RESEARCH ARTICLE

Aortic root evaluation prior to transcatheter aortic valve implantation—Correlation of manual and semi-automatic measurements

Barbora Horehledova1,2*, Casper Mihl1,2, Chris Schwemmer3, Babs M. F. Hendriks1,2, Nienke G. Eijsvoogel1,2, Bastiaan L. J. H. Kietselaer1,2,4, Joachim E. Wildberger1,2, Marco Das1,2,4

1 Department of Radiology and Nuclear Medicine, Maastricht University Medical Center, Maastricht, The Netherlands, 2 CARIM School for Cardiovascular Diseases, Maastricht University Medical Center, Maastricht, The Netherlands, 3 Computed Tomography Research & Development, Siemens Healthcare GmbH, Forchheim, Germany, 4 Department of Cardiology, Maastricht University Medical Center, Maastricht, The Netherlands

* Current address: Department of Cardiology, Stichting Zuyderland Medical Center, Heerlen, The Netherlands
† Current address: Department of Diagnostic and Interventional Radiology, Helios Kliniken Duisburg GmbH, Duisburg, Germany

barbora.horehledova@mumc.nl

Abstract

Background
Pre-procedural TAVI planning requires highly sophisticated and time-consuming manual measurements performed by experienced readers. Semi-automatic software may assist with partial automation of assessment of multiple parameters. The aim of this study was to evaluate differences between manual and semi-automatic measurements in terms of agreement and time.

Methods
One hundred and twenty TAVI candidates referred for the retrospectively ECG-gated CTA (2nd and 3rd generation dual source CT) were evaluated. Fully manual and semi-automatic measurements of fourteen aortic root parameters were assessed in the 20% phase of the R-R interval. Reading time was compared using paired samples t-test. Inter-software agreement was calculated using the Intraclass correlation coefficient (ICC) in a 2-way mixed effects model. Differences between manual and semi-automatic measurements were evaluated using Bland-Altman analysis.

Results
The time needed for evaluation using semi-automatic assessment (3 min 24 s ± 1 min 7 s) was significantly lower (p<0.001) compared to a fully manual approach (6 min 31 sec ± 1 min 1 sec). Excellent inter-software agreement was found (ICC = 0.93 ± 0.0; range:0.90–0.95).
The same prosthesis size from manual and semi-automatic measurements was selected in 92% of cases, when sizing was based on annular area. Prosthesis sizing based on annular short diameter and perimeter agreed in 99% and 96% cases, respectively.

Conclusion

Use of semi-automatic software in pre-TAVI evaluation results in comparable results in respect of measurements and selected valve prosthesis size, while necessary reading time is significantly lower.

Introduction

Transcatheter aortic valve implantation (TAVI) provides a minimally invasive therapeutical option to patients with severe aortic valve stenosis who are not eligible for conventional valve replacement [1–8]. Precise assessment of aortic root prior to the intervention is fundamental for patient’s outcome. It allows for recognition of suitable patients, selection of the correct valve for replacement, and therefore minimizes the risk of peri-procedural complications [9].

Need for comprehensive imaging with high spatial and temporal resolution, which is not impaired by dynamic movement of aortic root during cardiac cycle is the reason why multidetector row CT (MDCT) has been addressed as the method of choice in pre-TAVI evaluation [10–13]. MDCT assessment of aortic root was recently also considered a predictive factor for severity of paravalvular leakage, which further supports the role of MDCT in TAVI planning [11, 14].

However, tedious manual assessment of aortic root dimensions is highly sophisticated and therefore requires an experienced reader who is able to reliably extract necessary data from the scan. Semi-automatic software is designed to determine anatomical structures of aortic annulus on MDCT scan, allowing partial automation of measurements and in this respect simplifying the assessment, hereby making TAVI planning faster.

Similar assisting software tools, with different levels of automation, have been previously described in the limited extent of four or five aortic root dimensions [15, 16], however, in our clinical practice fourteen aortic root parameters are routinely assessed in each TAVI candidate, following the expert consensus guidelines on MDCT imaging before TAVI [17, 18].

The aim of this study was to evaluate the agreement and time effectiveness of a prototype of a semi-automatic software with the standard manual assessment in aortic root evaluation prior to TAVI.

Materials and methods

Study population and data collection

Between April 2014 and April 2016, 120 patients with severe AS were retrospectively evaluated. All patients were referred from the cardiology outpatient department for pre-interventional assessment of aortic root dimensions and peripheral arteries. Patients with a history of valve replacement were excluded from the data analysis.

