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ORIGINAL PAPER

Aortic annulus measurement with computed tomography angiography reduces aortic regurgitation after transfemoral aortic valve replacement compared to 3-D echocardiography: a single-centre experience

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Abstract

Background Accurate assessment of the aortic annulus is crucial for successful transcatheter aortic valve replacement (TAVR), in particular to prevent paravalvular regurgitation (PVR). We compared aortic annular sizing using multidetector computed tomography (MDCT) and three-dimensional transoesophageal echocardiography (3-D TEE) to determine the predictive value of MDCT.

Methods and results All patients admitted for transfemoral TAVR [$n=227$; 48.9% balloon expandable (Edwards Sapien 3); 51.1% self-expandable (Core Valve, Evolut R)] at our institution from January 2015 until December 2016 were analysed retrospectively. Aortic annular parameters were obtained either by MDCT or 3-D TEE. Additionally, we included a cohort of patients ($n=27$) assessed by both MDCT and 3D TEE between October 2017 and April 2018 to enable intra-individual comparison of the two methods. Indications for TAVR were severe degenerative aortic stenosis (AS; 94.7%) or re-stenosis after surgical AVR (5.3%). 74.4% were classified as high-gradient AS. The mean age was 80 (37–94) years and 75.8% presented with NYHA III/IV. STS risk of mortality was intermediate (3.5 ± 2.3). MDCT and 3-D TEE were performed in 116 and 111 patients for aortic annulus sizing, respectively. Significantly larger implants were chosen in the CT group irrespective of prosthesis type or post-dilatation. Follow-up (median at 79 days) revealed significantly less PVR in the MDCT compared to 3-D TEE group (absence of PVR in 59.3% and 40.7%, $p=0.016$), without differences in mortality. Patients without PVR or mild PVR had a better clinical performance according to NYHA class ($p=0.016$).

Conclusion MDCT is superior to 3-D TEE in terms of sizing accuracy and clinical outcomes. Reduction of PVR after TAVR with MDCT is likely due to valve annulus undersizing by TEE.

Keywords Paravalvular regurgitation · Aortic annulus sizing · Multidetector computed tomography · Three-dimensional transoesophageal echocardiography · Transcatheter aortic valve replacement

Introduction

Transcatheter aortic valve replacement (TAVR) has been transferred successfully into clinical routine and is meanwhile applicable even for patients showing intermediate

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perioperative risk [1–5]. The two main access routes utilized for TAVR are the transapical and the transfemoral route. The 2-year outcomes of the PARTNER II trial could prove superiority of the transfemoral access route compared to SAVR in intermediate-risk patients. Conversely, the outcomes after transthoracic TAVR were similar to or worse than those with surgery. Moreover, the transfemoral approach is less invasive and appeared to be superior to transthoracic TAVR [2]. Thus, it became the preferred approach in most institutions and the transapical approach is considered only when the transfemoral access seems unsuitable.

A major and hitherto unsolved problem of TAVR is the occurrence of paravalvular regurgitation (PVR) and subsequent aortic regurgitation with its potential clinical and prognostic implications. PVR is associated with a significant increase in mortality [6–8]. In patients with at least moderate PVR, mortality rises up to fourfold [9]. Hence, accurate preoperative assessment of the aortic annulus is crucial for successful TAVR [4, 10, 11]. Multidetector computed tomography (MDCT)-based measurements have become the gold standard for transcatheter heart valve sizing prior to TAVR, facilitating thorough understanding of patient's anatomy, valve leaflet and vascular calcification as well as access route evaluation [12–14]. Three-dimensional transoesophageal echocardiography (3-D TEE) has been proposed as a technique enabling annulus sizing equivalent to MDCT in experienced centres. Nevertheless, sizing accuracy may be limited by annulus calcification [15] and it has been recently described that both, PVR and mortality rates, decline with CT-based sizing [16, 17].

The aim of this study was to compare MDCT and 3-D TEE for aortic annular sizing prior to TAVR concerning the predictive value for PVR, balloon post-dilatation and reduction of mitral regurgitation in a real-world single-centre cohort at our institution.

Methods

Patients

In this retrospective analysis, we consecutively included all patients admitted for transfemoral TAVR at our institution between January 1st, 2015 and December 31st, 2016 ($n = 227$). Diameter, perimeter and aortic annular cross-sectional area were measured from pre-TAVR imaging using either MDCT or 3-D TEE. Additionally, we included a cohort of patients ($n = 27$) assessed by both, MDCT and 3D TEE, between October 2017 and April 2018 to enable direct intra-individual comparison of the two methods. In this group, data were obtained between October 1st and April 30th, 2018. Patients with symptomatic severe aortic valve stenosis (AVS, tricuspid) or re-stenosis after surgical AVR (5.3%) were considered candidates for TAVR. AVS were classified as high-gradient (HGAS), low-gradient (LGAS) or paradoxical low-flow–low-gradient (PLFAS) according to current guidelines [18]. LGAS is characterised by a reduced left ventricular ejection fraction (< 50%) and a discordance between the aortic valve area (AVA < 1 cm^2 and/or < 0.6 cm^2/m^2) and the mean gradient (MG < 40 mmHg). All patients included showed an intermediate to high surgical risk as assessed using the STS score. The decision to proceed with TAVR was made by the Heart Team according to current guideline recommendations [19]. Over 90% of TAVR procedures were performed under conscious sedation. In 48.9%, balloon-expandable Edwards Sapien (ES 3, Edwards Lifesciences, Irvine, California, USA) were implanted compared to 51.1% self-expandable Core Valve (Core Valve, Evolut R, 1 CoreValve™ 31 mm; Medtronic, Minneapolis, Minnesota, USA). Procedural time was defined as incision–suture time. The immediate result was examined fluoroscopically. In case of any aortic regurgitation, balloon dilatation of the prosthesis was performed until a sufficient result was obtained.

