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Original Research

Relevance of Motion Artifacts in Planning Computed Tomography on Outcomes After Transcatheter Aortic Valve Implantation

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ABSTRACT

Background: Motion artifacts in planning computed tomography (CT) for transcatheter aortic valve implantation (TAVI) can potentially skew measurements required for procedural planning. Whether such artifacts may affect safety or efficacy has not been studied.

Methods: We conducted a retrospective analysis of 852 consecutive patients (mean age, 82 years; 47% women) undergoing TAVI-planning CT at a tertiary care center. Two independent observers divided CTs according to the presence of motion artifacts at the annulus level (Motion vs. Normal group). Endpoints included surrogate markers for inappropriate valve selection: annular rupture, valve embolization or misplacement, need for a new permanent pacemaker, paravalvular leak (PVL), postprocedural transvalvular gradient, all-cause death.

Results: Forty-six (5.4%) patients presented motion artifacts on TAVI-planning CT (Motion group). These patients had more preexisting heart failure, moderate-severe mitral regurgitation, and atrial fibrillation. Interobserver variability of annular measurement (Normal vs. Motion group) did not differ for mean annular diameter but was significantly different for perimeter and area. Presence of motion artifacts on planning CT did not affect the prevalence of PVL (≥moderate PVL 0% vs. 2.5% $p = 0.5$), mean transvalvular gradient (6±3 mmHg vs 7±5 mmHg, $p = 0.1$), or the need for additional valve implantation (0% vs. 2.8%, $p = 0.6$). One annular rupture occurred (Normal group). Pacemaker implantation, procedural duration, hospital stay, 30-day outcomes, and all-cause mortality did not differ between the groups.

Conclusions: Motion artifacts on planning CT were found in about 5% of patients. Measurements for valve selection were possible without the need for repeat CT, with mean diameter-derived annulus measurement being the most accurate. Motion artifacts were not associated with worse outcomes.

ABBREVIATIONS

CT, computed tomography; PVL, paravalvular leak; TAVI, transcatheter aortic valve implantation; THVs, transcatheter heart valves.

Introduction

Computed tomography (CT) is the gold standard for preprocedural planning in patients scheduled for transcatheter aortic valve implantation (TAVI).[1] CT is used for visualization and measurement of the annulus, the left ventricular outflow tract, the sinus of Valsalva, origin of the coronary ostia, and the iliofemoral arteries. Furthermore, the perpendicular valve planes (implant views) are identified. Precise annular measurements lead to improved outcomes including fewer paravalvular leaks (PVLs).

Despite the widespread use of multidetector CT and electrocardiogram (ECG) triggering, motion artifacts (or pulsation artifacts) in the annular region are encountered quite frequently in clinical practice.[2] Patients with a greater likelihood of presenting this artifact are those with atrial fibrillation and those unable to follow commands or hold their breath.

We hypothesized that motion artifacts may reduce the precision and/or reproducibility of annular measurements required for valve selection and may result in worse hemodynamic (PVLs, valvular gradient) and clinical outcomes.

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Methods

Between June 2012 and December 2021, a total of 852 consecutive patients with severe aortic stenosis underwent TAVI at the Heart Center Lucerne. All patients underwent planning CT and were discussed in the interdisciplinary heart team. All patients were enrolled in the prospective SwissTAVI registry, which was approved by the local ethics committee (NCT01368250).[3–5] All patients provided written informed consent for the procedure and for prospective data acquisition and follow-up examinations.

Planning Computed Tomography

TAVI-planning CT was obtained in all patients with a Flash Dual Source scanner, Siemens Somatom Definition Flash (Siemens Medical, Erlangen, Germany) with ECG triggering in retrospective mode as previously described.[6,7] The phase between 30% and 70% of the heart rate was recorded and reconstruction was performed during systole as well as diastole. The complete data set was transferred to a dedicated post-processing workstation, measurements and analyses were performed with a commercially available software (Merlin, Phoenix-PACS, Freiburg, Germany). Analyses, measurements for access site and valve selection (aortic annulus, left ventricular outflow tract, aortic root and sinotubular junction dimentions and coronary height) were performed using a multiplanar double-oblique reconstruction.

