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# Prospective ECG-gated High-Pitch Photon-Counting CT Angiography: Evaluation of measurement accuracy for aortic annulus sizing in TAVR planning

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ABSTRACT

*Purpose:* In planning transcatheter aortic valve replacement (TAVR), retrospective cardiac spiral-CT is recommended to measure aortic annulus with subsequent CT-angiography (CTA) to evaluate access routes. Photon-counting detector (PCD)-CT enables to assess the aortic annulus in desired cardiac phases, using prospective ECG-gated high-pitch CTA. The aim of this study was to evaluate the measurement accuracy of aortic annulus using prospective ECG-gated high-pitch CTA against retrospective spiral-CT reference.

*Method:* Thirty patients underwent cardiac spiral-CT and prospective ECG-gated (30% R-R on aortic valve level) high-pitch CTA. Using propensity score matching, another 30 patients were identified whose CTA was performed using high-pitch mode without ECG-synchronization. Two investigators measured annular diameter, perimeter, and area on cardiac spiral-CT and high-pitch CTA.

*Results:* The aortic valve was imaged in systole in 90 % of prospective ECG-gated CTA cases but only 50 % of non-ECG-gated CTA cases ($p = 0.002$). There was a strong correlation ($r \geq 0.94$) without significant differences ($p \geq 0.09$) between cardiac spiral-CT and prospective ECG-gated high-pitch CTA for all annulus measurements. In contrast, significant differences were found in annular short-axis diameter and area between cardiac spiral-CT and non-ECG-gated high-pitch CTA ($p \leq 0.03$). Furthermore, prospective ECG-gated high-pitch CTA showed significantly reduced radiation exposure compared with cardiac spiral-CT (CTDI 4.52 vs. 24.10 mGy; $p < 0.001$).

*Conclusion:* PCD-CT-based prospective ECG-gated high-pitch scans with targeted systolic acquisition at the level of the aortic valve can simultaneously visualize TAVR access routes and accurately measure systolic annulus size. This approach could aid in optimizing protocols to achieve lower radiation doses in the growing population of younger, low-risk TAVR patients.

## 1. Introduction

Since its first human application in 2002 [1], transcatheter aortic valve replacement (TAVR) has revolutionized the management of severe symptomatic aortic stenosis (AS) [2,3]. In the last decade, the development of valve prostheses, advances in non-invasive imaging, growing interventional experience, and technical refinements have led to routine integration of TAVR into clinical practice [4]. The indications for TAVR have also expanded from high-risk to intermediate- and low-risk patients [5–7].

Computed tomography (CT) plays an essential role in patient evaluation prior to TAVR [8–10]. CT is considered the gold standard for the assessment of aortic root dimensions to determine the optimal prosthesis type and size, for evaluation of the peripheral access route, and estimating the risk of *peri*-interventional complications, such as annular injury and coronary occlusion [10,11]. Therefore, accurate measurements are important to avoid post-procedural complications, such as paravalvular leakage, device migration and embolization, conduction disorders, or even annular rupture [10,12–14].

According to the latest recommendations, image acquisition for

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TAVR planning should consist of an electrocardiogram (ECG)-synchronized CT-angiography (CTA) with coverage of at least the aortic root, followed by a general CTA of the thorax, abdomen, and pelvis for the assessment of the vascular access route [15,16]. In general, retrospective ECG-gated spiral-CT is used for aortic root and cardiac image acquisition [15]. However, despite the retrospective multiphase reconstruction, the image quality of the cardiac acquisition may be affected by blurring due to respiratory motion or the variability of R-R intervals [17]. Furthermore, retrospective spiral-CT is typically associated with a high radiation dose. In contrast, several previous studies using non-ECG-gated high-pitch CT have shown comparable diagnostic yields with reduced artifacts and radiation exposure [18–20].

A recently introduced photon-counting detector (PCD)-CT system provides a prospective ECG-gated high-pitch scan mode that has the potential to simultaneously assess the aortic root at a desired cardiac phase and the vascular access route. However, the feasibility and measurement accuracy of this scan mode for annular sizing is not well-investigated. Thus, the aim of this study was to evaluate the measurement accuracy of aortic annulus sizing using prospective ECG-gated high-pitch CTA against the reference, conventional retrospective ECG-gated spiral-CT on a PCD-CT.

## 2. Material and methods

This retrospective study was approved by the ethics committee of the state chamber of physicians in Rheinland-Palatinate, Germany (Registration No. 2022-16359), which waived the requirement for written informed consent.

### 2.1. Study population

A total of 60 patients were included in this study. Thirty patients underwent pre-TAVR PCD-CT including retrospective ECG-gated cardiac spiral-CT and prospective ECG-gated high-pitch CTA in October 2022. Another 30 patients from our institutional database who underwent pre-TAVR PCD-CT prior to the availability of ECG-gated high-pitch CTA were propensity score-matched based on age, sex, and heart rate (HR) during the scan.

### 2.2. PCD-CT

CT acquisition was performed on a first-generation, dual-source PCD-CT system (NAEOTOM Alpha, Siemens Healthineers, Forchheim, Germany). All scans were acquired at 120 kVp with automated tube current modulation (CARE Dose4D, Siemens; IQ-Level 40 for cardiac spiral-CT and 70 for high-pitch CTA). Collimation was set at 144 $\times$ 0.4 mm. The pitch factor was 0.3 in retrospective cardiac spiral-CT and 3.2 in high-pitch CTA. Gantry rotation time was 0.25 s.

The scan protocol consisted of three consecutive acquisitions. No nitrates or beta-blockers were administered. First, a prospective ECG-triggered non-enhanced scan of the heart was acquired for calcium scoring and visualization of the calcified aortic valve. Subsequently, 75 ml of iodinated contrast agent (Ultravist 370 mgI/ml, Bayer Healthcare, Berlin, Germany) was intravenously administered at a flow rate of 3 ml/s and bolus tracking performed in the ascending aorta. After reaching the threshold of 100 HU at 90 kV, the contrast-enhanced retrospective ECG-gated cardiac spiral-CT was initiated automatically. This was immediately followed by either prospective ECG-gated (study cohort) or non-ECG gated (control cohort) high-pitch CTA of the thorax, abdomen, and pelvis to evaluate the vascular access routes.

For prospective ECG-gated high-pitch CTA, the non-enhanced calcium score scan was used to determine the location of the aortic valve to set the ECG-pulsing window at this image level at 30 % of the R-R interval (Fig. 1).

Patients' mean HR and the presence of arrhythmia, such as tachycardia, atrial fibrillation, or premature ventricular complex, during the examination was assessed and documented from Digital Imaging and Communications in Medicine (DICOM) data.