TAVR sizing

There is a stable interventional expertise in performing TAVR in our centre since 2008 showing good results and low complication rates. Within the first study period, we exclusively applied 3-D TEE-based valve sizing to obtain aortic annular diameters, perimeters and cross-sectional area. In February 2016, our department shifted towards MDCT aortic annulus measurement. Additionally, CT was routinely performed to evaluate the ileofemoral vasculature to confirm accessibility for transfemoral TAVR. The diameters of the sinuses of Valsalva and the ascending aorta, the extent of sinotubular and aortic root calcification and the height of the coronary ostia were also considered when choosing type ansd size of the THV. Selection of an adequate prosthesis was made according to the manufacturer's instructions.

Echocardiographic measurement

Pre-procedural TEE was performed during the evaluation process before TAVR implantation, using a commercially available TEE transducer and ultrasound system (X7-2t Live 3-D-TEE transducer, Epiq-7, Philips, The Netherlands) applying standard techniques. The aortic root dimensions were measured during early systole in the 3-chamber long-axis view at approximately 120° angulation. A 3-D dataset was digitally stored for offline analysis (Fig. 1). All 3-D TEE analyses were carried out by two experienced cardiologists. Since nearly all procedures

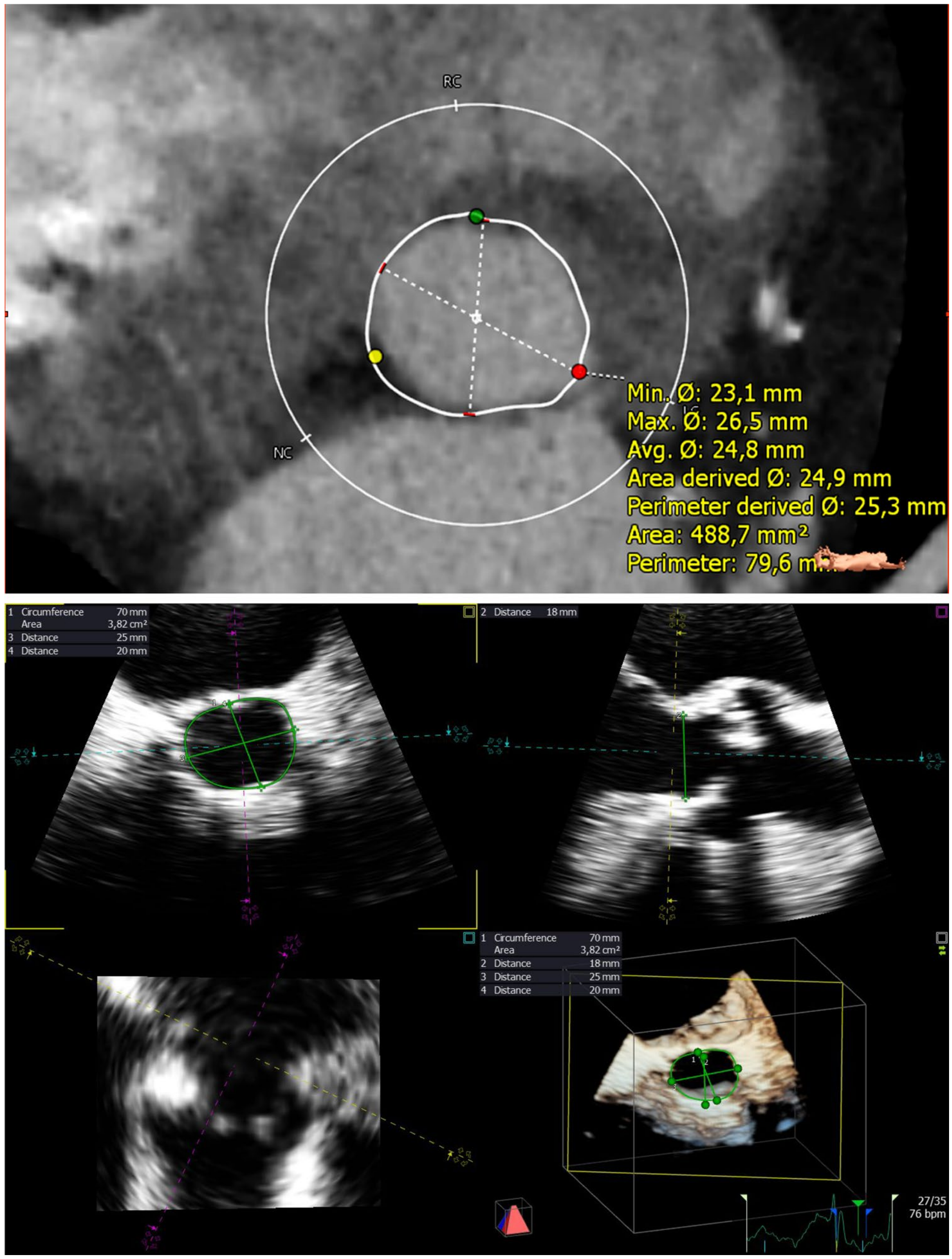

Fig. 1 Annulus sizing using MDCT and 3mensio Medical Imaging (above) and 3-D TEE (below)

were performed in conscious sedation, only fluoroscopy was available to immediately evaluate regurgitation during the TAVR intervention. PVR was graded at discharge and at follow-up in accordance with the American Society of Echocardiography recommendations for native valves. The following definition was applied: no PVR (no regurgitant colour flow), mild (jet arc length < 10% of the AV annulus short-axis view circumference), moderate (jet arc length 10–30% of the AV annulus short-axis view circumference) and severe (jet arc length > 30% of the AV annulus short-axis view circumference).