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The approval for this study was obtained from the Institutional Review Board and the local medical ethical consents...
research committee (METC). Due to the retrospective nature of this study a waiver of written informed consent was issued by the Institutional Review Board. The data were coded and analyzed anonymously. The local METC (METC—Maastricht University Medical Center) reference number is 15-4-202.

**Imaging protocol & post-processing**

Retrospectively ECG-gated spiral MDCT of the aortic root was performed on a 2nd and 3rd generation Dual source CT scanner (Somatom Definition Flash & Somatom Force, Siemens Healthcare GmbH, Forchheim, Germany) following an established institutional protocol [19]. Images were reconstructed at every 10% of the R–R interval with individually adapted field of view (FOV) at 0.6 mm slice thickness with an increment of 0.4mm using iterative reconstruction (strength 3) and l26f kernel. Measurements were performed with dedicated post-processing software (Syngo.via™ Siemens Healthcare GmbH, Forchheim, Germany).

**Objective CT image quality**

CT image quality was quantified, in terms of attenuation in Hounsfield Units (HU), standard deviation (SD), signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR). Vascular attenuation was assessed with manually placed circular regions of interest (ROI) at the level of sino-tubular junction. For noise and signal estimation another ROI was placed in the perivascular tissue in the left ventricular myocardium. CNR was calculated as vascular attenuation minus perivascular tissue attenuation, divided by the SD of the perivascular tissue attenuation. SNR was calculated as vascular attenuation divided by the SD of vascular attenuation [19]. Image quality was considered diagnostic with vascular attenuation values > 200 HU [20, 21] and CNR > 3 [22].

**Subjective CT image quality**

The subjective image quality, in terms of presence or absence of cardiac motion artifacts, was qualitatively evaluated by an experienced cardiovascular radiologist (CM) using previously published 4-point Likert scale [23]: grade 1—non-diagnostic: impaired image quality that precluded appropriate evaluation of the aortic root due to severe motion artifacts; grade 2—diagnostic: reduced image quality due to motion artifacts, but sufficient to assess aortic root dimensions; grade 3—good: presence of motion artifacts, but fully preserved ability to reliably assess aortic annulus dimensions; grade 4—excellent: complete absence of motion artifacts. Cardiac motion artifacts were defined as beam-hardening, stair-stepping, blurring, ghosting, streaking, linear bands, areas of isolated or multiple discontinuity or dark shadows [24].

**Aortic annulus and leaflet calcifications**

The presence of aortic annulus calcification was qualitatively analyzed and graded in consensus by 2 observers (BH, CM) using a 5-point Likert scale: grade 0: absent annulus calcification; grade 1—minimal (< 25% of total annulus circumference); grade 2—mild (25–50% of total annulus circumference); grade 3—moderate (50–75% of total annulus circumference); grade 4—severe (75–100% of total annulus circumference) [25]. The aortic valve leaflet calcifications were graded as present or absent.

**Time tracking**

Case evaluation time was recorded within each assessment. A time tracking macro tool (programmed in Microsoft Excel, Microsoft corporation, Redmond, WA, USA) was built in the
electronic worksheet. Therefore pre-TAVI measurements and reading time were recorded simultaneously to assure uniformity and accuracy of time measurements, regardless of method or reader performing the evaluation. The time tracking tool assessed the software loading time, describing the time before measurements could be carried out and time used for assessment of aortic root measurements as individual time points within evaluation. Mean necessary reading time was established for manual and semi-automatic approach. In manual assessment, the effective diameters derived from annular area and perimeter (\( \text{eff. } D_A \) and \( \text{eff. } D_P \), respectively) had to be additionally calculated with dedicated formulas (Fig 1), as these values are not directly available during manual analysis. However, the time needed to calculate effective diameters is not significant and was therefore disregarded.

Software loading time was tracked, but excluded from further evaluation because semi-automatic measurements were performed in preclinical interface.

**Measurements**

Pre-TAVI measurements were performed in fully manual and semi-automatic approach in each patient in the 20% phase of cardiac cycle, according to previous literature [26]. Results of earlier evaluation (manual or semi-automatic; inter-observer) were blinded during the subsequent data analysis with the remaining method. The following dimensions of the aortic root were assessed, in accordance to the expert consensus guidelines of the Society of Cardiovascular Computed Tomography (SCCT) [17]:

- short and long annulus diameter
- cross-sectional area of aortic annulus (defined as an area within an oval or ring formed by linking the most basal portions of the leaflet attachments)
- aortic annulus perimeter
- distance from the aortic annulus to the center of the ostium of the left and right coronary artery
- widest diameter at the sinotubular junction
- aortic root diameter at the level of the left and right coronary artery ostium

\[
\text{eff. } D_A = 2 \times \sqrt{\frac{\text{cross-sectional area}}{\pi}} \\
\text{eff. } D_P = \frac{\text{perimeter}}{\pi}
\]

