, such as coronary arteriosclerotic disease or congenital coronary artery anomalies, aortic diseases and other anatomical variations. In addition, MSCT scans are not available for patients with severe renal dysfunction and young patients. Thus, for patients with AR, the MSCT examination may not play as large a role in aortic annular quantification as previously reported. The present study only enrolled patients with pure AR and clarified whether 3D-TEE can serve as an alternative to MSCT scans in such patients to perform AA measurements. To our knowledge, this study is the first to address this issue.

The results of this study showed that the AA measurements obtained by 3D-TEE were accurate and highly correlated with the MSCT method with acceptable interobserver and intraobserver variability. However, with regard to the differences between the two measurements, some degree of overestimation and greater variability of AA dimensions obtained by 3D-TEE was observed, which was somewhat different from the results of previous studies (13-17). The different results can be explained based on several factors. First, the present study population was different compared with other studies. All the above studies included some patients with severe aortic stenosis, which may have interfered with the results. The results of our study also provide indirect evidence that the AA measurement obtained by 3D-TEE in AR patients is quite different from that in patients with aortic stenosis. Meanwhile, AR patients differ significantly regarding their AA dimensions compared to aortic stenosis patients (18). Greater variability in the measurements obtained by 3D-TEE is partially due to the larger AA dimensions in patients with AR. Second, 3D-TEE analytical software was different in the present study, which can perform automated reconstruction and analysis of the aortic root using a predefined algorithm. However, this imaging reconstruction algorithm is created based on a normal AA structure. There will be some deviation in the extraction of corresponding data from the abnormal AA. Moreover, because the analysis was performed in semiautomatic mode during the reconstruction process, this result may be explained by a "correction bias" either in the software's algorithm or introduced by the operator during the editing of reference points to correct the expected underestimation previously reported with 3D-TEE. A previous study using the same image processing software also reported overestimation of the AA diameter (19). Although this overestimation was not significant in statistical analyses, the results of the present study still need to be interpreted with caution and validated in additional studies.

Predictive value of AA dimensions for high-risk thoracic aorta aneurysm

According to the guidelines for the diagnosis and management of thoracic aortic disease, excessive thoracic aortic dilatation (maximum diameter ≥55 mm) poses a significant risk for the occurrence of acute aortic events, and patients with aneurysms beyond this size should be referred for preventive surgical intervention (20). We therefore selected this value as a grouping criterion for patients. Currently, MSCT is the preferred technique for accurately measuring aortic dimensions from different directions by the 3D reconstruction method (21). The present study indicated that clinicians should be vigilant about the presence of high-risk thoracic aortic aneurysms when 3D-TEE AA_{min} is greater than 25.74 mm, and MSCT scans are recommended for accurate assessments of the thoracic aorta condition in these patients. It is generally accepted that the AA is not entirely a circular structure. The annular eccentricity originates predominantly from the difference in AA_{min}. Dilatation of the aortic root or its distal artery generally results in AA morphological abnormalities. Jilaihawi and colleagues suggested that patients with larger ascending aorta dimensions had a slightly less elliptical annulus, as reflected by a larger eccentricity ratio, which was driven by a larger AA_{min} (22). Petersen and coworkers also found that the increase in AA_{min} gradually became obvious as the dimensions of the annulus extended (23). All of these studies illustrated that the AA_{min} was relatively sensitive to aortic morphological changes. Owing to the interrelations, the finding that thoracic aorta aneurysm could be predicted by AA_{min} can be partially explained.

Meanwhile, we noted that the AA diameter measured by 2D-TEE also had a certain predictive value by logistic regression analyses. From the perspective of viewing angle, the mid-esophageal long-axis view on TEE is equivalent to the single oblique sagittal view on MSCT scans (24). Thus, the AA diameter measured by 2D-TEE actually also reflects the situation of AA_{min}. In real clinical settings, the AA diameter measured by 2D-TEE can be conveniently obtained. However, the AUC value of this parameter was relatively smaller than that of 3D-TEE AA_{min} through statistical comparison. Hence, methods of selecting suitable aortic annular parameters applied to clinical decision-making remain worthy of exploration. Next, our research group will perform more comparative studies to clarify the superiority and inferiority of various indicators.