CT acquisition protocol

All examinations were performed on a 265 slice wide detector CT scanner (Revolution CT, GE Healthcare, Milwaukee, Wisconsin), using axial image acquisition, prospectively EGG gating and standard technical parameters: gantry rotation time 0.28 ms, collimation 256 0.625 mm, 100–120 kV tube voltage (weight-adjusted, kV Assist), and 500 milliampere with tube current modulation. An adaptive statistical iterative reconstruction algorithm (ASIR-V, 70%) was used instead of the standard filtered back-projection algorithm. Contrast enhancement was achieved using 60–80 ml of iopamidol 370 mg/ml (Solutrast®, Bracco ALTANA Pharma, Koblenz, Germany). For optimal synchronization, a bolus tracking method was utilized in the ascending aorta. No beta blockade was administered because of severe aortic stenosis. Slice thickness of reconstructed images was 0.6 mm.

CT measurements

MDCT datasets from 116 patients were analysed offline using the 3Mensio Structural Heart 8.1 SP1 (Pie Medical Imaging, Maastricht; The Netherlands) software for annulus measurement prior to TAVR implantation. Measurement was performed by at least two interventional cardiologists later performing the TAVR procedure. The aortic annulus was defined as the virtual ring at the level of the basal attachments of all three valvular cusps. Ten multi-planar reconstructions were manually oriented to display the aortic annulus at basal attachment points. As with 3-D TEE evaluations, two orthogonal planes were manually set, bisecting the aortic valve in sagittal and coronal planes. The third orthogonal plane (double-oblique transverse view) was set to bisect aortic annulus at the most caudal attachment points of all three native cusps, orientating/positioning the virtual ring as in TEE short-axis view. Dimensions of the aortic annulus were carefully assessed, including major and minor orthogonal diameters. Cross-sectional area and perimeter were measured by manually tracking luminal contours of double-oblique transverse planes (Fig. 1).

Endpoints

The aim of this study was to compare MDCT and 3-D TEE for aortic annular sizing prior to TAVR concerning the predictive value for PVR, balloon post-dilatation and reduction of mitral regurgitation in a single-centre cohort at our institution. PVR was assessed using 2-D transthoracic echocardiography at discharge and first follow-up, and was classified as mild, moderate or severe.

Statistical analysis

Continuous variables were expressed as mean+/-standard deviation or median and inter-quartile range. Categorical variables were presented as frequencies and percentages. Comparison between groups and univariate analysis of associated variables was performed using the Student's *t* test, while the analysis of variance or nonparametric tests was used for continuous variables and Chi square test for categorical variables. All computations relied on commercially available software (SPSS IBMS v24; SPPS Inc., Chicago, IL, USA), with statistical significance set at $p < 0.05$.

Results

TAVR was performed in patients with severe degenerative aortic valve stenosis (AVS; 94.7%) or re-stenosis after surgical AVR (5.3%). Severe AVS was classified into (only tricuspid valves were included) high gradient (HGAS, 74.4%), low gradient (LGAS defined as an AVA < 1 cm^2 in the presence of LVEF < 50% and MPG < 40 mmHg or $V_{max} < 4$ m/s; 16.7%) or paradoxical low-flow–low-gradient (PLFAS defined as an AVA < 1 cm^2, LVEF > 50%, a reduced left ventricular stroke volume (< 35 ml/m^2), MPG < 40 mmHg or $V_{max} < 4$ m/s; 8.8%). The mean age was 80 (37–94) years, 46.3% were male and 75.8% presented with class NYHA III/IV. Surgical risk was stratified according to logistic EuroSCORE (16 ± 11) and STS Risk of Mortality (3.5 ± 2.3). 48.9% of patients received a balloon-expandable Edwards Sapien 3 THV, in 51.1% of the patients, a self-expandable Core Valve Evolut R prosthesis (in one case a first generation Core Valve™ 31 mm) was implanted. The demographic and procedural characteristics of the study population are summarized in Tables 1 and 2. There were no significant differences between groups at baseline. Periprocedural complications necessitated extra-corporal-membrane oxygenation (ECMO)—implantation in five patients due to the following reasons: immediate valve-in-valve procedure due to severe aortic regurgitation in one patient, rupture of the ascending aorta in one patient, coronary artery occlusion in one patient, prolonged severe hypotension during positioning of the implant in two patients.

MDCT and 3-D TEE were performed in 116 and 111 patients, respectively, to obtain perimeter, maximum/minimum diameter and cross-sectional area of the aortic valve anulus. All measurements significantly differed between the 3-D TEE and the MDCT group ($p < 0.001$), except for minimum diameter. Parameters were approximately 10% smaller in TEE compared to MDCT evaluation. As a result, significantly larger implants were chosen in the MDCT group ($p = 0.018$), without differences in the selected valve types (Table 3). In a separate set of patients ($n = 27$) admitted for TAVR between October 1st and April 30th 2018, we applied both methods simultaneously for direct intra-individual comparison of annulus parameter accuracy (Table 4). Accordingly, this analysis showed larger perimeters and areas measured with MDCT compared to 3-D TEE.