*Fig 1. Formulas used for calculation of effective diameter. eff. \( D_A \) = effective diameter derived from aortic annulus area, eff. \( D_P \) = effective diameter derived from aortic annulus perimeter.*

https://doi.org/10.1371/journal.pone.0199732.g001
• widest portion of the coronary sinuses diameter
• length of left and right aortic valve leaflet
• eff. $D_P$ and eff. $D_A$

Agreement between manual and semi-automatic method and inter-reader agreement in semi-automatic approach were estimated in all measured parameters. In patients suitable for TAVI procedure the TAVI prosthesis size (Edwards Sapien Valve, Edwards Lifesciences Corp, Irvine, USA) was theoretically selected according to published recommendations [17, 27]. The agreement in selected prosthesis size derived from manual and semi-automatic method was evaluated.

Manual measurements

The manual assessment was performed with a dedicated software workflow (CT TAVI planning, Syngo.via™ VB10A Siemens). The 20% phase of the R-R interval was selected. Image data were manipulated in order to create an oblique transversal plane corresponding to the aortic annulus, crossing the most basal attachments of the aortic leaflets (Fig 2A), where aortic annulus diameters, area and perimeter were assessed. Eff. $D_A$ and eff. $D_P$ were calculated manually. An oblique transversal plane perpendicular to the course of the aorta was used to measure the dimensions of the widest portion of aortic root, the diameter at the level of sinotubular junction and at the level of coronary artery ostia. The oblique sagittal or coronal plane was used for the measurement of the distances from aortic annulus to the coronary artery ostia, and the length of the aortic leaflets (Fig 2B). Manual assessment was performed by a research fellow specially trained for this analysis (BH), with one year of experience in TAVI planning.

Semi-automatic measurements

Semi-automatic measurements were performed with a prototype version of syngo.CT Cardiac Planning software (Syngo.via™ VB20A, Siemens). The semi-automatic software automatically detects the three most basal attachment points of aortic valve leaflets, therefore opens the user interface directly in the annulus plane in the endsystolic phase. Measurements of short and long annulus diameter, annular area and perimeter are fully automatic. Likewise, eff. $D_A$ and

![CT TAVI planning, Syngo.via™ VB10A Siemens, Siemens Healthcare GmbH, Forchheim Germany. (A) The oblique transversal plane crossing the most basal attachments of the aortic valve leaflets. (B) The oblique sagittal (coronal) plane of the aortic valve showing leaflets.](https://doi.org/10.1371/journal.pone.0199732.g002)
eff. $D_p$ are calculated by the software and presented instantly. A centerline is computed through the aortic root and ascending aorta perpendicularly to the estimated aortic annulus plane. A dedicated tool (diameter ruler) displays automatically minimum and maximum diameters, perimeter, cross-sectional area and effective diameters at respective levels of the aortic root and ascending aorta while scrolling along the centerline. This allows for semi-automatic assessment of aortic root diameters (widest portion of aortic sinuses, diameter at sino-tubular junction, diameter at the level of coronary ostia). Another dedicated tool assists only with image manipulation in order to visualize both left and right coronary ostia in one oblique sagittal plane (see Fig 3). Measurements of the distance from the aortic annulus to the coronary ostia as well as the length of coronary leaflets are then assessed manually.

In addition, the reproducibility of semi-automatic measurements was evaluated. A research fellow specially trained in pre-TAVI evaluation with one year of experience (BH; reader 1) and a cardiovascular radiologist (CM; reader 2) performed the semi-automatic measurements independently and fully blinded to each other, in all 120 cases.

**Statistical analysis**

Dimensions of each anatomical structure and time needed for evaluations were evaluated using descriptive statistics (mean ± SD) calculated with independent samples t-test. Correlation and agreement between the manual and semi-automatic method were determined with the use of the paired samples t-test and Bland-Altman methods with 95% confidence interval (CI; mean difference ± 1.96 x SD). Inter-observer agreement was calculated using the Intra-class correlation coefficient (ICC) in a 2-way mixed effects model Bland-Altman methods with
95% CI. Statistical analysis was conducted using Statistical Package for Social Sciences version 23.0 (SPSS Inc., Chicago, IL, USA). All p-values are 2-sided, and a p-value < 0.05 was considered statistically significant.

Results

Baseline characteristics
Baseline characteristics are listed in Table 1. The study population consisted of 68 male and 52 female patients with an average age of 78 ± 8 years.

