Three dimensional evaluation of the aortic annulus using multislice computer tomography: are manufacturer’s guidelines for sizing for percutaneous aortic valve replacement helpful?

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Aims
To evaluate the effects of applying current sizing guidelines to different multislice computer tomography (MSCT) aortic annulus measurements on Corevalve (CRS) size selection.

Methods and results
Multislice computer tomography annulus diameters [minimum: Dmin; maximum: Dmax; mean: Dmean = (Dmin + Dmax)/2; mean from circumference: Dcirc; mean from surface area: DCSA] were measured in 75 patients referred for percutaneous valve replacement. Fifty patients subsequently received a CRS (26 mm: n = 22; 29 mm: n = 28). Dmin and Dmax differed substantially [mean difference (95% CI) = 6.5 mm (5.7–7.2), P < 0.001]. If Dmin were used for sizing 26% of 75 patients would be ineligible (annulus too small in 23%, too large in 3%), 48% would receive a 26 mm and 12% a 29 mm CRS. If Dmax were used, 39% would be ineligible (all annuli too large), 4% would receive a 26 mm, and 52% a 29 mm CRS. Using Dmean, Dcirc, or DCSA most patients would receive a 29 mm CRS and 11, 16, and 9% would be ineligible. In 50 patients who received a CRS operator choice corresponded best with sizing based on DCSA and Dmean (76%, 74%), but undersizing occurred in 20 and 22% of which half were ineligible (annulus too large).

Conclusion
Eligibility varied substantially depending on the sizing criterion. In clinical practice both under- and oversizing were common. Industry guidelines should recognize the oval shape of the aortic annulus.

Keywords
Percutaneous • Transcutaneous • Aortic valve • Sizing • Aortic root

Introduction
Percutaneous aortic valve replacement (PAVR) is increasingly being used to treat patients with severe aortic stenosis who are thought to be high risk or ineligible for surgery.1–9 Optimal valve function relies on, among others, accurate sizing, i.e. selection of prosthesis size to match patient anatomy. In contrast to surgical AVR where sizing is done under direct vision, the use of imaging of the aortic root is mandatory for sizing before PAVR.

The aortic annulus, on which sizing is based, is defined as a virtual ring with three anatomical anchors at the nadir of each aortic leaflet, i.e. the three caudal points of the crown shaped line of attachment of the leaflets.10 Patient matrices provided by the manufacturers are used in clinical practice for the selection of the valve size and are based on transthoracic echocardiography (TTE) or transoesophageal echocardiography (TEE) defined annulus dimensions. Yet, TTE and TEE produce 2D tomograms, whereas the aortic root has a complex 3D geometry, with a base (annulus) that is often elliptical.10 Furthermore, one cannot precisely appreciate the exact position for the measurement of annulus diameter, which by definition should go through the centre of the virtual ‘ring’, thereby leading to underestimation of...
annulus dimension.\textsuperscript{11–18} In contrast, with a 3D imaging modality such as cardiac multislice computer tomography (MSCT), multiple axial diameter measurements of the non-circular annulus are possible.

We assessed the geometry of the aortic root with dual source MSCT in 75 patients with severe aortic stenosis who were referred for PAVR. The purpose of this study was to evaluate the effects of applying current sizing guidelines to different annulus diameter measurements on size selection of the CoreValve Revalving\textsuperscript{TM} System (CRS).

**Methods**

This study complies with the declaration of Helsinki. Seventy-five patients with severe aortic stenosis who had MSCT for the purpose of assessment of the peripheral vessels and determining the optimal C-arm angulation in preparation of the PAVR procedure were studied, of whom 50 subsequently had PAVR with implantation of a CRS prosthesis (size 26 mm in 22 and 29 mm in 28 patients). In these patients, the operator selected CRS size during PAVR on the basis of a combination of clinical variables (gender, body height, and weight), visual assessment of the left ventricular outflow tract (LVOT) and aortic root on TTE and contrast angiography of the aortic root. Detailed measurements of the annulus on MSCT were not available at the time of PAVR.