Post-dilatation rates were equal between the two groups (27.9 and 26.7%, respectively), but procedural and fluoroscopy time were significantly reduced in patients evaluated with MDCT (77 ± 20 and 17 ± 7 min in 3-D TEE, 65 ± 30 and 14 ± 7 min in MDCT, respectively). Complications and adverse events associated with the TAVR procedure

Table 1 Patient's characteristics at baseline

	All (*N* = 227)	3-D TEE guided sizing (*N* = 111)	MDCT guided sizing (*N* = 116)	*p* value
Age (years)	80 ± 7	79 ± 8	80 ± 6	0.805
Male sex, *n*/*N* (%)	105/227 (46.3)	56/111 (50.5)	49/116 (42.2)	0.215
BMI	28 ± 5.4	28 ± 5.7	28 ± 5.1	0.457
Logistic EuroSCORE	16 ± 11	16 ± 11	15.7 ± 11	0.517
STS risk of mortality	3.5 ± 2.3	3.7 ± 2.5	3.4 ± 2.2	0.235
NYHA class, *n*/*N* (%)				0.45
III	145/219 (66.2)	72/105 (68.6)	73/114 (64)	
IV	21/219 (9.6)	12/105 (11.4)	9/114 (7.9)	
CCS, *n*/*N* (%)				0.677
3	33/206 (16)	17/96 (17.7)	16/110 (14.5)	
4	6/206 (2.9)	4/96 (4.2)	2/110 (1.8)	
PAD, *n*/*N* (%)	45/226 (19.9)	23/111 (20.7)	22/115 (19.1)	0.765
Diabetes, *n*/*N* (%)	84/226 (37.2)	38/111 (34.2)	46/115 (40)	0.37
Atrial fibrillation, *n*/*N* (%)	73/221 (33)	36/106 (34)	37/115 (32.2)	0.549
CAD, *n*/*N* (%)	129/231 (57.1)	70/111 (63.1)	59/115 (51.3)	0.234
Previous SAVR, *n*/*N* (%)	12/227 (5.3)	5/111 (4.5)	7/116 (6)	0.607
Previous cardiac intervention, *n*/*N* (%)				0.179
PCI	43/221 (19.5)	25/106 (23.6)	18/115 (15.7)	
CABG	11/221 (5)	6/106 (5.7)	5/115 (4.3)	
PCI + CABG	14/221 (6.3)	9/106 (8.5)	5/115 (4.3)	
COPD, *n*/*N* (%)	74/215 (34.4)	39/108 (36.1)	35/107 (32.7)	0.487
PH, *n*/*N* (%)	127/193 (65.8)	61/93 (65.6)	66/100 (66)	0.952
Chronic kidney disease, *n*/*N* (%)				0.178
≥ Stage 3 (GFR < 59 ml/min)	114/226 (50.5)	54/111 (48.6)	60/115 (52.2)	

Table 2 Procedural characteristics

	All (*N* = 227)	3-D TEE guided sizing (*N* = 111)	MDCT guided sizing (*N* = 116)	*p* value
Urgency†				**0.009**
Elective, *n*/*N* (%)	206/227 (90.7)	95/111 (85.6)	111/116 (95.7)	
Urgent, *n*/*N* (%)	21/227 (9.3)	16/111 (14.4)	5/116 (4.3)	
Conscious sedation, *n*/*N* (%)	187/205 (91.2)	94/99 (94.9)	93/106 (87.7)	0.068
Procedural time (min)†	70 ± 27	77 ± 20	65 ± 30	< **0.001**
Fluoroscopy time (min)†	15 ± 7	17 ± 7	14 ± 7	< **0.001**
Contrast agent (ml)	120 ± 40	121 ± 37	119 ± 42	0.37
Post-dilatation, *n*/*N* (%)	62/227 (27.3)	31/111 (27.9)	31/116 (26.7)	0.839
ECMO, *n*/*N* (%)	5/227 (2.2)	1/111 (0.9)	4/116 (3.4)	0.191
Days in hospital	16 ± 9	17 ± 8	16 ± 9	0.32

$p < 0.05$ are in bold

†There were significant differences between the two groups regarding procedural time, fluoroscopy time and urgency ($p < 0.001$)

are listed in Table 5. There was no significant difference in adverse events between the two groups, especially no differences with respect to the need for pacemaker implantation or surgical complications in larger prosthesis.

2-D transthoracic echocardiography after TAVR was performed at discharge. Rate of PVR differed significantly between the MDCT group and the TEE group ($p = 0.048$) with a notably higher number of patients not showing PVR in the MDCT group (59.3 and 40.7%, respectively; $p = 0.006$).

Within 30 days after the procedure, 5 patients died (30-day mortality of 2.2%). This was due to pneumonia/sepsis in

Table 3 Intergroup comparison of 3-D TEE and MDCT-based aortic annulus sizing

	3-D TEE-guided sizing (*N* = 111)	MDCT-guided sizing (*N* = 116)	*p* value
THV type, *n*/*N* (%)			0.384
ES 3	51/111 (46)	60/116 (52)	
Core Valve Evolut R (1 CoreValve™ 31 mm)	60/111 (54)	56/116 (48)	
THV size, *n*/*N* (%)			**0.018**
23 mm	31/109 (28.4)	22/116 (19)	
26 mm	49/109 (45)	42/116 (36.2)	
29 mm	28/109 (25.7)	52/116 (44.8)	
31 mm	1/109 (0.9)	0	
Post-dilatation, *n*/*N* (%)	31/111 (27.9)	31/116 (26.7)	0.839
Aortic annulus parameters			**< 0.001**
Annulus perimeter (mm)	71.1 ± 6.9	77.6 ± 7.4	
Annulus diameter maximum (mm)	23.8 ± 2	27.3 ± 2.9	
Annulus diameter minimum (mm)	21.2 ± 2.2	21.4 ± 2.3	
Annulus area (cm^2)	4 ± 0.8	4.6 ± 0.9	

$p < 0.05$ are in bold

Table 4 Prosthesis characteristics from 27 TAVR patients

	3-D TEE parameters	MDCT parameters	*p* value
THV type, *n*/*N* (%)			
ES 3	14/27 (51.9)		
Core Valve Evolut R	9/27 (33.3)		
Core Valve Evolut Pro	4/27 (14.8)		
THV size, *n*/*N* (%)			
23 mm	6/27 (22.2)		
26 mm	9/27 (33.3)		
29 mm	9/27 (33.3)		
34 mm	3/27 (11.1)		
Aortic annulus parameters			
Annulus perimeter (mm)	70.7 ± 13.5	78.2 ± 9.8	**0.003**
Annulus diameter maximum (mm)	24.2 ± 3.0	24.6 ± 3.1[a]	
Annulus diameter minimum (mm)	23.0 ± 9.7		
Annulus area (cm^2)	4.1 ± 1.1	4.8 ± 1.3	**< 0.001**

$p < 0.05$ are in bold

Intergroup comparison of 3-D TEE and MDCT-based aortic annulus parameters

[a]Area derived diameter

two patients and directly associated with the valve procedure in three patients.