Objective CT image quality
All examinations were of diagnostic quality, allowing aortic valve evaluation in all 120 included cases. The mean attenuation value at sinotubular junction was 426 ± 108 HU, with mean SNR 12 ± 6 and mean CRN 11 ± 5.

Subjective CT image quality
Cardiac motion artifacts were completely absent (grade 4) in 101 images (84%), non-significant motion artifacts (grade 3) occurred in 19 scans (16%). No scans presented with non-diagnostic or diagnostic level of artifacts (grade 1 or 2).

Aortic annulus and leaflet calcifications
The annulus calcification was present in total of 118 cases (98%). In 105 patients (88%) was the extent of annular calcification graded as minimal and in 13 as mild (18%). In 5 cases (4%) the aortic annulus calcification extended caudally into the left ventricular outflow tract. The aortic valve leaflets were calcified in all assessed patients.

Time tracking
All time tracking values in all established time points are stated in Table 2. Mean necessary reading time for manual measurements was 6 min 31 s ± 1 min 1 s. Mean necessary reading time for semi-automatic measurements were 3 min 24 s ± 1 min 7 s.

Manual and semi-automatic measurements
All manual and semi-automatic measurements are stated in the S1 Table. Excellent inter-software agreement was found between manual and semi-automatic method (ICC = 0.93 ± 0.02 for parameters with possible semi-automatic assessment and ICC = 0.83 ± 0.17 for all accessed dimensions; Table 3) [28]. The lowest ICC between manual and semi-automatic assessment

| Table 1. Baseline characteristics. |
|-----------------------------------|
| **Baseline characteristics**      | **Mean** | **Range** |
| Age [years]                       | 78 ± 8   | 43–90    |
| Gender                            | Male / Female | 68 (57%) / 52 (43%) |
| Height [cm]                       | 167 ± 10 | 135–193 |
| Weight [kg]                       | 77 ± 19  | 45–150  |
| BMI [kg/m²]                       | 28 ± 6   | 16–46   |

cm = centimeter; kg = kilogram; m = meter

https://doi.org/10.1371/journal.pone.0199732.t001
was established for distance from aortic annulus to left and right coronary ostium (ICC = 0.46 and 0.51, respectively). The highest agreement was found in measurement of area, perimeter and effective diameters (ICC = 0.95). The mean difference between manual and semi-automatic assessment of short diameter, annular area and perimeter, eff. DA and eff. DP were 0.31 mm (95% CI: -2.18 to 2.81), 14.38 mm² (95% CI: -58.37 to 87.13), 0.39 mm (95% CI: -5.70 to 6.49), 0.35 mm (95%: -1.48 to 2.18), and 0.12 mm (95% CI: -1.83 to 2.06), respectively (Fig 4A–4D).

Excellent inter-observer correlation in semi-automatic software was found in all assessed dimensions (ICC = 0.92 ± 0.12). The lowest observed mean ICC was found for the length of the cusps (ICC = 0.65) and the highest was found for the widest portion of the coronary sinuses diameter (ICC = 0.99). The mean inter-observer difference was ≤ -0.1 mm for annular diameters, -0.2 mm (95% CI: -4.02 to 3.62,) for annular perimeter and—3.3 mm² (95% CI: -54.59 to 47.99) for annular area (Fig 5).

Table 2. Time tracking of manual and semi-automatic measurements.

|                      | Manual assessment: | Semi-automatic assessment: |
|----------------------|--------------------|-----------------------------|
|                      | Mean ± SD          | Mean ± SD                   |
| Total Reading time   | 7 min 36 s ± 1 min 7 s | 3 min 55 s ± 1 min 19 s     |
| Loading time         | 1 min 5 s ± 0 min 23 s | 0 min 31 s ± 0 min 21 s     |
| Measurements time    | 6 min 31 s ± 1 min 1 s | 3 min 24 s ± 1 min 7 s     |

Total reading time = loading time + measurements time; Loading time = time before measurements could be carried; Measurement time = time for assessing evaluated measurements; SD = standard deviation

Table 3. Intraclass correlation agreement (ICC) between manual and semi-automatic approach and inter-observer agreement in semi-automatic approach.