**Multislice computer tomography acquisition**

All patients were scanned using dual source CT (Somatom Definition, Siemens Medical Solutions, Forchheim, Germany). The system is equipped with two X-ray tubes and detectors offset by 90\degree on a single gantry.

Multislice computer tomography scanning parameters were: 2\times\) detector collimation of 32\times0.6 mm with a z-axis flying focal spot, rotation time 330 ms, tube voltage 120 kV. The pitch varied between 0.2 for low heart rates (<40 b.p.m.) and 0.53 for high heart rates (>100 b.p.m.), with individually adapted pitch values for heart rates >40 and <100 b.p.m. Each tube provided 412 mA/rot (625 mA), and full X-ray tube current (100\%) was given during the 14–46% of the R–R interval. The scan ranged from the top of the aortic arch to the diaphragm. The volume of iodinated contrast material (Visipaque\textsuperscript{R} 320 mg/mL, GE Health Care, Eindhoven, The Netherlands) was adapted to the expected scan time. A contrast bolus (50–60 mL) was injected in an antecubital vein at a flow rate of 5.0 mL/s

![Figure 1](https://academic.oup.com/eurheartj/article-abstract/31/7/849/431511/317284531511)  

**Figure 1** Definition of cut planes on MSCT. The three cut planes (coronal, sagittal, and axial to the body) are first centred on the aortic valve by clicking on it. The coronal (B) and then sagittal (A) cut planes are adjusted to obtain three orthogonal planes through the aortic root were the nadir of each of the three aortic leaflets could be seen simultaneously in one axial image (orange arrows, D). Annulus measurements (minimum and maximum) were made on the axial image (D). The red and green lines represent the oblique sagittal (A) and oblique coronal planes (B), respectively, as defined using the coapation line between the left and non-coronary cusps (C). The black lines represent the closest planes to true coronal and sagittal on the axial image (D). The yellow lines indicate where the minimum and maximum diameters were measured in this patient (D). In the majority of patients, the minimum and maximum diameters were obtained along the red and green lines. The median (IQ range) X-ray gantry angulation for the oblique coronal view was LAO 4\degree (RAO 4 to LAO 14), caudal 10\degree (caudal 16 to cranial 1), whereas in the proportion of patients where the maximum diameter was at a different angulation this was obtained at median (IQ range) LAO 26\degree (LAO 15 to 31), cranial 9\degree (1–23). The oblique coronal plane (green line) is the view used for fluoroscopic guidance during PAVR procedures (E).
followed by a second contrast bolus of 30–40 at 3.0 mL/s. Bolus tracking was used to synchronize contrast opacification of the aortic root with the start of the scan. End-systolic datasets were reconstructed using a single-segmental reconstruction algorithm: slice thickness 1.5 mm; increment 0.4 mm; medium-to-smooth convolution kernel (B26f) resulting in a spatial resolution of 0.6–0.7 mm in-plane and 0.4–0.5 mm through-plane, and a temporal resolution of 83 ms. The radiation dose for each scan ranged from 8 to 20 mSv depending on body habitus and table speed (slower table speed at lower heart rates increases radiation dose).

Definitions of the axial plane of the valve and the optimal gantry angulation for fluoroscopy

Analyses of MSCT datasets were performed on dedicated workstations using Siemens Circulation software. Axial cuts through the aortic root were obtained by aligning the three perpendicular analysis windows (one axial and two longitudinal, respectively, oblique sagittal and oblique coronal), so that the most caudal attachments of all three aortic leaflets could be seen simultaneously in one axial image (Figure 1). The oblique sagittal plane was then modified by defining it in the axial window at the level of leaflet coaptation as the line running through the commissure and along the coaptation line of the left and non-coronary leaflets thereby dividing the right coronary sinus into visually equal halves. The oblique coronal plane (similar to the AP view on fluoroscopy) was defined as the line orthogonal to and crossing the oblique sagittal plane at the point of central leaflet coaptation (i.e. the point where all three leaflets meet). Subsequently, measurements of the root were performed at various levels on the appropriate axial slices (Figure 1D). This definition of the viewing planes was used because the oblique coronal plane then gives the angulation of the X-ray gantry that is used to guide CRS positioning during PAVR procedures, i.e. the ‘implanter’s view’ (Figure 1E).