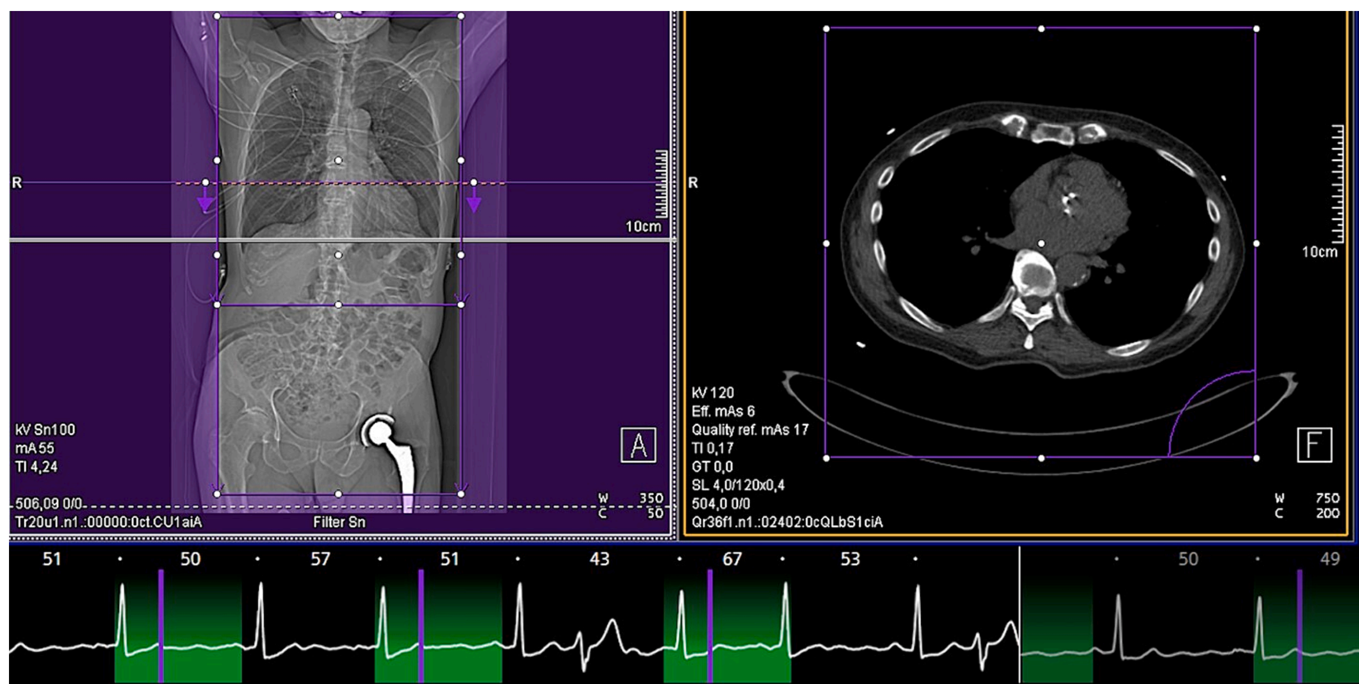


**Fig. 1.** Planning of prospective ECG-gated high-pitch CTA The planning of prospective ECG-gated high-pitch CTA was based on the non-enhanced scan (axial CT image). The aortic valve was located in the non-enhanced scan in order to set the ECG-pulsing window at the optimal level (purple dotted line on the left CT-scout). Image acquisition was set at 30% of the R-R interval (purple line on the ECG curve). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 2.3. Image reconstruction

All contrast-enhanced images were reconstructed using a vascular kernel (Bv) with a sharpness level of 36 and quantum iterative reconstruction (QIR) at a strength level of 3. Images were reconstructed with a slice thickness of 0.8 mm and increment of 0.4 mm. Images from the ECG-gated cardiac spiral-CT were reconstructed in systole at a 30 % R-R interval, as well as a multiphase series in steps of 10 % of the R-R interval. Additional cardiac reconstruction was performed from the high-pitch CTA using an identical field of view (FOV) as the cardiac spiral-CT.

The non-enhanced images were reconstructed according to the manufacturer's guidelines for calcium scoring with 3-mm slice thickness and 1.5-mm increment using the default kernel Qr36.

### 2.4. Assessment of the aortic root

The aortic root was evaluated on the retrospective ECG-gated spiral-CT scans at a 30 % R-R interval and on the high-pitch CTA in both study cohorts. The anatomical structures of the aortic root were assessed according to the expert consensus guidelines from the Society of Cardiovascular Computed Tomography (SCCT) [15]. After identifying the aortic annular plane in multiplanar reformations using a commercial picture archiving and communication system (Sectra, Linköping, Sweden), the aortic annulus dimensions were measured to assess the diameter (mean diameter, short- and long-axis diameter, [$meandiameter = \frac{short-axisdiameter+long-axisdiameter}{2}$]), perimeter, and area (Fig. 2). The success or failure of systolic triggering was evaluated based on whether the maximum opening area of the aortic valve was met. All measurements were performed independently by two readers: one trained reader (R.R.) with 1 year of experience under the close supervision of a radiologist (M.H.) with more than 5 years of experience in cardiovascular imaging, and one board-certified radiologist (Y.Y.) with more than 12 years of experience in the field. To minimize recall bias, the anonymized CT images were presented in random order with no scan information and readers were blinded to the scan information and each other's determination.

### 2.5. Radiation dose

Radiation exposure was compared using the CT dose index (CTDI) in mGy and dose-length product (DLP) in mGy*cm. The DLP was determined using an automatically generated protocol based on the CTDI. Both measures were acquired using the dose report from DICOM documents. Effective dose was calculated according to the latest publication from International Commission on Radiological Protection (ICRP) [21].

### 2.6. Statistical analysis

Dedicated statistical software (SPSS Version 23; IBM Corporation, Armonk, NY, USA) was used for all statistical analyses. The Shapiro-Wilk test was used to test all data for normal distribution. Data are reported as the mean ± standard deviation or median with quartiles (Q1, Q3). Categorical data are reported as absolute frequencies with respective proportions. A p-value $< 0.05$ was considered significant.

The study cohorts were compared using Chi-Quadrat, independent *t*-test, or Mann-Whitney-U tests, as appropriate. Agreement between different methods was assessed by Pearson's correlation coefficients and Bland-Altman analyses. The strength of the linear relationship corresponding to the correlation coefficient value was interpreted as follows: $r > 0.8$, very strong; $r = 0.6–0.8$, moderately strong; $r = 0.3–0.6$, fair; $r < 0.3$, poor [22]. Interobserver agreement was evaluated by intraclass correlation coefficients (ICCs) in a two-way random-effects model. Levels of agreement were defined as follows: poor, <0.5; moderate, 0.5–0.75; strong, 0.76–0.9; excellent, >0.9 [23].