|                              | ICC manual & semi-automatic measurements | ICC semi-automatic measurements | Automated measurements |
|------------------------------|------------------------------------------|---------------------------------|------------------------|
| Short annulus diameter       | 0.911                                    | 0.967                           |                        |
| Long annulus diameter        | 0.916                                    | 0.965                           |                        |
| Annulus area                 | 0.945                                    | 0.98                            |                        |
| Eff. DA                      | 0.947                                    | 0.984                           |                        |
| Perimeter                    | 0.950                                    | 0.984                           |                        |
| Eff. DP                      | 0.950                                    | 0.983                           |                        |
| Widest portion of aortic root| 0.92                                     | 0.988                           |                        |
| Diameter—Left ostium         | 0.902                                    | 0.977                           |                        |
| Diameter—Right ostium        | 0.898                                    | 0.963                           |                        |
| Diameter—sinotubular junction| 0.918                                    | 0.970                           |                        |
| Dist. annulus to the left ostium| 0.464                                | 0.918                           |                        |
| Dist. annulus to the right ostium| 0.513                                | 0.883                           |                        |
| Left leaflet length          | 0.696                                    | 0.652                           |                        |
| Right leaflet length         | 0.734                                    | 0.649                           |                        |

dist. = distance; eff. DA = diameter derived from aortic annulus area; eff. DP = diameter derived from aortic annulus perimeter; eff. = effective; ICC = Intraclass correlation coefficient

https://doi.org/10.1371/journal.pone.0199732.t002

https://doi.org/10.1371/journal.pone.0199732.t003
Fig 4. Bland-Altman plots demonstrating agreement between fully manual and semi-automatic MDCT measurements of annular dimensions commonly used in prosthesis size selection shown with 95% confidence interval. The middle line presents the mean difference (expressed in mm for aortic annulus diameters and perimeter, mm\(^2\) for aortic annulus area) and the upper and lower lines represent 95% confidence interval. (A) Short Axis Diameter; (B) Aortic Annulus Area; (C) Effective Diameter (Area); (D) Aortic Annulus Perimeter; (E) Effective Diameter (Perimeter).

https://doi.org/10.1371/journal.pone.0199732.g004
TAVI prosthesis size selection

Ninety-five patients finally were eligible for TAVI procedure (Fig 6). Theoretical prosthesis sizing based on short annular diameter was possible in 94 cases, as appropriate prosthesis size is not available for one patient with annulus diameter of 29.1 mm. Prosthesis sizing derived from short annular diameter resulted in size agreement in 93 cases (99%). In one case the manual assessment suggested TAVI prosthesis one size larger compared to the semi-automatic assessment. The same prosthesis size was suggested in 86 cases (92%) when sizing was based on annular area and in 86 cases (96%) based on annular perimeter.

Discussion

This study demonstrates that the evaluated semi-automatic software provides reliable aortic root measurements with an excellent inter-observer agreement. The prototype of the semi-automatic software is able to automatically recognize aortic annulus dimensions with an excellent agreement to manual assessment (ICC = 0.91–0.95), while the semi-automatic software is significantly less time consuming.
Precise measurements of aortic annulus dimensions are not only essential for selection of patients suitable for TAVI procedure, they are also crucial for particular selection of prosthesis size, which directly impacts patient’s outcome [9, 14]. Special attention was therefore paid to the annular dimensions suggested to be used in prosthesis size selection according to the industry guidelines. The mean difference between manual and semi-automatic measurements was 0.35 mm for annular diameters, 0.39 mm for annular perimeter and 14.38 mm² for annular area with an excellent ICC of 0.91 or higher. Even though the difference was statistically significant for short aortic annulus, annular area and eff. Dₐ, it should not be considered as clinically relevant according to previous literature [29]. This assumption is further supported with a 92–99% agreement between manual and semi-automatic assessment, when hypothetical valve sizing was applied in this study. Particularly, when agreement in suggested valve size of 59.4% was reported for manual measurements performed by different readers in study by Lou et al. in 2015 [15].

The moderate agreement in the annulus to coronary artery ostium distance (ICC = 0.46; 0.51) can be explained by the different data segmentation between methods. In a manual approach, measurements are carried out in a coronal plane, whereas the semi-automatic software arranges the aortic root along a calculated centerline, perpendicular to the aortic annulus plane, slightly affecting ostial position. However, comparable moderate agreement (ICC 0.48; inter-rater difference of up to 6.7 mm) was previously also reported for inter-rater agreement in manual assessment [30]. More importantly, the mean difference of 3.5 mm in

---

Fig 6. Theoretical TAVI prosthesis size selection (Edwards Sapien Valve). n = number; TAVI = transcatheter aortic valve implantation. Theoretical prosthesis size selection according to recommendations for Edwards Sapien Valve (Edwards Lifesciences Corp, Irvine, USA).

https://doi.org/10.1371/journal.pone.0199732.g006
annulus-ostium distance was previously considered acceptable in study by Watanabe et al. [16].