Definition of the base of the leaflets (annulus) and measurements of interest

The aortic annulus or base of the native leaflets was defined as the axial plane where the most caudal attachment of all three aortic leaflets could be seen simultaneously, (Figure 1D). The smallest ($D_{\text{min}}$) and largest ($D_{\text{max}}$) orthogonal diameters were measured on the axial image at this level. In the majority of patients, $D_{\text{min}}$ and $D_{\text{max}}$ were measured parallel to the oblique sagittal and oblique coronal planes (Figure 1). The oblique sagittal plane approximates the parasternal long-axis view on TTE and the mid-oesophageal long-axis view on TEE and usually provides the smallest diameter ($D_{\text{min}}$). This view corresponds with the manufacturer’s guideline of sizing. The oblique coronal plane approximates the postero-anterior view on cine-angiography (implanter’s view) and usually provides the largest diameter ($D_{\text{max}}$).

In addition to $D_{\text{min}}$ and $D_{\text{max}}$ the annulus luminal circumference ($c$) and cross-sectional surface area (CSA) were measured from which the mean diameters ($D_{\text{circ}}, D_{\text{CSA}}$) were derived from equations: $D_{\text{circ}} = c/\pi$ and $D_{\text{CSA}} = 20 \times \text{square root}\ (\text{CSA}/\pi)$.

Statistical methods

Variables are given as the mean and standard deviation (SD) or, if the distribution was not Gaussian, as the median and interquartile range (IQ range). The different diameter measurements were all normally distributed and were compared in the same patient using the Student t-test for paired data. Statistical analysis was done using SPSS 16.0. Statistical significance was defined as $P < 0.05$.

Results

The baseline characteristics of the total study population are shown in Table 1.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean (SD) or median (interquartile range)</th>
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<tbody>
<tr>
<td>Total number</td>
<td>75</td>
</tr>
<tr>
<td>Age</td>
<td>81 (76–85)</td>
</tr>
<tr>
<td>Gender (% male)</td>
<td>51</td>
</tr>
<tr>
<td>Height (m)</td>
<td>165 (160–173)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>73 (63–83)</td>
</tr>
</tbody>
</table>

Antecedents

Stroke/TIA, n (%) 16 (21)
AMI 19 (25)
CABG 19 (25)
PCI 16 (21)
PVD 7 (28)

Comorbidity

Diabetes mellitus 10 (13)
COPD 18 (24)
Serum creatinine 90 (71–115)

Echo-Doppler

LV FVT normal 45 (63)
LV FVT moderate 24 (33)
LV FVT impaired 13 (4)
Peak velocity 4.6 (4.0–4.9)

TIA, transient ischaemic attack; AMI, acute myocardial infarction; CABG, coronary artery bypass surgery; PCI, percutaneous coronary intervention; PVD, peripheral vascular disease; LV, left ventricle.
In the 50 patients who subsequently received a CRS, the annulus diameter measured on TTE (parasternal long-axis view) was 22.7 mm (2.2) and lay between $D_{\text{min}}$ and $D_{\text{CSA}}$ [mean (SD) 21.5 (2.8) and 24.0 (2.7), respectively].

Sizing based on different annulus diameter measurements

The CRS size selection based on the application of industry guidelines (26 mm CRS: 20–23 mm annulus; 29 mm CRS: 23–27 mm annulus) to the different estimations of annulus diameter are shown in Table 3. If $D_{\text{min}}$ were used for sizing, 74% of the patients would be eligible for CRS implantation (48% for a 26 mm CRS, 12% for a 29 mm CRS, and 14% for either a 26 mm or a 29 mm CRS given the overlap in the manufacturer’s guidelines). Yet, 26% of the patients would be ineligible for CRS implantation (annulus too small in 23% and too large in 3%).