Definition of Motion Artifact and Classification

Motion artifact was defined as a double contour of the annulus, making clear-cut targets for measurement of diameter/perimeter/area difficult. If motion artifacts were present during the first scan, the scan was repeated up to 2 additional times aiming to obtain artifact-free images. If 3 sets of images presented motion artifacts, no further scan was performed. These patients were classified in the Motion artifact group (46, 5.4% of the cohort). Importantly, if the patient had any set of images free of motion artifact, they were classified in the Normal group. In the Normal group, 120 patients (14.2% of the cohort) presented at least one set of CT images with motion artifacts at the annular level.

CTs were analyzed by 2 independent TAVI operators with extensive experience in CT analysis and sizing of transcatheter heart valves (THVs). The classification was binary according to the presence or absence of motion artifact at the annular level. Motion artifacts at other anatomical locations did not qualify since they do not affect sizing measurements for THV.

Blinded Assessment of Interobserver Variability

Two TAVI operators with extensive experience in CT planning independently assessed mean annular diameter and annular perimeter of a randomly selected cohort of 20 CTs without motion artifact and 20 with motion artifact presented in random order. Random selection was performed with Google random number generator (https://www.google.com/search?q=random+number).

Study Endpoints

In order to assess an inadvertent oversizing or undersizing of the valve, surrogate parameters of an inappropriate valve choice were assessed. Annular rupture and new permanent pacemakers served as a surrogate for oversizing. Need for additional valve implantation (as a consequence of valve embolization or "pop-out"), PVL, and elevated mean transvalvular gradient on predischarge echocardiography served as surrogate parameters of undersizing. All-cause death during long-term follow-up was compared between groups.

All events, defined according to the updated definitions of the Valve Academic Research Consortium (VARC-3),[8] were adjudicated by an independent clinical events committee in a prospective fashion.

Statistical Analysis

Continuous variables are presented as mean ± SD or median (interquartile range) as appropriate, categorical variables as n (%). When normally distributed, continuous variables were compared with Student's *t*-test; if not fitting a normal distribution, the Wilcoxon rank sum test was used. The Fisher exact test was used for comparisons of categorical variables. Event-free survival rates were estimated using the Kaplan-Meier method and compared with the log-rank test. Univariate and multivariable Cox regression analyses were performed to identify predictors for

Table 1
Baseline characteristics

Baseline characteristic	All (n = 852)	Motion artifact (n = 46)	Normal (n = 806)	*p* value
Age, years	81 ± 6	82 ± 5	81 ± 6	0.568
Female sex	393 (46.1%)	20 (43.5%)	373 (46.3%)	0.76
BMI, kg/m^2	27.1 ± 5.1	28.2 ± 4.4	27.3 ± 5.1	0.13
Hypertension	768 (79.6%)	35 (76.1%)	643 (79.8%)	0.55
Diabetes	194 (22.8%)	10 (21.7%)	184 (22.8%)	0.86
Peripheral arterial disease	136 (16.0%)	5 (10.9%)	131 (16.3%)	0.41
Coronary artery disease	439 (51.5%)	26 (56.5%)	413 (51.2%)	0.55
Prior myocardial infarction	85 (10.0%)	9 (19.6%)	76 (9.4%)	**0.039**
Prior PCI	165 (19.4%)	9 (19.6%)	156 (19.4%)	1.0
Prior CABG	52 (6.1%)	0 (0%)	52 (6.5%)	0.11
Heart failure	233 (27.4%)	14 (30.4%)	219 (27.2%)	0.61
Prior stroke/TIA	93 (10.9%)	3 (6.5%)	90 (11.2%)	0.47
Atrial fibrillation	174 (20.4%)	21 (45.7%)	153 (19.0%)	**<0.001**
eGFR, ml/min	55 ± 25	56 ± 25	55 ± 22	0.57
COPD	118 (13.9%)	3 (6.5%)	115 (14.3%)	0.19
Aortic valve area, cm^2	0.76 ± 0.18	0.76 ± 0.14	0.76 ± 0.18	0.96
Mean gradient, mmHg	46 ± 16	41 ± 16	46 ± 16	0.05
LVEF (%)	56 ± 13	51 ± 15	56 ± 13	**0.01**
Mitral regurgitation ≥ moderate	33 (34.2%)	6 (14.0%)	26 (3.6%)	**0.007**
NT-pro-BNP, pg/mL	1472 (590-3843)	2631 (1069-6223)	1428 (571-3770)	**0.02**
EuroSCORE II, %	5.0 ± 4.4	4.5 ± 3.9	5.0 ± 4.5	0.52
STS PROM, %	4.5 ± 0.41	4.2 ± 0.5	4.5 ± 0.1	0.68