## 3. Results

### 3.1. Patient characteristics

In the overall study population of 60 patients, the mean age was 79.0 ± 8.6 years and 44 (73 %) patients were male. Due to the propensity score matching, baseline patient characteristics were similar in the two cohorts (age: p = 0.93; sex: p = 0.77; HR: p = 0.65). Among all of the patients, arrhythmia during image acquisition occurred in 15 patients

**Table 1**
Patient characteristics.

| Characteristic | Study cohort ECG-gated high-pitch CTA | Control cohort Non-ECG-gated high-pitch CTA | Total |
|---|---|---|---|
| No. of patients | 30 | 30 | 60 |
| Age, years | 79 ± 7 | 79 ± 10 | 79 ± 9 |
| Sex, male/ female | 22 (73 %) / 8 (27 % ) | 22 (73 %) / 8 (27 %) | 44 (73 %) / 16 (27 %) |
| BMI, kg/m$^2$ | 26.8 ± 4.6 | 26.0 ± 4.6 | 26.4 ± 4.6 |
| HR, bpm | 67 ± 13 | 68 ± 16 | 67 ± 15 |
| Arrhythmia | 8 (26.7 %) | 7 (23.3 %) | 15 (25 %) |
| Tachycardia | 1 (3.3 %) | 1 (3.3 %) | 2 (3.3 %) |
| Atrial fibrillation | 5 (16.7 %) | 2 (6.7 %) | 7 (11.7) |
| Premature ventricular complex | 2 (6.7 %) | 4 (13.3 %) | 6 (10.0 %) |

Data are presented as mean ± SD or n (%), unless otherwise specified.
N, number of patients; BMI, body mass index; HR, heart rate; bpm, beats per minute.

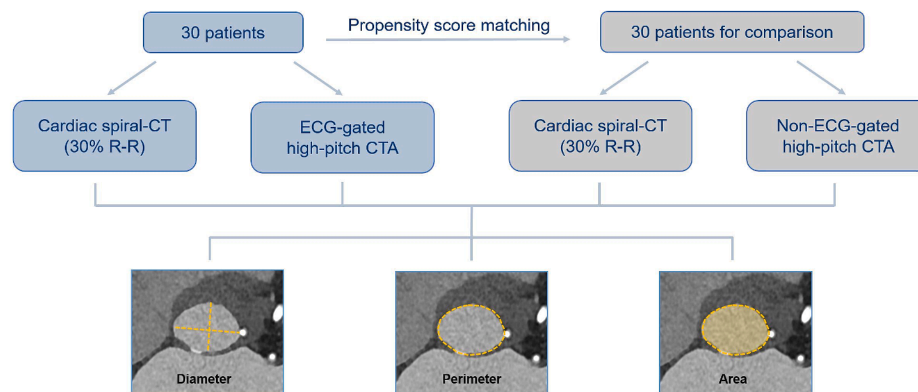


**Fig. 2.** Measurements in study cohorts Measurements of the aortic annulus were performed in both cohorts in cardiac spiral-CT at cardiac phase 30% R-R interval and in high-pitch CTA. Annular mean diameter, perimeter, and area were assessed.

(25 %) and was not significantly different between the cohorts (p = 0.75). Detailed patient characteristics are summarized in Table 1.

### 3.2. Aortic annulus measurements

There was an excellent correlation and no significant difference (p ≥ 0.09) between retrospective cardiac spiral-CT and prospective ECG-gated high-pitch CTA in regard to mean diameter (r = 0.94), perimeter (r = 0.99), and area (r = 0.99; Table 2 and Fig. 3). However, the comparison between cardiac spiral-CT and non-ECG-gated high-pitch CTA showed a significant difference in the short-axis diameter (17.2 mm vs 18.9 mm, p = 0.03) and area (525.6 $mm^2$ vs. 515.8 $mm^2$, p = 0.02) of the aortic annulus. Furthermore, Bland-Altman plots demonstrated homogenous scatter and smaller bias around the mean difference line of the aortic annular perimeter and area obtained by retrospective spiral-CT and prospective ECG-gated high-pitch CTA compared to retrospective spiral-CT and non-ECG-synchronized high-pitch CTA, respectively (Fig. 4).

### 3.3. Evaluation of the aortic valve

In the study cohort with prospective ECG-gated high-pitch CTA, the aortic valve was correctly captured in systole in 27 patients (90 %). All 3 patients (10 %) with unsuccessful systolic triggering had arrhythmias: 2 patients had atrial fibrillation and 1 patient had premature ventricular complex. In the comparison cohort, the aortic valve was significantly less frequently acquired in systole (15 patients, 50 %, p = 0.002). Examples are shown in Fig. 5.

### 3.4. Radiation dose

Compared with retrospective ECG-gated cardiac spiral-CT, the CTDI was significantly lower in the prospective ECG-gated high-pitch CTA (4.5 ± 1.13 mGy vs. 24.1 ± 7.60 mGy; p < 0.001). Despite a much longer scan length, the high-pitch CTA also resulted in significantly less radiation exposure (DLP: 317.0 ± 92.26 mGy*cm vs. 424.2 ± 136.99 mGy*cm; Effective dose: 4.7 mSv vs. 5.9 mSv; all p < 0.001).

## 4. Discussion

This retrospective study compared pre-intervention aortic annular measurements from three different PCD-CT acquisition techniques in patients undergoing TAVR. All patients underwent retrospective ECG-gated cardiac spiral-CT as the clinical reference and high-pitch CTA with or without prospective ECG gating.

We observed that prospective ECG-gated high-pitch CTA correlated well with retrospective spiral-CT, as no significant differences were found in the aortic annular measurements. In addition, the approach resulted in successful systolic acquisition of the aortic valve in almost all patients and a significantly lower radiation dose. In contrast, a significant difference was found in the annulus area with non-ECG-gated high-pitch CTA, and systolic acquisition of the aortic valve was missed in half of the patients.

CT is currently accepted as the gold standard for precise assessment of the aortic root and vascular access routes for TAVR planning. In accordance with current guidelines, retrospective ECG-gated cardiac spiral-CT with coverage of the entire cardiac cycle is most often used for aortic root acquisition in pre-TAVR CT [10,15]. However, this method inherently leads to a high radiation dose. As TAVR is generally performed in elderly patients with high surgical risk, the dose reduction may appear secondary. However, due to its rapid development, the indications for TAVR have expanded from high-risk patients to patients with intermediate risk, and now even patients at low risk for surgical valve replacement [2,3,5–7,24–28]. This expansion led to rejuvenation of the TAVR patient population with an average patient age in the early 70 s [6,7,28]. Thus, radiation exposure to evaluate this relatively younger patient population is becoming a concern. Furthermore, many TAVR patients suffer from atrial arrhythmias with HR variability [29,30] and multimorbidity with labored breathing, which may result in blurred CT images in retrospective gating due to respiratory motion or changing R-R intervals [17]. In contrast, high-pitch scan mode with a significantly shorter acquisition time reduces motion artifacts [31,32]. Therefore, prospective ECG-gated high-pitch CTA with a lower radiation dose, robust safety, and comparable diagnostic accuracy has potential to become a part of standard CT protocols for pre-TAVR assessment.