If $D_{\text{max}}$ were used, 61% of the patients would be eligible for CRS implantation (4% for a 26 mm CRS, 52% for a 29 mm CRS, and 5% would receive either a 26 mm or a 29 mm CRS) and 39% would not be eligible for a CRS implantation because of too large an annulus in all.

If $D_{\text{mean}}$, $D_{\text{circ}}$, or $D_{\text{CSA}}$ were used the majority of patients would be eligible for a 29 mm CRS and 11, 16, and 9%, respectively, would not be eligible because of too large an annulus in all.

Retrospective comparison of sizing based on the application of industry guidelines to different multislice computer tomography annulus diameter measurements with the operator choice of CRS size in 50 patients in whom a CRS was implanted

Sizing based on $D_{\text{min}}$ corresponded to operator choice in 44% of patients but would have led to a smaller prosthesis than was selected by the operator in a 26%, whereas a further 24% would not have been eligible for a CRS due to too small an annulus (Figure 2). Sizing based on $D_{\text{max}}$ corresponded to operator choice in 30% but would have led to the selection of a larger prosthesis in 32%, whereas a further 36% of patients would not have been eligible for a CRS due to too large an annulus. Sizing based on the mean diameters $D_{\text{mean}}$ and $D_{\text{CSA}}$ corresponded best with operator choice (in 74% and 76%, respectively), whereas sizing based on $D_{\text{circ}}$ corresponded in only 60%.

<table>
<thead>
<tr>
<th>Measured or derived MSCT annulus diameter</th>
<th>All patients ($n = 75$)</th>
<th>Patients with CRS ($n = 50$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum ($D_{\text{min}}$)</td>
<td>21.4 (2.8)</td>
<td>21.5 (2.8)</td>
</tr>
<tr>
<td>Maximum ($D_{\text{max}}$)</td>
<td>26.9 (2.8)</td>
<td>26.7 (2.9)</td>
</tr>
<tr>
<td>Mean ($D_{\text{mean}}$)</td>
<td>24.1 (2.6)</td>
<td>24.0 (2.7)</td>
</tr>
<tr>
<td>‘Mean’ from circumference ($D_{\text{circ}}$)</td>
<td>24.3 (2.1)</td>
<td>25.0 (2.7)</td>
</tr>
<tr>
<td>‘Mean’ from CSA ($D_{\text{CSA}}$)</td>
<td>23.6 (2.0)</td>
<td>24.0 (2.6)</td>
</tr>
</tbody>
</table>

All measures are expressed as mean (SD) in mm, CSA, cross-sectional surface area.
Table 3  Eligibility of percutaneous aortic valve replacement based upon different annulus dimensions either measured or derived from multislice computer tomography

<table>
<thead>
<tr>
<th>MSCT annulus measurement (n = 75)</th>
<th>Annulus suitable for CRS with inflow</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Eligible for CRS (%)</td>
</tr>
<tr>
<td>$D_{min}$</td>
<td>74</td>
</tr>
<tr>
<td>$D_{max}$</td>
<td>61</td>
</tr>
<tr>
<td>$D_{mean}$</td>
<td>89</td>
</tr>
<tr>
<td>$D_{CIRC}$</td>
<td>84</td>
</tr>
<tr>
<td>$D_{CSA}$</td>
<td>91</td>
</tr>
</tbody>
</table>

Manufacturer: 26 mm CRS: 20–23 mm annulus; 29 mm CRS: 23–27 mm annulus.

$^a$Annulus too small in 23%.

$^b$Annulus too big in 40%.

$^c$Annulus too big in 11%.

$^d$Annulus too big in 16%.

$^e$Annulus too big in 9%.