Notes. Bold values indicate statistical significance ($p < 0.05$).
Abbreviations: BMI, body mass index; CABG, coronary artery bypass grafting; COPD, chronic obstructive pulmonary disease; eGFR, estimated glomerular filtration rate; LVEF, left ventricular ejection fraction; NT-pro-BNP, N-terminal pro brain natriuretic peptide; PCI, percutaneous coronary intervention; STS PROM, society of thoracic surgeons Predicted Risk of Morbidity and Mortality; TIA, transient ischemic attack.

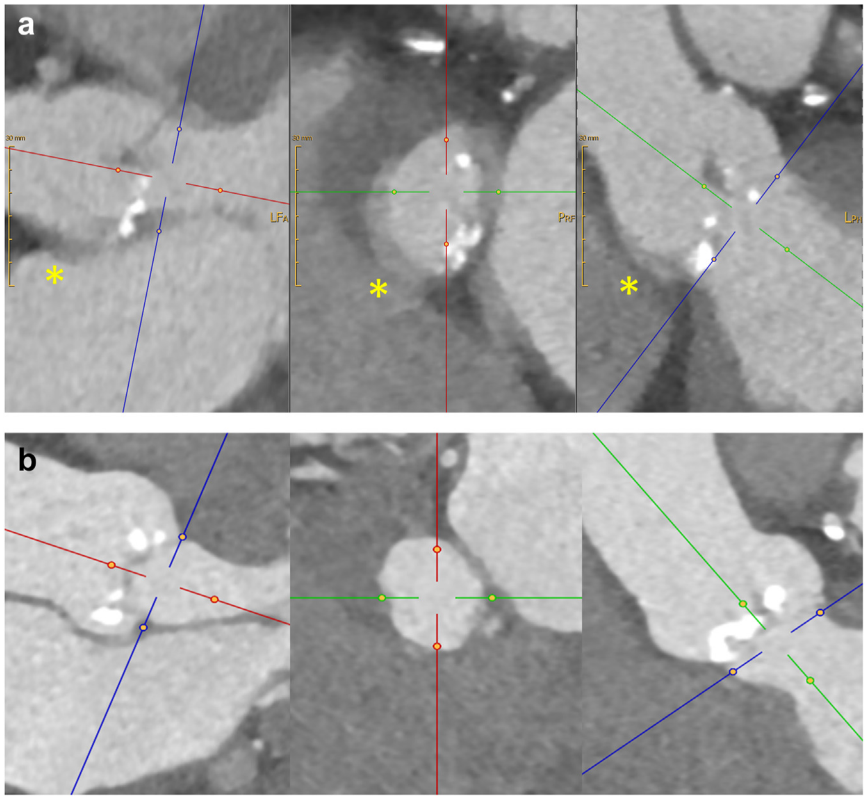

Figure 1. Examples of planning CT. (a) Motion artifacts (*) affecting the ascending aorta, aortic root, annulus (middle panel). (b) Normal CT scan. Abbreviation: CT, computed tomography.

mortality and hospitalization for heart failure during follow-up. Variables with a univariate p value <0.1 were included in the multivariable model. A two-tailed p value <0.05 was considered statistically significant. Statistical analyses were performed with STATA (Version 13, StataCorp, College Station, TX). Interobserver agreement was assessed with correlation coefficients and Bland-Altman plots, differences in interobserver variability between Motion and Normal group (comparison of slopes and intercepts) using Prism 9 (Version 9.0.2, GraphPad Software, San Diego, CA).

Results

Baseline characteristics are shown in Table 1. The mean age was 81 ± 6 years, 47% of patients were female. Motion artifacts were present in 46 patients (5.4% of the cohort). Patients with motion artifacts more commonly had prior myocardial infarction (19.6% vs. 9.4% $p = 0.039$), atrial fibrillation (45.7% vs. 19.0%, $p < 0.001$), mitral regurgitation ≥ moderate (14.0% vs. 3.6%, $p = 0.007$), higher NT-pro-BNP (2631 (1069-6223) pg/mL vs. 1428 (571-3770) pg/mL, $p = 0.02$), and had a lower LVEF (51 ± 15% vs. 56 ± 13%, $p = 0.01$).