Qureshi et al. compared retrospective ECG-gated spiral-CT with non-ECG-gated high-pitch CTA and demonstrated strong correlations in the aortic annular perimeter and area measured between the two different scanning protocols [19]. This result is similar to our findings in the control cohort using high-pitch CTA without ECG-synchronization. However, due to dynamic changes in the aortic annulus dimension during the cardiac cycle [33], manufacturers base their valve sizing recommendations on systolic measurements. Therefore, the non-ECG-synchronized approach, with possible acquisition of the aortic root in diastole and subsequent risk of under-sizing the prosthesis, is not satisfactory. In this context, our study demonstrated the advantages of adequate ECG-synchronization. Compared to the scanning protocol without ECG-synchronization, prospective ECG-gated high-pitch CTA has superior correlation with, as well as less bias than, the reference standard. Furthermore, the aortic valve was successfully acquired in systole in almost all of the patients, whereas half were missed by non-ECG-gated CTA, which makes ECG-gated high-pitch CTA much more reliable for aortic annular measurement.

Capilli et al. also investigated the performance of high-pitch CTA in annulus measurements compared with retrospective ECG-gated spiral-CT [34]. Due to the use of ECG-synchronization in high-pitch CTA, they achieved comparable improved results as Qureshi et al., with stronger correlation and less bias between the annular area measured by high-pitch CTA and cardiac spiral-CT. In this study, the high-pitch CTA scan started at 10 % of the R-R-interval at the upper border of the cardiac level (region of the carina), assuming to reach the region of the aortic root between 15 % and 25 % of the R-R interval. Compared to their estimated systolic high-pitch CTA, in our study, with the help of new developments in PCD-CT, the aortic valve was visualized in the desired systolic phase. Therefore, our study showed even superior results in assessing the aortic annulus by prospective ECG-gated high-pitch CTA.

**Table 2**
Summary of aortic annular measurements.

| Annulus measurement | Comparison cardiac spiral-CT vs. high-pitch CTA | Spiral-CT | CTA | Mean difference (95 % CI) | P value | R correlation |
|---|---|---|---|---|---|---|
| | ECG-gated | 28.4 ± 2.6 | 28.3 ± 2,7 | 0.1 (−0.2—0.5) | 0.49 | 0.94 |
| **Diameter** | non-ECG-gated | 28.8 ± 3.5 | 28.8 ± 3.4 | −0.3 (−0.3—0.3) | 0.84 | 0.97 |
| | ECG-gated | 81.3 ± 8.2 | 80.9 ± 8.7 | 0.4 (−0.1—0.9) | 0.09 | 0.99 |
| **Perimeter** | non-ECG-gated | 82.5 ± 10.0 | 82.0 ± 9.8 | 0.5 (−1.4—1,1) | 0.12 | 0.98 |
| | ECG-gated | 505.7 ± 106.4 | 501.0 ± 112.1 | 4.7 (−1.9—11.4) | 0.16 | 0.99 |
| **Area** | non-ECG-gated | 525.6 ± 129.9 | 515.8 ± 128.5 | 9.8 (1.4—18.2) | 0.02 | 0.98 |

Data are presented as mean ± SD. Unit used in measurement diameter and perimeter is mm, area is $mm^2$.

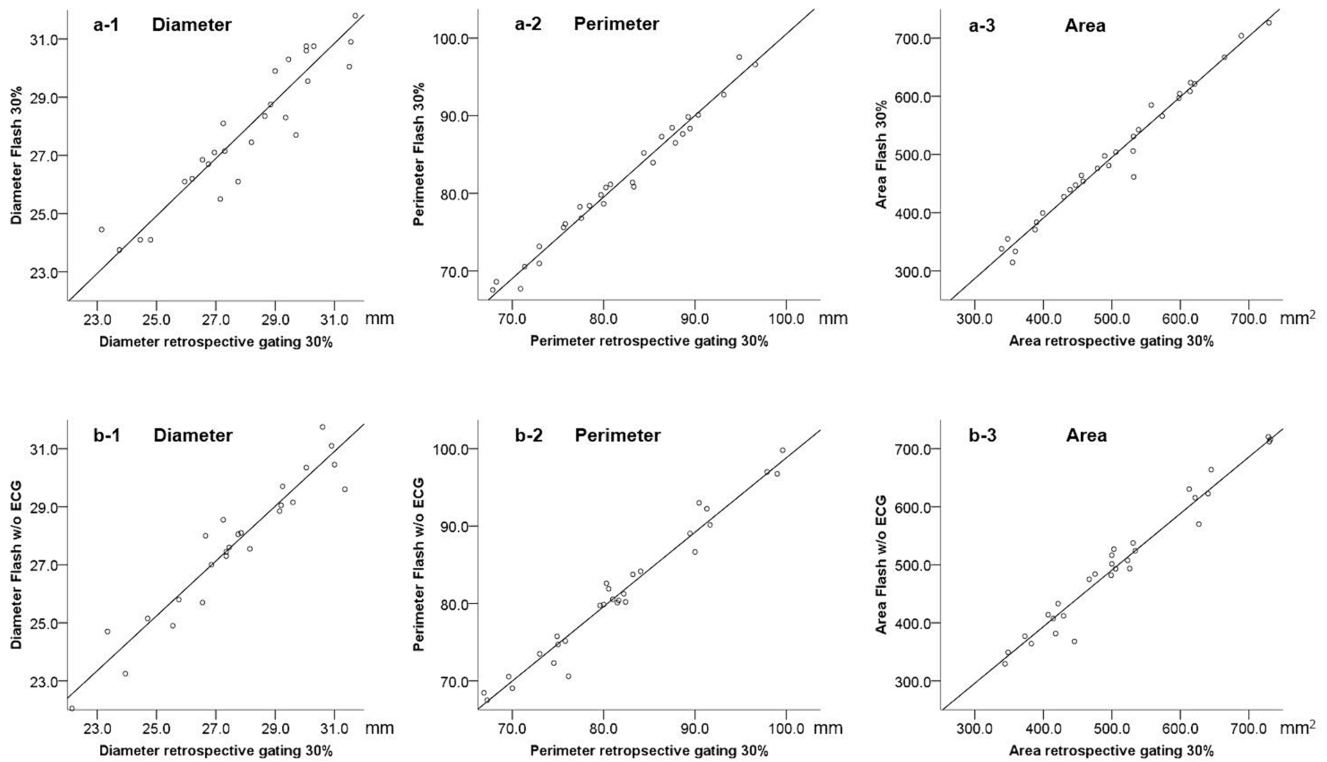


**Fig. 3.** Correlation scatterplots Top row: Retrospective ECG-gated cardiac spiral-CT compared to prospective ECG-gated high-pitch CTA. Bottom row: Retrospective ECG-gated cardiac spiral-CT compared to non-ECG-gated high-pitch CTA.