Clinical implications

Currently, surgical procedures have increasingly higher requirements for preoperative imaging assessment. However, there are no certain cardiovascular imaging examinations to achieve a complete preoperative diagnosis and evaluation of patients with AR alone. Different approaches have advantages and disadvantages (4,21). Previous studies showed that TEE had unique advantages in differentiating the etiology and confirming the degree of AR (25,26). The current study confirmed that the 3D-TEE method may also be used to accurately measure primary AA dimensions, which increased the clinical application value of 3D-TEE for patients with AR. Meanwhile, MSCT has unique advantages in the evaluation of thoracic aorta, especially in the detection of high-risk thoracic aorta aneurysms. The results of the current study demonstrated that AA_{min} obtained by 3D-TEE showed a suggestive effect on the presence of high-risk thoracic aorta aneurysms. At

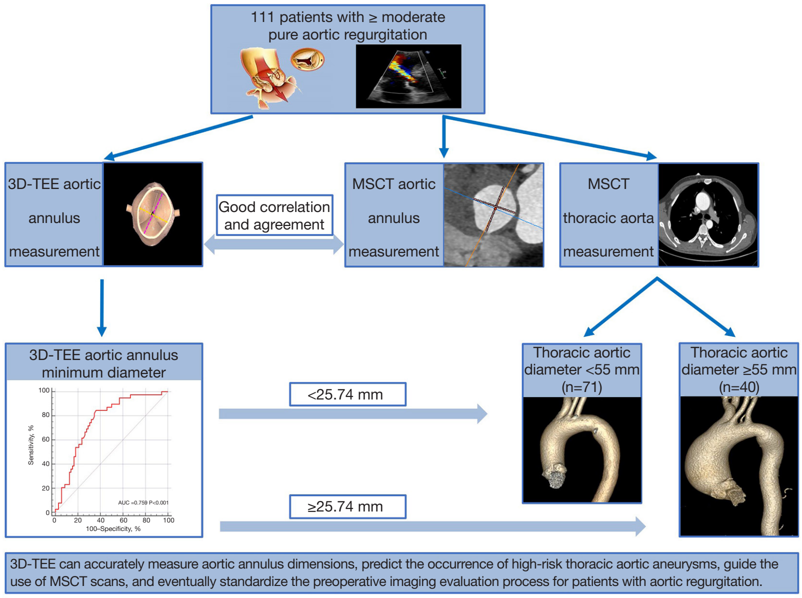

Figure 4 Schematic summarizing the main conclusions of the study. 3D-TEE, three-dimensional transesophageal echocardiography; MSCT, multi-slice computed tomography.

our institute, almost all the patients with severe AR received MSCT reconstruction of the whole aorta before surgery. It seems unreasonable for some of the patients. We expect that our results will help reduce (at least to some extent) unnecessary examinations in these patients and standardize the preoperative imaging evaluation process, especially in the era of rapid development of transcatheter repair or replacement techniques. However, the preoperative evaluation process includes more complicated situations and factors and cannot be determined by a single study. The present study only provides references from one aspect, and additional research is needed to explore this further.

Limitations

The study was a single-center observational study, without long-term follow-up of the patients to assess clinical outcomes. The conclusion of this study requires verification in large and prospective studies. The AA dimensions were only analyzed when MSCT imaging was in the systolic period. Many studies have confirmed that AA dimensions measured during systole and diastole are different (27,28). However, MSCT scans were performed by prospectively ECG-triggered acquisition mode, and therefore, only images at 25–75% of the R-R interval were available in the present study, which was based on the principle to maximally limit the amount of patient radiation exposure and satisfied the ethical considerations. Meanwhile, it is widely recognized by clinicians that AA measurements should ideally be performed in the systolic period to achieve the greatest annular stretch (29). Thus, the measurement schemes met the practical clinical requirements. Furthermore, the consistency between the 3D-TEE measurements and prosthetic valve size was not examined in this study primarily because the prosthetic aortic valves were produced from different manufacturers. We also did not measure the diameter of the prosthetic aortic valve size using a standardized ruler. Relevant data require further collection and exploration. Finally, the high reproducibility of these measurements is likely dependent on training and experience. Thus, these results cannot necessarily be generalized to less-experienced physicians. The present study did not make distinctions between the etiologies of AR. The AA morphometric characteristics may vary among patients with different etiologies. These results should be interpreted with caution, and more nuanced stratified analyses and subgroup comparisons are still needed.

Conclusions

The main conclusion of the present study is summarized in *Figure 4*. 3D-TEE allows accurate assessment of the

AA dimensions in patients with pure AR and shows good reproducibility. The AA minimum diameter measured by 3D-TEE could emerge as the most valuable predictive factor for high-risk thoracic aorta aneurysm detected by MSCT examination. 3D-TEE and MSCT need to be combined to complement each other to improve the diagnostic value and minimize the damage to patients.

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Footnote

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Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. This study was conducted following the Declaration of Helsinki (as revised in 2013). The protocol was approved by the Institutional Ethics Committee of Fuwai Hospital (No. 2019-1201), and informed consent was obtained from all individual participants.

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