Figure 2  Comparison of proposed CRS size selection based on different annulus diameter measurements (manufacturer's guidelines: 26 mm; CRS: 20–23 mm annulus; 29 mm CRS: 23–27 mm annulus) with operator choice in 50 patients in whom a CRS was implanted.
In patients where oversizing was evident the majority had received a small (26 mm) CRS, whereas in patients where undersizing was evident the majority had received a large (29 mm) CRS.

### Evaluation of a potential adverse procedural outcome associated with a discrepancy in sizing between the application of current industry guidelines to different multislice computer tomography annulus diameters and the implanted prosthesis size (operator choice)

There were no cases of unexplained device embolization and aortic root rupture occurred in one patient after predilatation. The odds of an adverse procedural outcome (aortic regurgitation greater than Grade 2, unexplained device embolization, or aortic root rupture) associated with a discrepancy in size selection between the application of current industry guidelines for sizing to different MSCT annulus diameters and the implanted prosthesis size (operator choice) were calculated for each of the MSCT annulus diameters (Table 4). A trend was seen towards a higher risk of adverse events when operator choice of valve size disagreed with the aggregate diameter measurements ($D_{\text{mean}}$, $D_{\text{circ}}$, $D_{\text{CSA}}$), but none of the odds ratios were statistically significant and confidence intervals were wide (Table 4).

### Discussion

The present study shows that incorrect valve sizing based on the application of industry guidelines to different annulus diameter measurements is a frequent occurrence. Incorrect sizing was least frequent (but still present in 24% of patients) when industry guidelines were applied to the mean diameter calculated from the annulus CSA ($D_{\text{CSA}}$). Measurement of the annulus CSA is not mentioned in current guidelines and cannot be measured accurately using 2D TTE, the most commonly used imaging modality. The $D_{\text{mean}}$ calculated from the minimum and maximum annulus diameters gave a very similar prevalence of incorrect sizing (26%) to $D_{\text{CSA}}$, but again are ideally measured on axial images, which may not be obtainable by 2D TTE. Industry guidelines are based on an idealized symmetrical aortic root, whereas in the present study the annulus was non-circular and often oval similar to other the findings of studies using 3D imaging modalities including 64-slice MSCT, 3D TTE, or cardiac magnetic resonance imaging (CMRI).13–17 We defined the annulus as a virtual ‘ring’ with three anatomical anchor points at the nadir of each of the three aortic cusps. This definition of the annulus on MSCT is in keeping with the anatomical definition, but has not been used by other 3D imaging studies.8 Possibly the nadir of the cusps are more readily discernable with dual source MSCT due to improved temporal resolution compared with 64-slice MSCT and improved spatial resolution compared with CMRI or 3D TTE.

We observed that sizing based on $D_{\text{max}}$ and $D_{\text{CSA}}$ also corresponded best to operator choice, whereas based on $D_{\text{min}}$ or $D_{\text{max}}$ 0–50% of the patients received a CRS that was too large and 22–38% of the patients received a CRS that was too small. Although, based on $D_{\text{CSA}}$, 10 patients received undersized CRS, it has to be borne in mind that 4 of 10 were implanted before October 2007 when the size 29 CRS first became available. Furthermore, the modality used most often for sizing remains TTE, usually on the parasternal long-axis view. This measurement would correspond most closely with $D_{\text{min}}$ on MSCT. In addition, both TTE and TOE tend to underestimate the diameter compared with surgical sizing or MSCT by 1–2 mm on average, most likely due to the difficulty in defining a measurement that cuts through the true centre of the annulus on 2D images.11–13,18 As a result, one might anticipate a higher prevalence of undersizing that was observed in this retrospective study. Other factors apart from TTE measurements must have influenced the sizing decision such as clinical variables (height and weight) or procedural factors such as the expansion size/pressure of the pre-dilatation balloon.15