Every patient was scheduled for at least one follow-up examination. Time to follow-up did not differ significantly between the 3-D TEE and MDCT group: 79 days (mean value ± 31 days; median 76 days, IQR 29 days) in the 3-D TEE and 79 days (mean value ± 75 days; median 53 days, IQR 56 days) in the MDCT group. 2-D TTE revealed a significantly higher number of patients not showing PVR in the MDCT group compared to the TEE group (no PVR in 57.6% and 35.3%, respectively, $p = 0.016$; Fig. 2 and supplementary Table S1). Moderate to severe PVR was quantified in 14.2%, while the absence of PVR was apparent in 46.9% at follow-up.

PVR at follow-up correlated with NYHA class as a major clinical symptom (Fig. 3 and supplementary Table S2). Patients without or only mild PVR at follow-up suffered from significantly less dyspnoea compared to patients with at least moderate PVR ($p = 0.016$). However, no significant difference in NYHA class, CCS class or mitral regurgitation after TAVR could be demonstrated between the 3-D TEE and MDCT group.

Table 5 Adverse events related to TAVR procedure

	All (*N* = 227)	3-D TEE guided sizing (*N* = 111)	MDCT guided sizing (*N* = 116)	*p* value
Stroke				0.303
Nondisabling	2/227 (0.9)	2/111 (1.8)	0/116 (0)	
Disabling	3/227 (1.3)	1/111(0.9)	2/116 (1.7)	
Bleeding, *n*/*N* (%)				0.399
Major	18/227 (7.9)	12/111 (10.8)	6/116 (5.2)	
Life threatening	5/227 (2.2)	2/111 (1.8)	3/116 (2.6)	
Vascular complication, *n*/*N* (%)				0.329
All	22/227 (9.7)	8/111 (7.2)	15/116 (12.9)	
Major	4/227 (1.8)	1/111 (0.9)	3/116 (2.6)	
New pacemaker	40/227 (17.6)	19/111 (17.1)	21/116 (18.1)	0.845
Repeat procedure (ViV), *n*/*N* (%)	4/227 (1.8)	2/111 (1.8)	2/116 (1.7)	0.965
AKIN				0.252
Stage 1, *n*/*N* (%)	5/227 (2.2)	2/111 (1.8)	3/116 (2.6)	
Stage 2, *n*/*N* (%)	2/227 (0.9)	0/111 (0)	2/116 (1.7)	
Stage 3, *n*/*N* (%)	2/227 (0.9)	0/111 (0)	2/116 (1.7)	
Need for surgery, *n*/*N* (%)	1/227 (0.4)	0/111 (0)	1/116 (0.9)	0.327
Death within 30 days, *n*/*N* (%)	5/227 (2.2)	1/111 (0.9)	4/116 (3.4)	0.181
Rehospitalization cardiology unit within 30 days, *n*/*N* (%)	8/227 (3.5)	2/111 (1.8)	6/116 (5.2)	0.169

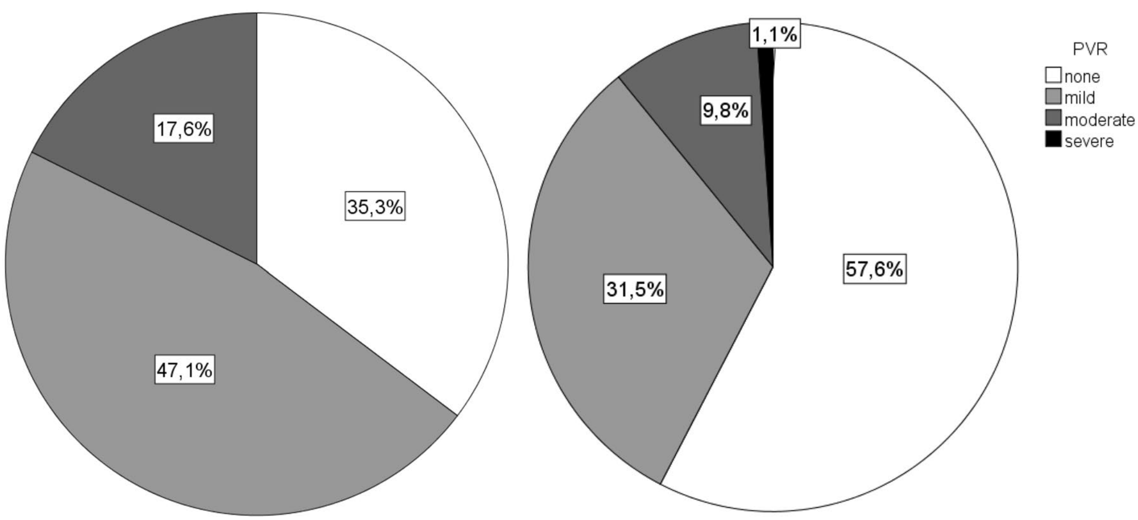

Fig. 2 Decrease in PVR after TAVR at follow-up comparing 3-D TEE (left) and MDCT-derived aortic annulus parameters (right; $p = 0.016$)

Discussion

3-D TEE may present an alternative method for annulus sizing when planning TAVR. The main result of the present study can be summarized as follows. MDCT-derived parameters for aortic annulus sizing lead to a significant increase in patients without PVR after TAVR compared to 3-D TEE, as revealed by transthoracic echocardiography both at discharge and at follow-up.