Figure 1 shows an example of a motion artifact at the annulus level on TAVI-planning CT (Figure 1a), with a normal CT for comparison (Figure 1b).

Interobserver Variability

The resulting TAVI-planning measurements in a subset of randomly selected patients (motion artifact n = 20 and normal n = 20) independently assessed by 2 operators are depicted in Figure 2. Measurements comprised the mean annular diameter derived by the long and short diameter (Figure 2a), annular perimeter (Figure 2b), and annular area (Figure 2c). The 2 independent operators achieved similar agreement with a numerically lower r^2-value in the motion artifact group: the mean annulus diameter r^2 was 0.82 and 0.85 for motion artifact and normal CT, respectively (Figure 2a), perimeter r^2 0.84 and 0.93 for motion artifact and normal CT, respectively (Figure 2b), and area r^2 0.72 and 0.91 for motion artifact and normal CT, respectively (Figure 2c). The statistical difference was further analyzed with slope and intercept comparison: Motion and Normal group did not have a different interobserver variability for mean diameter ($p = 0.4$), but interobserver variability differed significantly for perimeter ($p = 0.002$) and area ($p = 0.01$), Figure 3.

Bland-Altman plots showed several differences. Mean diameter motion artifact: bias −0.5 mm, 95% CI (−2.7 to 1.7), normal: bias −0.6 mm, 95% CI (−2.3 to 1.2), (Figure 2a). Perimeter motion artifact: bias −1.6 mm, 95% CI (−8.3 to 5.2), normal: bias −2.5 mm, 95% CI (−7.1 to 2.1), (Figure 2b). Area motion artifact: bias −33.9 mm^2, 95% CI (−114.1 to 46.3), normal: bias −33.2 mm^2, 95% CI (−96.1 to 29.8), (Figure 2c). We interpret these differences as not clinically relevant, especially mean diameter (bias difference of 0.1 mm between Normal and Motion). Additionally, there was no consistent bias toward oversizing or undersizing when motion artifacts were present. Both operators measured an annular size between 2 valve sizes (as suggested by the IFU of Evolut Pro +, Medtronic, Dublin, Ireland) in 1 case in the motion artifact group (5%) and 1 case in the normal group (5%).

Procedural Characteristics and Outcomes

There were no significant differences in procedural characteristics (Table 2). Presence of motion artifacts was not associated with a difference in type of valve implanted, nor was it associated with need for a second valve (due to valve embolization or "pop-out") or with prolonged procedure time. The in-hospital outcomes were comparable in patient with and without motion artifacts; in particular, no difference was present in regards to mean transvalvular gradient or PVLs on predischarge echocardiography. Patients with motion artifacts did have a higher rate