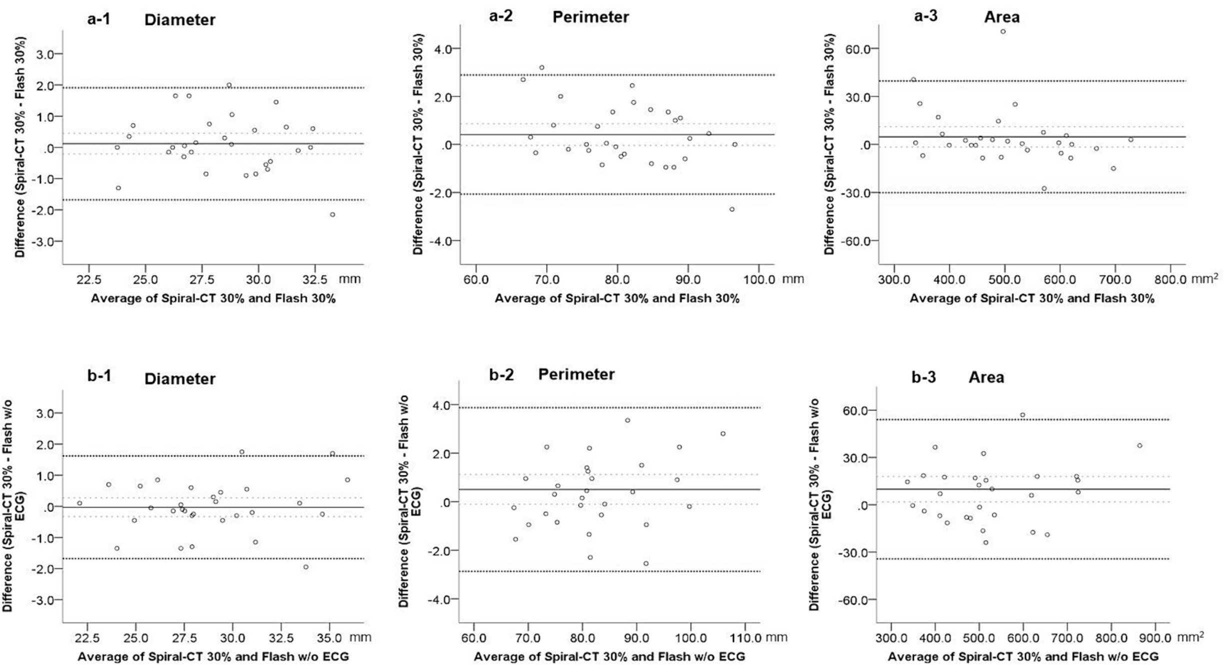


**Fig. 4.** Bland-Altman plots Top row: Retrospective ECG-gated cardiac spiral-CT compared to prospective ECG-gated high-pitch CTA. Bottom row: Retrospective ECG-gated cardiac spiral-CT compared to non-ECG-gated high-pitch CTA.

Recently, Hagar et al. compared the diagnostic value of ultra-high-resolution CTA (UHR-CTA) to that of high-pitch CTA in TAVR planning on PCD-CT [35]. In their study, high-pitch CTA was performed at 25 % of the R-R interval to depict the aortic annulus in the systolic phase. Compared to retrospective ECG-gated UHR-CTA, high-pitch CTA also achieved satisfying results with a strong positive correlation in the annular area-derived diameter. Probably due to the minimal difference in the capture time point in the R-R interval, the correlation and bias in annular measurements between the different scan methods were slightly inferior to our results.

In our study, due to arrhythmia, the aortic valve was not met in systole in 10 % of patients during the prospective ECG-gated high-pitch

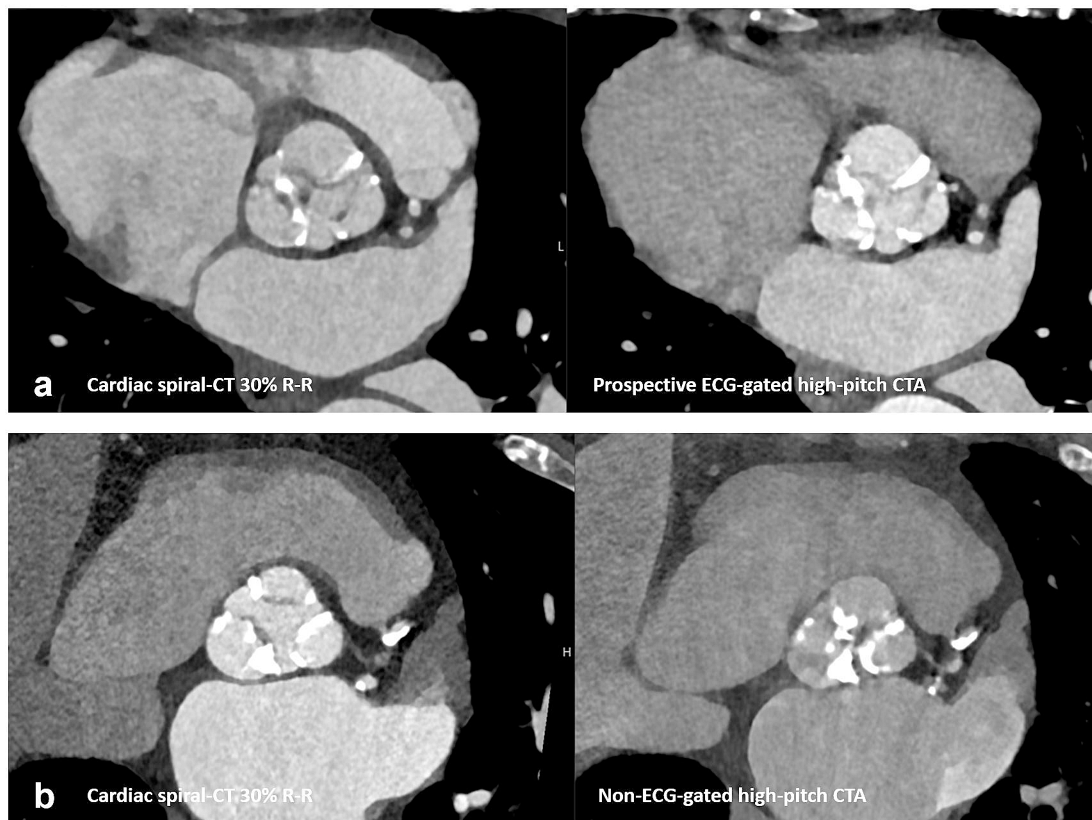


**Fig. 5.** Example of the impact of ECG-synchronization in high-pitch CTA on assessment of the aortic valve (a) In the prospective ECG-gated high-pitch CTA with ECG-gating at the 30% R-R interval, the aortic valve was hit exactly in systole. **(b)** In contrast, in high-pitch CTA without ECG-synchronization, the aortic valve was met in diastole.

scan. Capilli et al. showed that the high-pitch protocol was associated with significant prosthesis under-sizing based on the annulus diameter in patients with atrial fibrillation [34]. Hagar et al. also demonstrated that high-pitch CTA with lower image quality, presumably due to arrhythmia was more likely to lead to different prosthesis sizing [35]. Thus, immediate image evaluation after high-pitch CTA, and possibly supplementary acquisition, such as UHR-CTA, should be considered in cases necessitating enhanced image details.