1. MDCT versus 3-D TEE

In the beginning of the TAVR era, aortic annulus sizing was predominantly based on 2-D TTE and TEE [12]. It is now accepted that 2-D echocardiography does not accurately account for the elliptical geometry of the annulus and often underestimates the annulus diameter [14, 20]. In the last years, cardiologists have shifted towards the use of MDCT for transcatheter aortic valve size selection. CT provides a more reliable and detailed anatomical assessment of the

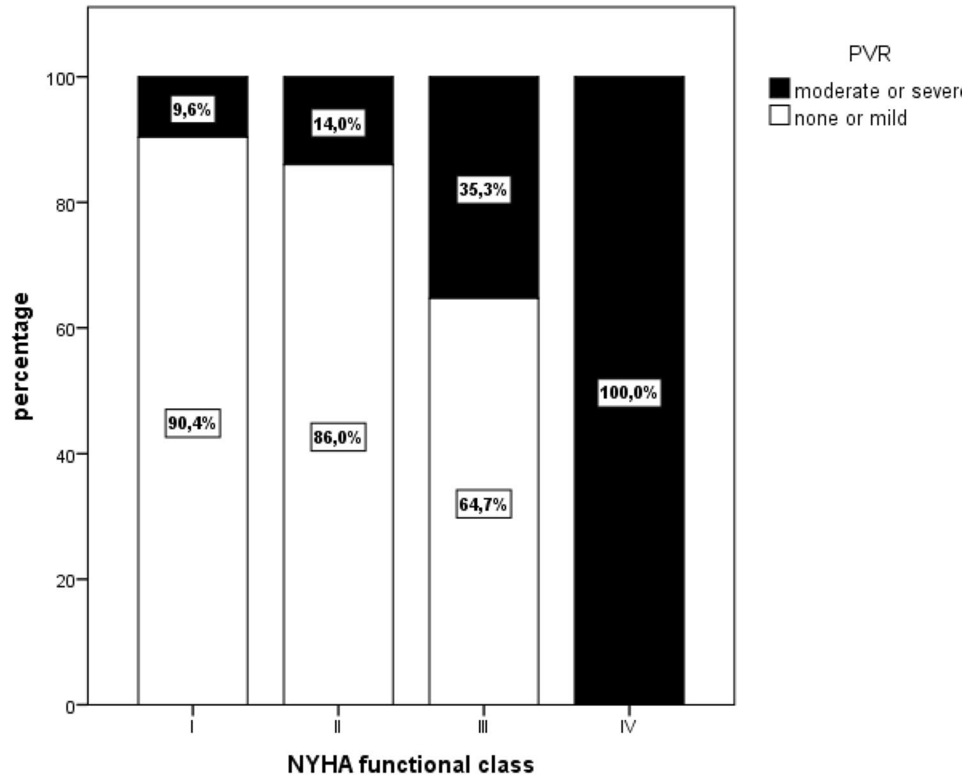

Fig. 3 Significant reduction of NYHA class with none/mild PVR at follow-up ($p = 0.016$)

aortic valvular complex, yet it yields larger aortic annular diameters compared to echocardiography [12, 17]. Previous studies have evaluated the use of MDCT for THV sizing. MDCT showed the best agreement with annulus measurement during conventional surgery and reduced rates of significant PVR [21]. Hence, the medical community has embraced it as the gold standard for THV size selection. 3-D TEE has been proposed as a technique that could provide annulus sizing quality equivalent to MDCT. Technical improvements in 3-D TEE using multi-planar reconstruction of the aortic root and of the outflow tract and semiautomatic quantification software added to its diagnostic accuracy [15]. It plays a key role in a patient evaluation before and during the TAVR procedure. Besides, echocardiography comprises the generally appreciated advantages of being used without radiation or contrast agent, cost effectiveness and broad availability [22].

In our single-centre retrospective study, we demonstrated that aortic annulus parameters obtained with MDCT were significantly larger than those measured with 3-D TEE. Larger implants based on MDCT-derived parameters account for a significant reduction of PVR after TAVR compared to 3-D TEE. This confirms previous observations [16, 23]. Vaquerizo et al. showed an agreement of only 38% of the two methods when determining implant size by the aortic annulus area [23].

There are three predictive factors positively correlating with PVR after TAVR: valve undersizing [24], higher aortic valve calcification evaluated with CT/Agatston score [25, 26] and implantation depth [27]. Larger and eccentric annuli were identified as predictors of PVR in multiple studies and most likely reflect inadequate sizing of the THV [28]. Differences in aortic annular measurements obtained by 3-D TEE and MDCT may be attributed to the lower spatial resolution of 3-D TEE volumetric imaging. Partial acoustic shadowing of the annulus creates regions of dropout, and ectopic calcification or acoustic artefacts (side lobes) may falsify the annular border. Offline analysis of the obtained datasets using novel automated software may also contribute to measurement accuracy. A recent study showed automated 3-D TEE slightly underestimating the aortic annulus maximum diameter, perimeter and area, as compared to MDCT. Especially in patients with low aortic valve calcification, an excellent interobserver agreement and consensus with MDCT of 88% could be proven [29].