Nevertheless, the calculated centerline in semi-automatic software also offers a higher confidence while assessing the semi-manual measurements of aortic root diameters (ICC = 0.90–0.92). A dedicated tool “diameter ruler” works along the calculated centerline in the curved planar reformation (CPR) segment, directly presenting the minimum and maximum diameter at respective level of aortic root while scrolling. This feature allows the reader to distinguish the true maximum diameter faster and in more sophisticated way in comparison to manual assessment, where multiple manual measurements at different levels of aortic root have to be performed.

Therefore, apart from the increased level of user convenience regarding measurements, semi-automatic software also demonstrated a greater efficiency in terms of time consumption. Evaluating pre-TAVI scans with semi-automatic software was approximately 3 minutes faster, allowing to process twice as many pre-TAVI datasets, while delivering comparable results. Manual assessment was slower mainly due to need for initial data manipulation, in order to recognize aortic annulus plane.

Inter-observer agreement in this study was nearly perfect using the semi-automatic software, which offered reproducible results in terms of measurements, without necessarily reflecting the experience of the reader. Data segmentation, in matter of recognition or position of basal insertions of aortic valve cusps, may not satisfy the reader completely in some cases (e.g. due to poor image quality, etc.) [15], however, only in 4 out of the 120 cases in this study the reader decided to redefine the basal hinge points.

A limitation of this study was that only two readers were able to perform semi-automatic measurements on the prototype version of software due to limited availability of workstations with the prototype software, and only one of these readers performed the manual measurements in all 120 cases. This study aimed to evaluate inter-software agreement and reproducibility rather than accuracy, because of the absence of true reference standard, such as direct anatomic measurement. Correlation of pre-TAVI measurements to post-interventional outcome was not possible in most cases, as our institution serves as a TAVI referral center and many patients undergo follow up in an external facilities.

Conclusion

The use of semi-automatic software in pre-TAVI evaluation results in comparable outcome in respect of measurements and selected valve prosthesis size in comparison to a manual approach, while the necessary reading time is significantly lower.

Inter-observer agreement of semi-automatic measurements is excellent, proposing a possibility to standardize aortic annulus measurements, with a high confidence level regardless of reader experience.

Supporting information

S1 Table. Pre-TAVI evaluation assessment with manual and semi-automatic approach expressed as mean values ± SD and mean difference with 95% confidence interval from Bland–Altman analysis. CI = confidence interval; man = manual; mm = millimeter; SA = semi-automatic method; SA1 = semi-automatic method performed by readered 1; SA2 = semi-automatic method performed by readered 2; sign. = significance. (DOCX)
Author Contributions

Conceptualization: Barbora Horehledova, Babs M. F. Hendriks, Nienke G. Eijsvoogel, Bastiaan L. J. H. Kietselaer, Joachim E. Wildberger, Marco Das.

Data curation: Barbora Horehledova, Casper Mihl.

Formal analysis: Barbora Horehledova.

Investigation: Barbora Horehledova, Casper Mihl.

Methodology: Barbora Horehledova, Casper Mihl, Babs M. F. Hendriks, Nienke G. Eijsvoogel, Bastiaan L. J. H. Kietselaer, Joachim E. Wildberger, Marco Das.

Project administration: Marco Das.

Software: Chris Schwemmer.

Supervision: Casper Mihl, Bastiaan L. J. H. Kietselaer, Joachim E. Wildberger, Marco Das.

Validation: Barbora Horehledova, Casper Mihl, Babs M. F. Hendriks, Nienke G. Eijsvoogel, Bastiaan L. J. H. Kietselaer, Joachim E. Wildberger, Marco Das.

Visualization: Barbora Horehledova.

Writing – original draft: Barbora Horehledova, Joachim E. Wildberger, Marco Das.

Writing – review & editing: Barbora Horehledova, Casper Mihl, Chris Schwemmer, Babs M. F. Hendriks, Nienke G. Eijsvoogel, Bastiaan L. J. H. Kietselaer, Joachim E. Wildberger, Marco Das.

References

1. Iung B, Baron G, Butchart EG, Delahaye F, Gohike-Barwolf C, Levang OW, et al. A prospective survey of patients with valvular heart disease in Europe: The Euro Heart Survey on Valvular Heart Disease. Eur Heart J. 2003; 24(13):1231–43. PMID: 12831818.

2. Grube E, Laborde JC, Gerckens U, Felderhoff T, Sauren B, Buellesfeld L, et al. Percutaneous implantation of the CoreValve self-expanding valve prosthesis in high-risk patients with aortic valve disease: the Siegburg first-in-man study. Circulation. 2006; 114(15):1616–24. https://doi.org/10.1161/CIRCULATIONAHA.106.639450 PMID: 17015786.