Furthermore, this study corroborates previous studies reporting significantly lower radiation doses with high-pitch CTA compared to cardiac spiral-CT [18,19,34,35]. In recent trials, TAVR showed a clear early safety benefit over surgical aortic valve replacement in low-risk patient populations. This led to expanding TAVR indications in younger patients [6,7,28,36]. Therefore, the advantage of high-pitch CTA with reduced radiation exposure is growing in interest. Considering that current TAVR-planning CT protocols usually consist of cardiac spiral-CT and an additional CTA, the protocol simplification solely using high-pitch CTA could lead to an approximate 60 % reduction in radiation dose. Acquisition with prospective ECG-gated high-pitch CTA enables both the evaluation of TAVR access routes and sufficient assessment of the aortic root, as well as a comparably accurate measurement of the aortic annulus. In addition, the high-pitch CTA scan protocol has the advantage of decreasing the scan time and contrast medium exposure [37,38].

This study has some limitations. First, patient numbers were limited in this single-center study. Second, the impact on prosthesis sizing based on annular measurements from cardiac spiral-CT and prospective ECG-gated high-pitch CTA was not investigated in this study. Because the choice of prosthesis type and size does not simply depend on the annular dimensions, many other factors, such as calcification of the aortic valve, location of the coronary ostium, and operator experience, influence prosthesis selection, especially in the overlap between two different prosthesis sizes following the manufacturer's recommendation. Therefore, only absolute measurements of the aortic annulus were compared in our study. Previous studies have already shown excellent agreement in hypothetical balloon-expandable prosthesis sizing. Qureshi et al. demonstrated that non-ECG-gated high-pitch CTA and retrospective cardiac spiral-CT lead to the selection of almost the same hypothetical transcatheter valve size [19]. The studies by Hagar et al. and Capilli et al. also showed approximately 90 % agreement in hypothetical prosthesis selection between cardiac spiral-CT and ECG-synchronized high-pitch CTA [34,35]. However, in patients with atrial fibrillation, smaller prostheses were chosen based on results from high-pitch CTA compared with retrospective spiral-CT [34]. Based on these hypothetical results, prospective trials investigating the real-world impact of scan protocols on prosthesis choice should be considered. Finally, our study did not focus on low-risk TAVR candidates and mostly included patients with intermediate to high-risk in whom there was significant annular calcification. Theoretically, low-risk patients may have less calcification in the aortic valve, making it more complicated to locate it on the non-enhanced CT scan. Thus, future studies in low-risk patients with mildly calcified annuli are needed to evaluate the utility of prospective ECG-gated high-pitch CTA.

## 5. Conclusion

Pre-intervention prospective ECG-gated high-pitch scans with targeted systolic acquisition at the level of the aortic valve derived from PCD-CT can simultaneously visualize TAVR access routes and accurately measure the systolic annulus size. This could aid in optimizing pre-intervention scan protocols for lower radiation doses in the growing population of younger, low-risk TAVR patients.

Editor conflict of interest statement

Given their role as Editor, Tilman Emrich (Associate Editor) and Moritz Halfmann (Section Editor) had no involvement in the peer-review of this article and has no access to information regarding its peer-review.

## CRediT authorship contribution statement

**Y. Yang:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft. **R. Richter:** Data curation, Formal analysis, Investigation. **M.C. Halfmann:** Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – review & editing. **D. Graafen:** Data curation, Methodology, Software, Validation, Writing – review & editing. **M. Hell:** Conceptualization, Project administration, Resources. **M. Vecsey-Nagy:** Conceptualization, Writing – review & editing. **G. Laux:** Conceptualization, Resources, Visualization. **L. Kavermann:** Conceptualization, Resources, Visualization. **T. Jorg:** Writing – review & editing. **M. Geyer:** Conceptualization, Resources, Writing – review & editing. **A. Varga-Szemes:** Conceptualization, Writing – review & editing. **T. Emrich:** Conceptualization, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – review & editing.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: T. Emrich receives speaker fee, institutional research-/ travel support from Siemens Healthineers and is advisory board member from Siemens Healthineers and consultant from Circle Cardiovascular Imaging. Y. Yang, M. C. Halfmann, D. Graafen and T. Jorg receive institutional research support from Siemens Healthineers. A. Varga-Szemes receives institutional research support and/or personal fee from Bayer, Elucid and Siemens Healthineers.

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## References

[1] A. Cribier, H. Eltchaninoff, A. Bash, N. Borenstein, C. Tron, F. Bauer, G. Derumeaux, F. Anselme, F. Laborde, M.B. Leon, Percutaneous transcatheter implantation of an aortic valve prosthesis for calcific aortic stenosis: first human case description, Circulation 106 (24) (2002) 3006–3008.

[2] S.R. Kapadia, M.B. Leon, R.R. Makkar, E.M. Tuzcu, L.G. Svensson, S. Kodali, J. G. Webb, M.J. Mack, P.S. Douglas, V.H. Thourani, V.C. Babaliaros, H.C. Herrmann, W.Y. Szeto, A.D. Pichard, M.R. Williams, G.P. Fontana, D.C. Miller, W.N. Anderson, J.J. Akin, M.J. Davidson, C.R. Smith, P.t. investigators, 5-year outcomes of transcatheter aortic valve replacement compared with standard treatment for patients with inoperable aortic stenosis (PARTNER 1): a randomised controlled trial, Lancet 385 (9986) (2015) 2485–2491.

[3] D.H. Adams, J.J. Popma, M.J. Reardon, S.J. Yakubov, J.S. Coselli, G.M. Deeb, T. G. Gleason, M. Buchbinder, J. Hermiller Jr., N.S. Kleiman, S. Chetcuti, J. Heiser, W. Merhi, G. Zorn, P. Tadros, N. Robinson, G. Petrossian, G.C. Hughes, J. K. Harrison, J. Conte, B. Maini, M. Mumtaz, S. Chenoweth, J.K. Oh, U.S.C. C. Investigators, Transcatheter aortic-valve replacement with a self-expanding prosthesis, N Engl J Med 370 (19) (2014) 1790–1798.

[4] G. Lee, J. Chikwe, M. Milojevic, H.C. Wijeysundera, G. Biondi-Zoccai, M. Flather, M.F.L. Gaudino, S.E. Fremes, D.Y. Tam, ESC/EACTS vs ACC/AHA Guidelines for the Management of Severe Aortic Stenosis, Eur Heart J 44 (10) (2023) 796–812.

[5] J. Fu, M.S. Popal, Y. Li, G. Li, Y. Qi, F. Fang, J.S.W. Kwong, B. You, X. Meng, J. Du, Transcatheter versus surgical aortic valve replacement in low and intermediate risk patients with severe aortic stenosis: systematic review and meta-analysis of randomized controlled trials and propensity score matching observational studies, J Thorac Dis 11 (5) (2019) 1945–1962.