2. PVR, mortality and clinical symptoms

PVR independently predicts mortality after TAVR [6–8]. A recent meta-analysis showed a significant increase in overall 1-year mortality in patients showing moderate or severe PVR [6]. According to a recent study, the incidence of PVR after SAVR is now as low as 2.2%, but with a significantly higher prevalence in TAVR [30–32]. Depending on the method of assessment, the reported prevalence after TAVR ranges from 40 to 67% for trivial to mild leaks and from

7 to 20% for moderate to severe leaks [27]. In the PARTNER trial, trace/mild PVR was found in 66% of patients and moderate/severe in 12% [1]. Moderate to severe PVR was detected in 14.2%, while the absence of PVR was apparent in 46.9% at follow-up (50% at discharge, respectively).

We used two-dimensional TTE to screen for PVR after TAVR. 2-D echocardiographic evaluation is subjective and difficult in PVR evaluation due to multiple eccentric jets, acoustic shadowing from the calcifications, reverberations, and Doppler attenuation from the prosthesis, mostly leading to underestimation of its severity [27, 33, 34]. The impact of mild PVR on long-term outcomes has yielded conflicting results. Earlier reports suggested that mild PVR is benign and well tolerated [33]. However, the 2-year results from the PARTNER trial proved that even mild PVR is associated with increased mortality [30]. Data on 663 patients from the Italian registry found grade $\geq 2+$ PVR to be associated with early 30-day mortality, and a hazard ratio of 3.79 for patients with PVR $\geq 2+$ also for late mortality beyond 30 days [9].

Overall, patients without or only mild PVR had fewer clinical symptoms measured using NYHA functional class when presenting at follow-up. Hence, we anticipated a significant improvement in NYHA class in the MDCT group due to PVR reduction, but this could not be demonstrated.

TAVR patients are typically featured by high surgical risk due to age and accompanying co-morbidities. Acute renal failure due to administration of contrast agent for MDCT and during the TAVR procedure is often feared. Fortunately, in our cohort, only minor deterioration of renal function, mainly stage 1 AKIN according to VARC-2 criteria, occurred [35]. Furthermore, larger implants utilized in the MDCT group did not lead to an increase in need for pacemaker implantation (18.1% and 17.1% in MDCT and 3-D TEE, respectively), surgical or vascular complications, and over 90 percent of the procedures could be performed successfully in conscious sedation. An immediate valve-in-valve procedure had to be performed in 4 patients (1.7%) using 2 Core Valve Evolut R and 2 Edwards Sapien 3 implants, respectively.

Limitations

In our single-centre study, all data were obtained retrospectively. Our results indicate that based on 3-D TEE evaluation and sizing of the aortic annulus, smaller prostheses were chosen for TAVR as compared to MDCT measurements. The majority of patients underwent either 3-D TEE or MDCT prior to TAVR. Early in our experience with TAVR, we used 3-D TEE, subsequently followed by the broad application of MDCT. Both methods were established in clinical routine and performed by an experienced cardiologist before patient enrolment for this study to reduce study bias. Nevertheless, different phases of the learning curve represent major confounders of our study, also reflected in the differing documented operating time. The retrospective longitudinal study design remains a significant drawback. We tried to overcome this aspect by including data from a small set of patients who underwent both 3-D TEE and MDCT for sizing.

Clinical performance was assessed by each patient individually. A more objective evaluation of performance capacity is of need. Furthermore, technical improvements in 3-D TEE software with more automated measurements and different views of the annulus for more accurate anatomical identification and sizing might reduce the current limitations of 3-D TEE measurements. Additionally, to our knowledge, no prospective study comparing ES3 and Core Valve Evolut R prosthesis regarding PVR has been conducted until now.

The first follow-up was performed after 79 days on average. Hence, our observations regarding clinical outcome are limited. Longer and prospective observational periods are necessary to precisely link clinical performance and echocardiographic findings.

Conclusion

When compared to 3D TEE, a MDCT-based prosthesis selection strategy can help reducing the paravalvular regurgitation rate after TAVR. Valve undersizing due to smaller aortic annulus measurements by 3-D TEE and subsequently implanted prosthesis are probable reasons. PVR significantly impacted on patient's clinical symptoms at follow-up, but could be reduced by accurate annulus measurement and adequate valve sizing. The benefit of novel automated software to precisely measure the aortic annulus from a 3-D TEE dataset needs to be evaluated further, and next-generation transcatheter aortic valves designed to minimize paravalvular leak will have a major role to play in the future of TAVR [27].

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

References

1. Leon MB et al (2010) Transcatheter aortic-valve implantation for aortic stenosis in patients who cannot undergo surgery. N Engl J Med 363(17):1597–1607
2. Leon MB et al (2016) Transcatheter or surgical aortic-valve replacement in intermediate-risk patients. N Engl J Med 374(17):1609–1620