3. Cribier A, Eltchaninoff H, Tron C, Bauer F, Agatiello C, Sebagh L, et al. Early experience with percutaneous transcatheter implantation of heart valve prosthesis for the treatment of end-stage inoperable patients with calcific aortic stenosis. J Am Coll Cardiol. 2004; 43(4):698–703. https://doi.org/10.1016/j.jacc.2003.11.026 PMID: 14975485.

4. Grube E, Schuler G, Buellesfeld L, Gerckens U, Linke A, Wenaweser P, et al. Percutaneous aortic valve replacement for severe aortic stenosis in high-risk patients using the second- and current third-generation self-expanding CoreValve prosthesis: device success and 30-day clinical outcome. J Am Coll Cardiol. 2007; 50(1):69–76. https://doi.org/10.1016/j.jacc.2007.04.047 PMID: 17601548.

5. Webb JG, Chandavimol M, Thompson CR, Ricci DR, Carere RG, Munt BI, et al. Percutaneous aortic valve implantation retrograde from the femoral artery. Circulation. 2006; 113(8):842–50. https://doi.org/10.1161/CIRCULATIONAHA.105.582882 PMID: 16461813.

6. Webb JG, Pasupati S, Humphries K, Thompson C, Altweig L, Moss R, et al. Percutaneous transarterial aortic valve replacement in selected high-risk patients with aortic stenosis. Circulation. 2007; 116(7):755–63. https://doi.org/10.1161/CIRCULATIONAHA.107.698258 PMID: 17646579.

7. Svensson LG. Aortic valve stenosis and regurgitation: an overview of management. J Cardiovasc Surg (Torino). 2008; 49(2):297–303. PMID: 18431353.

8. Cribier A, Eltchaninoff H, Bash A, Borenstein N, Tron C, Bauer F, et al. Percutaneous transcatheter implantation of an aortic valve prosthesis for calcific aortic stenosis: first human case description. Circulation. 2002; 106(24):3006–8. PMID: 12473543.

9. Buzzatti N, Maisano F, Latib A, Cioni M, Taramasso M, Mussardo M, et al. Computed tomography-based evaluation of aortic annulus, prosthesis size and impact on early residual aortic regurgitation
after transcatheter aortic valve implantation. Eur J Cardiothorac Surg. 2013; 43(1):43–50; discussion 1. https://doi.org/10.1093/ejcts/ezs155 PMID: 22551969.

10. Kempfert J, Van Linden A, Lehmkuhl L, Rastan AJ, Holzhey D, Blumenstein J, et al. Aortic annulus sizing: echocardiographic versus computed tomography derived measurements in comparison with direct surgical sizing. Eur J Cardiothorac Surg. 2012; 42(4):627–33. https://doi.org/10.1093/ejcts/ezs064 PMID: 22402450.

11. Jilaihawi H, Kashif M, Fontana G, Furugen A, Shiota T, Friede G, et al. 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. 2012; 59(14):1275–86. https://doi.org/10.1016/j.jacc.2011.11.045 PMID: 22365424.

12. Smid M, Ferda J, Baxa J, Cech J, Hajek T, Kreuzberg B, et al. Aortic annulus and ascending aorta: comparison of preoperative and perioperative measurement in patients with aortic stenosis. Eur J Radiol. 2010; 74(1):152–5. https://doi.org/10.1016/j.jrad.2009.01.028 PMID: 19233583.

13. de Heer LM, Budde RP, Mali WP, de Vos AM, van Herwerden LA, Kluin J. Aortic root dimension changes during systole and diastole: evaluation with ECG-gated multidetector row computed tomography. Int J Cardiovasc Imaging. 2011; 27(8):1195–204. https://doi.org/10.1007/s10554-011-9838-x PMID: 21359833.

14. Willson AB, Webb JG, Labounty TM, Achenbach S, Moss R, Wheeler M, et al. 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. 2012; 59(14):1287–94. https://doi.org/10.1016/j.jacc.2011.12.015 PMID: 22365425.

15. Lou J, Obuchowski NA, Krishnaswamy A, Popovic Z, Flamm SD, Kapadia SR, et al. Manual, semiautomated, and fully automated measurement of the aortic annulus for planning of transcatheter aortic valve replacement (TAVR/TAVI): analysis of interchangeability. Journal of cardiovascular computed tomography. 2015; 9(1):42–9. https://doi.org/10.1016/j.jcct.2014.11.003 PMID: 25533222.

16. Watanebe Y, Morice MC, Bouvier E, Leong T, Hayashida K, Lefevre T, et al. Automated 3-dimensional aortic annular assessment by multidetector computed tomography in transcatheter aortic valve implantation. JACC Cardiovasc Interv. 2013; 6(9):955–64. https://doi.org/10.1017/jnci.2013.005 PMID: 23954060.