[6] M.J. Mack, M.B. Leon, V.H. Thourani, R. Makkar, S.K. Kodali, M. Russo, S. R. Kapadia, S.C. Malaisrie, D.J. Cohen, P. Pibarot, J. Leipsic, R.T. Hahn, P. Blanke, M.R. Williams, J.M. McCabe, D.L. Brown, V. Babaliaros, S. Goldman, W.Y. Szeto, P. Genereux, A. Pershad, S.J. Pocock, M.C. Alu, J.G. Webb, C.R. Smith, P. Investigators, Transcatheter Aortic-Valve Replacement with a Balloon-Expandable Valve in Low-Risk Patients, N Engl J Med 380 (18) (2019) 1695–1705.

[7] J.J. Popma, G.M. Deeb, S.J. Yakubov, M. Mumtaz, H. Gada, D. O'Hair, T. Bajwa, J. C. Heiser, W. Merhi, N.S. Kleiman, J. Askew, P. Sorajja, J. Rovin, S.J. Chetcuti, D.H. Adams, P.S. Teirstein, G.L. Zorn, 3rd, J.K. Forrest, D. Tchetche, J. Resar, A. Walton, N. Piazza, B. Ramlawi, N. Robinson, G. Petrossian, T.G. Gleason, J.K. Oh, M.J. Boulware, H. Qiao, A.S. Mugglin, M.J. Reardon, I. Evolut Low Risk Trial, Transcatheter Aortic-Valve Replacement with a Self-Expanding Valve in Low-Risk Patients, N Engl J Med 380(18) (2019) 1706-1715.

[8] H. Jilaihawi, M. Kashif, G. Fontana, A. Furugen, T. Shiota, G. Friede, R. Makhija, N. Doctor, M.B. Leon, R.R. Makkar, 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) (2012) 1275–1286.

[9] A. Hamdan, V. Guetta, E. Konen, O. Goitein, A. Segev, E. Raanani, D. Spiegelstein, I. Hay, E. Di Segni, M. Eldar, E. Schwammenthal, Deformation dynamics and mechanical properties of the aortic annulus by 4-dimensional computed tomography: insights into the functional anatomy of the aortic valve complex and implications for transcatheter aortic valve therapy, J Am Coll Cardiol 59 (2) (2012) 119–127.

[10] S. Achenbach, V. Delgado, J. Hausleiter, P. Schoenhagen, J.K. Min, J.A. Leipsic, 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) (2012) 366–380.

[11] A.G. Bertaso, D.T. Wong, G.Y. Liew, M.S. Cunnington, J.D. Richardson, V. S. Thomson, B. Lorraine, G. Kourlis, D. Leech, M.I. Worthley, S.G. Worthley, Aortic annulus dimension assessment by computed tomography for transcatheter aortic valve implantation: differences between systole and diastole, Int J Cardiovasc Imaging 28 (8) (2012) 2091–2098.

[12] T. Jurencak, J. Turek, B.L. Kietselaer, C. Mihl, M. Kok, V.G. van Ommen, L.A. van Garsse, E.C. Nijssen, J.E. Wildberger, M. Das, MDCT evaluation of aortic root and aortic valve prior to TAVI. What is the optimal imaging time point in the cardiac cycle? Eur Radiol 25 (7) (2015) 1975–1983.

[13] A.B. Willson, J.G. Webb, M. Freeman, D.A. Wood, R. Gurvitch, C.R. Thompson, R. R. Moss, S. Toggweiler, R.K. Binder, B. Munt, A. Cheung, C. Hague, J. Ye, J. A. Leipsic, Computed tomography-based sizing recommendations for transcatheter aortic valve replacement with balloon-expandable valves: Comparison with transesophageal echocardiography and rationale for implementation in a prospective trial, J Cardiovasc Comput Tomogr 6 (6) (2012) 406–414.

[14] R. Gurvitch, J.G. Webb, R. Yuan, M. Johnson, C. Hague, A.B. Willson, S. Toggweiler, D.A. Wood, J. Ye, R. Moss, C.R. Thompson, S. Achenbach, J.K. Min, T.M. Labounty, R. Cury, J. Leipsic, Aortic annulus diameter determination by multidetector computed tomography: reproducibility, applicability, and implications for transcatheter aortic valve implantation, JACC Cardiovasc Interv 4 (11) (2011) 1235–1245.

[15] P. Blanke, J.R. Weir-McCall, S. Achenbach, V. Delgado, J. Hausleiter, H. Jilaihawi, M. Marwan, B.L. Norgaard, N. Piazza, P. Schoenhagen, J.A. Leipsic, Computed tomography imaging in the context of transcatheter aortic valve implantation (TAVI) / transcatheter aortic valve replacement (TAVR): An expert consensus document of the Society of Cardiovascular Computed Tomography, J Cardiovasc Comput Tomogr 13 (1) (2019) 1–20.

[16] M. Francone, R.P.J. Budde, J. Bremerich, J.N. Dacher, C. Loewe, F. Wolf, L. Natale, G. Pontone, A. Redheuil, R. Vliegenthart, K. Nikolaou, M. Gutberlet, R. Salgado, CT and MR imaging prior to transcatheter aortic valve implantation: standardisation of scanning protocols, measurements and reporting-a consensus document by the European Society of Cardiovascular Radiology (ESCR), Eur Radiol 30 (5) (2020) 2627–2650.

[17] K. Kalisz, J. Buethe, S.S. Saboo, S. Abbara, S. Halliburton, P. Rajiah, Artifacts at Cardiac CT: Physics and Solutions, Radiographics 36 (7) (2016) 2064–2083.

[18] S. Shnayien, N.L. Beetz, K.K. Bressem, B. Hamm, S.M. Niehues, Comparison of a High-Pitch Non-ECG-Gated and a Prospective ECG-Gated Protocol for Preprocedural Computed Tomography Imaging Before TAVI/TAVR, Rofo 195 (2) (2023) 139–147.

[19] W.T. Qureshi, R. Malhotra, E.J. Schmidlin, M. Ahmed, A. Kundu, A.M. Hafiz, J. Walker, N. Kakouros, Evaluation of ECG-gated and Fast Low-Angle Shot (FLASH) Dual Source Computed Tomography Scanning Protocols for Transcatheter Aortic Valve Replacement, Acad Radiol 28 (12) (2021) 1669–1674.

[20] B. Horehledova, C. Mihl, E. Boswijk, G. Crombag, E.C. Nijssen, P.J. Nelemans, L. F. Veenstra, J.E. Wildberger, M. Das, Retrospectively ECG-gated helical vs. non-ECG-synchronized high-pitch CTA of the aortic root for TAVI planning, PLoS One 15 (5) (2020) e0232673.

[21] J. Valentin, P. International Commission on Radiation, Managing patient dose in multi-detector computed tomography(MDCT). ICRP Publication 102, Ann ICRP 37 (1) (2007) 1-79, iii.

[22] H. Akoglu, User's guide to correlation coefficients, Turk J Emerg Med 18 (3) (2018) 91–93.

[23] T.K. Koo, M.Y. Li, A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research, J Chiropr Med 15 (2) (2016) 155–163.