3. Reardon MJ, Van Mieghem NM, Popma JJ (2017) Surgical or transcatheter aortic-valve replacement reply. N Engl J Med 377(2):197–198
4. Vahl TP, Kodali SK, Leon MB (2016) Transcatheter aortic valve replacement 2016 a modern-day “Through the Looking-Glass” adventure. J Am Coll Cardiol 67(12):1472–1487
5. Gaede L et al (2017) Trends in aortic valve replacement in Germany in 2015: transcatheter versus isolated surgical aortic valve repair. Clin Res Cardiol 106(6):411–419
6. Takagi H, Umemoto T, Grp A (2016) Impact of paravalvular aortic regurgitation after transcatheter aortic valve implantation on survival. Int J Cardiol 221:46–51
7. Kodali S et al (2015) Paravalvular regurgitation after transcatheter aortic valve replacement with the Edwards sapien valve in the PARTNER trial: characterizing patients and impact on outcomes. Eur Heart J 36(7):449–456
8. de Brito FS Jr et al (2015) Outcomes and predictors of mortality after transcatheter aortic valve implantation: results of the Brazilian registry. Catheter Cardiovasc Interv 85(5):E153–E162
9. Tamburino C et al (2011) Incidence and predictors of early and late mortality after transcatheter aortic valve implantation in 663 patients with severe aortic stenosis. Circulation 123(3):299–308
10. Bloomfield GS et al (2012) A practical guide to multimodality imaging of transcatheter aortic valve replacement. JACC Cardiovasc Imaging 5(4):441–455
11. Genereux P et al (2012) Transcatheter aortic valve implantation 10-year anniversary: review of current evidence and clinical implications. Eur Heart J 33(19):2388–2398
12. Willson AB et al (2012) 3-dimensional aortic annular assessment by multidetector computed tomography predicts moderate or severe paravalvular regurgitation after transcatheter aortic valve replacement: a multicenter retrospective analysis. J Am Coll Cardiol 59(14):1287–1294
13. Schultz CJ et al (2011) Correlates on MSCT of paravalvular aortic regurgitation after transcatheter aortic valve implantation using the Medtronic CoreValve prosthesis. Catheter Cardiovasc Interv 78(3):446–455
14. Achenbach S et al (2012) SCCT expert consensus document on computed tomography imaging before transcatheter aortic valve implantation (TAVI)/transcatheter aortic valve replacement (TAVR). J Cardiovasc Comput Tomogr 6(6):366–380
15. Khalique OK et al (2017) Impact of methodologic differences in three-dimensional echocardiographic measurements of the aortic annulus compared with computed tomographic angiography before transcatheter aortic valve replacement. J Am Soc Echocardiogr 30(4):414–421
16. Mylotte D et al (2014) Erroneous measurement of the aortic annular diameter using 2-dimensional echocardiography resulting in inappropriate CoreValve size selection: a retrospective comparison with multislice computed tomography. JACC Cardiovasc Interv 7(6):652–661
17. Jilaihawi H et al (2012) Cross-sectional computed tomographic assessment improves accuracy of aortic annular sizing for transcatheter aortic valve replacement and reduces the incidence of paravalvular aortic regurgitation. J Am Coll Cardiol 59(14):1275–1286
18. Baumgartner H et al (2017) 2017 ESC/EACTS Guidelines for the management of valvular heart disease. Eur Heart J 38(36):2739–2791
19. Baumgartner H et al (2017) 2017 ESC/EACTS guidelines for the management of valvular heart disease The Task Force for the Management of Valvular Heart Disease of the European Society of Cardiology (ESC) and the European Association for Cardio-Thoracic Surgery (EACTS). Eur Heart J 38(36):2739–2739+
20. Hahn RT et al (2013) Guidelines for performing a comprehensive transesophageal echocardiographic examination: recommendations from the American Society of Echocardiography and the Society of Cardiovascular Anesthesiologists. J Am Soc Echocardiogr 26(9):921–964
21. Kim WK et al (2016) Cyclic changes in area- and perimeter-derived effective dimensions of the aortic annulus measured with multislice computed tomography and comparison with metric intraoperative sizing. Clin Res Cardiol 105(7):622–629
22. Bleakley C, Eskandari M, Monaghan M (2017) 3D transoesophageal echocardiography in the TAVI sizing arena: should we do it and how do we do it? Echo Res Pract 4(1):R21–R32
23. Vaquerizo B et al (2016) Three-dimensional echocardiography vs. computed tomography for transcatheter aortic valve replacement sizing. Eur Heart J Cardiovasc Imaging 17(1):15–23
24. Detaint D et al (2009) Determinants of significant paravalvular regurgitation after transcatheter aortic valve: implantation impact of device and annulus discongruence. JACC Cardiovasc Interv 2(9):821–827
25. Ewe SH et al (2011) Location and severity of aortic valve calcium and implications for aortic regurgitation after transcatheter aortic valve implantation. Am J Cardiol 108(10):1470–1477
26. Mauri V et al (2018) Predictors of paravalvular regurgitation and permanent pacemaker implantation after TAVR with a next-generation self-expanding device. Clin Res Cardiol 107(8):688–697
27. Athappan G et al (2013) Incidence, predictors, and outcomes of aortic regurgitation after transcatheter aortic valve replacement: meta-analysis and systematic review of literature. J Am Coll Cardiol 61(15):1585–1595
28. Abdel-Wahab M et al (2011) Aortic regurgitation after transcatheter aortic valve implantation: incidence and early outcome. Results from the German transcatheter aortic valve interventions registry. Heart 97(11):899–906
29. Podlesnikar T et al (2018) Influence of the quantity of aortic valve calcium on the agreement between automated 3-dimensional transesophageal echocardiography and multidetector row computed tomography for aortic annulus sizing. Am J Cardiol 121(1):86–93
30. Kodali SK et al (2012) Two-year outcomes after transcatheter or surgical aortic-valve replacement. N Engl J Med 366(18):1686–1695
31. Sponga S et al (2012) Impact of residual regurgitation after aortic valve replacement. Eur J Cardiothorac Surg 42(3):486–492
32. Duncan BF et al (2015) Paravalvular regurgitation after conventional aortic and mitral valve replacement: a benchmark for alternative approaches. J Thorac Cardiovasc Surg 150(4):860–868
33. Raffa GM et al (2012) Aortic valve replacement for paraprosthetic leak after transcatheter implantation. J Card Surg 27(1):47–51
34. Zamorano JL et al (2011) EAE/ASE recommendations for the use of echocardiography in new transcatheter interventions for valvular heart disease. J Am Soc Echocardiogr 24(9):937–965
35. Kappetein AP et al (2013) Updated standardized endpoint definitions for transcatheter aortic valve implantation: the Valve Academic Research Consortium-2 consensus document. J Thorac Cardiovasc Surg 145(1):6–23