17. Achenbach S, Delgado V, Hausleiter J, Schoenhagen P, Min JK, Leipsic JA. SCCT expert consensus document on computed tomography imaging before transcatheter aortic valve implantation (TAVI)/transcatheter aortic valve replacement (TAVR). Journal of cardiovascular computed tomography. 2012; 6(6):366–80. https://doi.org/10.1016/j.jcct.2012.11.002 PMID: 23217460.

18. Lehmkuhl L, Foldyna B, Von Aspern K, Lucke C, Grothoff M, Nitzsche S, et al. Inter-individual variance and cardiac cycle dependency of aortic root dimensions and shape as assessed by ECG-gated multislice computed tomography in patients with severe aortic stenosis prior to transcatheter aortic valve implantation: is it crucial for correct sizing? The international journal of cardiovascular imaging. 2013; 29(3):693–703. https://doi.org/10.1007/s10554-012-0123-4 PMID: 22986896.

19. Kok M, Turek J, Mihl C, Reimartz SD, Gohmann RF, Nijssen EC, et al. Low contrast media volume in pre-TAVI CT examinations. Eur Radiol. 2015. https://doi.org/10.1007/s00330-015-4080-x PMID: 25952628.

20. Bae KT. Optimization of contrast enhancement in thoracic MDCT. Radiol Clin North Am. 2010; 48(1):9–29. PMID: 19995627.

21. Weininger M, Barraza JM, Kemper CA, Kalafut JF, Costello P, Schoepf UJ. Cardiothoracic CT angiography: current contrast medium delivery strategies. AJR Am J Roentgenol. 2011; 196(3):W260–72. https://doi.org/10.2214/AJR.10.5814 PMID: 21343473.

22. Leber AW, Knez A, Becker C, Becker A, White C, Thilo C, et al. Non-invasive intravascular coronary angiography using electron beam tomography and multislice computed tomography. Heart. 2003; 89(6):633–9. PMID: 12748218.

23. Hausleiter J, Martinoff S, Hadamitzky M, Martuscelli E, Pschierer I, Feuchtnier GM, et al. Image quality and radiation exposure with a low tube voltage protocol for coronary CT angiography results of the PROTECTION II Trial. JACC Cardiovasc Imaging. 2010; 3(11):1113–23. https://doi.org/10.1016/j.jcmg.2010.08.016 PMID: 21070998.

24. Kalisz K, Bueth J, Saboo SS, Abbara S, Halliburton S, Rajiah P. Artifacts at Cardiac CT: Physics and Solutions. Radiographics. 2016; 36(7):2064–83. https://doi.org/10.1148/rg.2016160079 PMID: 27768543.

25. Rivard AL, Bartel T, Bianco RW, O'Donnell KS, Bonatti J, Dichtl W, et al. Evaluation of aortic root and valve calcifications by multi-detector computed tomography. J Heart Valve Dis. 2009; 18(6):662–70. PMID: 20099715.
26. Jurencak T, Turek J, Kietseelaer BL, Mihl C, Kok M, van Ommen VG, et al. MDCT evaluation of aortic root and aortic valve prior to TAVI. What is the optimal imaging time point in the cardiac cycle? Eur Radiol. 2015; 25(7):1975–83. https://doi.org/10.1007/s00330-015-3607-5 PMID: 25708961.

27. Murphy DT, Blanke P, Alaamri S, Naoum C, Rubinshtein R, Pache G, et al. Dynamism of the aortic annulus: Effect of diastolic versus systolic CT annular measurements on device selection in transcatheter aortic valve replacement (TAVR). J Cardiovasc Comput Tomogr. 2016; 10(1):37–43. https://doi.org/10.1016/j.jcct.2015.07.008 PMID: 26239964.

28. Cicchetti DV. Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology. Psychological assessment. 1994; 6(4):284.

29. Van Linden A, Kempfert J, Blumenstein J, Mollmann H, Kim WK, Alkaya S, et al. Manual versus automatic detection of aortic annulus plane in a computed tomography scan for transcatheter aortic valve implantation screening. Eur J Cardiothorac Surg. 2014; 46(2):207–12; discussion 12. https://doi.org/10.1093/ejcts/etz600 PMID: 24431165.

30. Imai K, Ikeda M, Enchi Y, Niimi T. A detection method for streak artifacts and radiological noise in a non-uniform region in a CT image. Phys Med. 2010; 26(3):157–65. https://doi.org/10.1016/j.ejmp.2009.11.003 PMID: 20036595.