[24] M.B. Leon, C.R. Smith, M. Mack, D.C. Miller, J.W. Moses, L.G. Svensson, E. M. Tuzcu, J.G. Webb, G.P. Fontana, R.R. Makkar, D.L. Brown, P.C. Block, R. A. Guyton, A.D. Pichard, J.E. Bavaria, H.C. Herrmann, P.S. Douglas, J.L. Petersen, J.J. Akin, W.N. Anderson, D. Wang, S. Pocock, P.T. Investigators, Transcatheter aortic-valve implantation for aortic stenosis in patients who cannot undergo surgery, N Engl J Med 363 (17) (2010) 1597–1607.

[25] C.R. Smith, M.B. Leon, M.J. Mack, D.C. Miller, J.W. Moses, L.G. Svensson, E. M. Tuzcu, J.G. Webb, G.P. Fontana, R.R. Makkar, M. Williams, T. Dewey, S. Kapadia, V. Babaliaros, V.H. Thourani, P. Corso, A.D. Pichard, J.E. Bavaria, H. C. Herrmann, J.J. Akin, W.N. Anderson, D. Wang, S.J. Pocock, P.T. Investigators, Transcatheter versus surgical aortic-valve replacement in high-risk patients, N Engl J Med 364 (23) (2011) 2187–2198.

[26] M.J. Reardon, N.M. Van Mieghem, J.J. Popma, N.S. Kleiman, L. Sondergaard, M. Mumtaz, D.H. Adams, G.M. Deeb, B. Maini, H. Gada, S. Chetcuti, T. Gleason, J. Heiser, R. Lange, W. Merhi, J.K. Oh, P.S. Olsen, N. Piazza, M. Williams, S. Windecker, S.J. Yakubov, E. Grube, R. Makkar, J.S. Lee, J. Conte, E. Vang, H. Nguyen, Y. Chang, A.S. Mugglin, P.W. Serruys, A.P. Kappetein, S. Investigators, Surgical or Transcatheter Aortic-Valve Replacement in Intermediate-Risk Patients, N Engl J Med 376 (14) (2017) 1321–1331.

[27] S. Arora, J.A. Misenheimer, W. Jones, A. Bahekar, M. Caughey, C.J. Ramm, T. G. Caranasos, M. Yeung, J.P. Vavalle, Transcatheter versus surgical aortic valve replacement in intermediate risk patients: a meta-analysis, Cardiovasc Diagn Ther 6 (3) (2016) 241–249.

[28] R. Waksman, T. Rogers, R. Torguson, P. Gordon, A. Ehsan, S.R. Wilson, J. Goncalves, R. Levitt, C. Hahn, P. Parikh, T. Bilfinger, D. Butzel, S. Buchanan, N. Hanna, R. Garrett, F. Asch, G. Weissman, I. Ben-Dor, C. Shults, R. Bastian, P. E. Craig, H.M. Garcia-Garcia, P. Kolm, Q. Zou, L.F. Satler, P.J. Corso, Transcatheter Aortic Valve Replacement in Low-Risk Patients With Symptomatic Severe Aortic Stenosis, J Am Coll Cardiol 72 (18) (2018) 2095–2105.

[29] A.M. Greve, E. Gerdts, K. Boman, C. Gohlke-Baerwolf, A.B. Rossebo, C.A. Nienaber, S. Ray, K. Egstrup, T.R. Pedersen, L. Kober, R. Willenheimer, K. Wachtell, Prognostic importance of atrial fibrillation in asymptomatic aortic stenosis: the Simvastatin and Ezetimibe in Aortic Stenosis study, Int J Cardiol 166 (1) (2013) 72–76.

[30] B. Iung, V. Algalarrondo, Atrial Fibrillation and Aortic Stenosis: Complex Interactions Between 2 Diseases, JACC Cardiovasc Interv 13 (18) (2020) 2134–2136.

[31] M. Beeres, B. Schell, A. Mastragelopoulos, E. Herrmann, J.M. Kerl, T. Gruber-Rouh, C. Lee, P. Siebenhandl, B. Bodelle, S. Zangos, T.J. Vogl, V. Jacobi, R.W. Bauer, High-pitch dual-source CT angiography of the whole aorta without ECG synchronisation: initial experience, Eur Radiol 22 (1) (2012) 129–137.

[32] B. Bodelle, C. Fischbach, C. Booz, I. Yel, C. Frellesen, M. Beeres, T.J. Vogl, J. E. Scholtz, Free-breathing high-pitch 80kVp dual-source computed tomography of the pediatric chest: Image quality, presence of motion artifacts and radiation dose, Eur J Radiol 89 (2017) 208–214.

[33] L. Lehmkuhl, B. Foldyna, K. Von Aspern, C. Lucke, M. Grothoff, S. Nitzsche, J. Kempfert, M. Haensig, A. Rastan, T. Walther, F.W. Mohr, M. Gutberlet, Inter-individual variance and cardiac cycle dependency of aortic root dimensions and shape as assessed by ECG-gated multi-slice computed tomography in patients with severe aortic stenosis prior to transcatheter aortic valve implantation: is it crucial for correct sizing? Int J Cardiovasc Imaging 29 (3) (2013) 693–703.

[34] F. Capilli, M. Benndorf, M. Soschynski, M.T. Hagar, A. Kharabish, F.J. Neumann, G. Pache, C.L. Schlett, F. Bamberg, T. Krauss, Assessment of aortic annulus dimensions for transcatheter aortic valve replacement (TAVR) with high-pitch dual-source CT: Comparison of systolic high-pitch vs. multiphasic data acquisition, Eur J Radiol 133 (2020) 109366.

[35] M.T. Hagar, T. Kluemper, M. Hein, C. von Zur Muhlen, S. Faby, F. Capilli, C. Schuppert, R. Schmitt, P. Ruile, D. Westermann, C.L. Schlett, F. Bamberg, T. Krauss, M. Soschynski, Photon-counting CT-angiography in pre-TAVR aortic annulus assessment: effects of retrospective vs. prospective ECG-synchronization on prosthesis valve selection, Int J Cardiovasc Imaging (2024).

[36] C. Tamburino, M. Barbanti, P. D`Errigo, M. Ranucci, F. Onorati, R.D. Covello, F. Santini, S. Rosato, G. Santoro, D. Fusco, C. Grossi, F. Seccareccia, O.R. Group, 1-Year Outcomes After Transfemoral Transcatheter or Surgical Aortic Valve Replacement: Results From the Italian OBSERVANT Study, J Am Coll Cardiol 66(7) (2015) 804-812.

[37] O.A. Smettei, S. Sayed, M.A.H. A, F. Alharbi, R.M. Abazid, Ultra-fast, low dose high-pitch (FLASH) versus prospectively-gated coronary computed tomography angiography: Comparison of image quality and patient radiation exposure, J Saudi Heart Assoc 30(3) (2018) 165-171.

[38] R. Duarte, D. Miranda, G. Fernandez-Perez, J.C. Costa, Coronary CT angiography using a prospective protocol. Comparison of image quality and radiation dose between dual source CT and single source CT, Radiologia 55 (4) (2013) 315–322.