On the basis of the observations from this study and the recognition that TTE and TOE remain the imaging modalities used most frequently for sizing, we anticipate that undersizing will also be common in other populations. This would seem to be supported by a number of case reports of unexpected device embolization.19–21 In our series, none of the valves embolized despite undersizing, which suggests that the CRS is anchored at the level of the calcified native leaflets in addition to (good) apposition in the LVOT. An interesting observation is that of apparently successful implantation procedures despite that one or even both annulus diameters on MSCT do not comply with industry guidelines on sizing. This observation indicates that how the CRS anchors and

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**Table 4  Odds of an adverse outcome**

<table>
<thead>
<tr>
<th>Different annulus diameters from MSCT used for sizing by application of current industry guidelines</th>
<th>$D_{\text{min}}$</th>
<th>$D_{\text{max}}$</th>
<th>$D_{\text{mean}}$</th>
<th>$D_{\text{circ}}$</th>
<th>$D_{\text{CSA}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Odds of adverse outcome when operator choice disagreed (95% CI)</td>
<td>0.90 (0.29–2.77)</td>
<td>1.02 (0.31–3.36)</td>
<td>1.71 (0.48–6.10)</td>
<td>1.50 (0.48–4.60)</td>
<td>1.38 (0.37–5.06)</td>
</tr>
</tbody>
</table>

Aortic regurgitation higher than Grade 2, unexplained device embolization (occurred in two patients due to operator error was not included) or aortic root rupture (occurred in one patient after predilatation) when there was a discrepancy between sizing by applying current industry guidelines to different multislice computer tomography diameters and operator choice. CI, confidence interval; MSCT, multislice computer tomography.
seals in the LVOT in some patients are not yet fully understood, but also that prospective studies are required to evaluate the medium to long-term effects of patient to prosthesis mismatch following PAVR. There are no published data on sizing in PAVR. Sub-optimal sizing of a surgically implanted prosthesis is associated with a reduced prognosis. Although the surgically implanted prosthesis is sewn in place the PAVR prosthesis relies on good sizing and apposition to maintain both position in the LVOT and functional integrity. One might therefore expect an important physiological effect of sub-optimal sizing on outcome following PAVR, although it is possible that in the aged, frail, and comorbid patients who receive PAVR the prognostic effect would be minimal. Furthermore, compression of the semi-rigid circular frame of the CRS inflow may in the orthogonal plane (diameter) leading to an elliptical shape, but also that prospective studies are required to evaluate the medium to long-term effects of patient to prosthesis mismatch following PAVR.

The aortic annulus is often elliptical and differences in the minimum and maximum diameter can lead to substantial differences in the selection of prosthesis size, which may result in under-sizing or oversizing. If $D_{CSA}$ were to be used for sizing only 11% of patients referred for PAVR would not be eligible for either a 26 mm or a 29 mm inflow CRS. Undersizing during PAVR based on current guidelines is likely to be common and may affect all prosthesis types. Industry guidelines for sizing should recognize that the aortic annulus is oval in shape. Our data show that using $D_{CSA}$ or $D_{mean}$ may improve sizing and reduce both over- and undersizing, but further studies are required.

**Limitations**

The present study is retrospective and the findings should be viewed as hypothesis generating. The study shows that the issue of sizing is far more complex than current industry guidelines would suggest but more detailed studies are required to understand how to optimally size followed by prospective validation studies. Only one 3D imaging modality (MSCT) was used for the evaluation of the non-circular annulus. Although other 3D imaging modalities such as 3D echocardiography and MRI also allow appreciation of the 3D anatomy of the aortic root these have other limitations and further studies are needed to evaluate the applicability for sizing. We believe that MSCT is the modality of choice for evaluation of patient anatomy before PAVR, but comparisons with other 3D modalities and the 2D modalities of TTE and TEE are needed to establish a gold standard for the measurement of annulus diameter. The absence of a significant association between apparently incorrect sizing and aortic regurgitation reflects the multiple potential causes of AR (including incorrect implantation depth, prevention of apposition, or perforation of the pericardial skirt by calcium among others) in addition to incorrect sizing, but may also be the result of the relatively small number of patients studied.

**Conclusions**

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**Conflict of interest:** none declared.

**References**