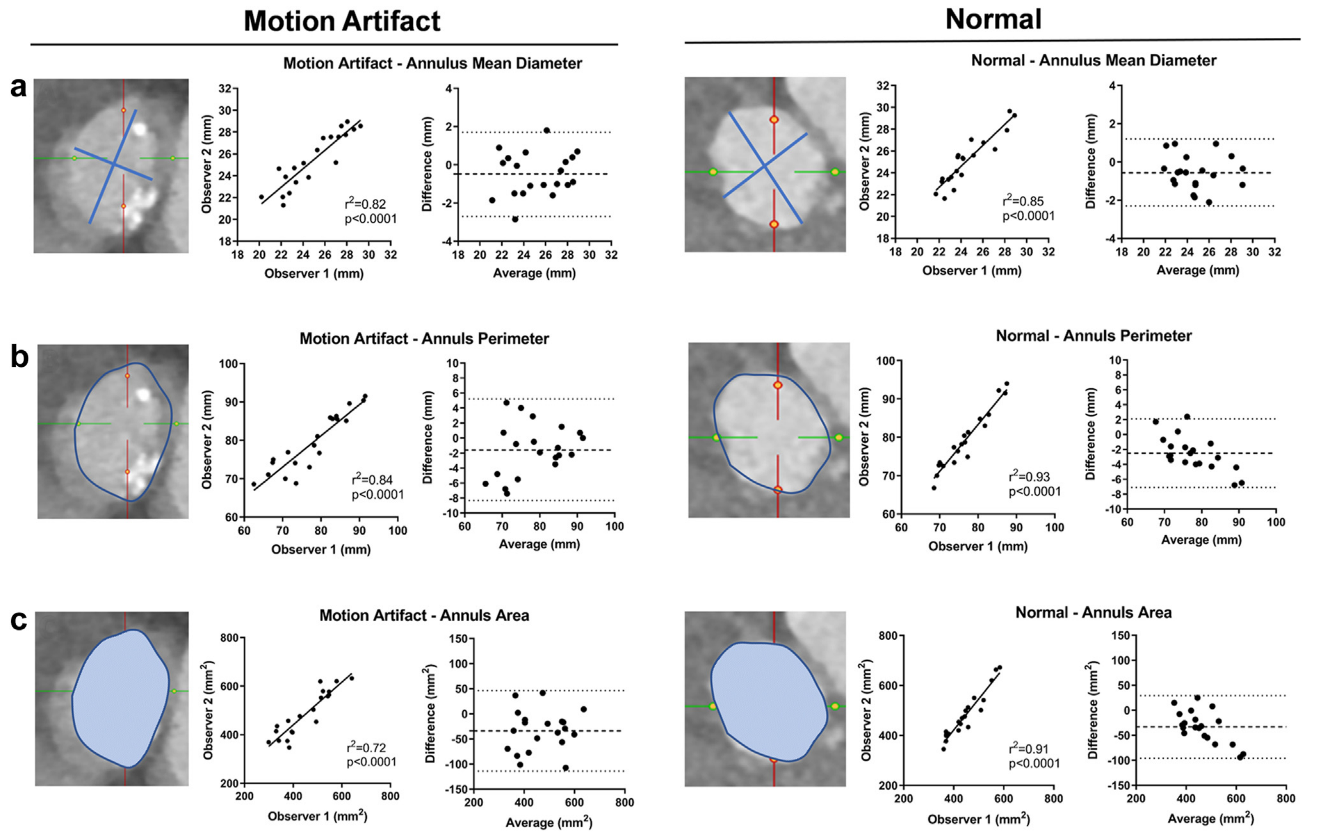

Figure 2. Interobserver variability. Correlation (left) and Bland-Altman plots (right) for interobserver variability for Annulus in long axis (a), annular perimeter (b) and annular area (c). In Bland-Altman plots bias is shown with a dashed line, 95% limits of agreement with dotted lines.

of PVLs. A graphical depiction of the prevalence of PVLs on discharge echocardiography is present in Figure 4. Thirty-day outcomes including implantation of a new pacemaker did not differ between the 2 groups (Table 2).

After a median follow-up of 17 (8-39) months, all-cause mortality did not differ between patients with normal CT or motion artifacts at the annular level (hazard ratio (HR) 1.0, 95% CI 0.6-1.9, $p = 0.9$, Figure 5).

Univariate and multivariable predictors for all-cause mortality are shown in Table 3. In multivariable analysis, female sex, heart failure, atrial fibrillation, and kidney function remained significant predictors, with heart failure and atrial fibrillation being the strongest predictors (HR 1.71 [1.24-2.37] and HR 1.30[1.05-1.78], respectively, Table 3).

Discussion

We asked the question: "do motion artifacts at the annulus level during TAVI-planning CT affect measurement for valve selection and outcomes?". In 852 consecutive patients undergoing TAVI, 5.4% presented motion artifacts on TAVI-planning CT (Motion group); the main distinguishing feature was a greater proportion of atrial fibrillation, which is known to interfere with ECG triggering during CT scan. Moreover, patients in the Motion group had a lower LVEF, a higher proportion of mitral regurgitation ≥ moderate, and higher NT-pro-BNP, all of which are associated with atrial fibrillation and furthermore could have led to more difficulties in breath-holding during image acquisition, possibly contributing to motion artifacts.

Measurements required for valve selection were possible in all patients with motion artifacts. When assessed by 2 independent operators, a randomly selected sample of $n = 20$ patients showed that no major discrepancy in measurements was present using mean diameter derived from long and short axis, but significant differences were present in the interobserver variability for perimeter and area. Bland-Altman plots did not show a consistent bias toward either oversizing or undersizing in the Motion group. Importantly, Bland-Altman plots demonstrated that the

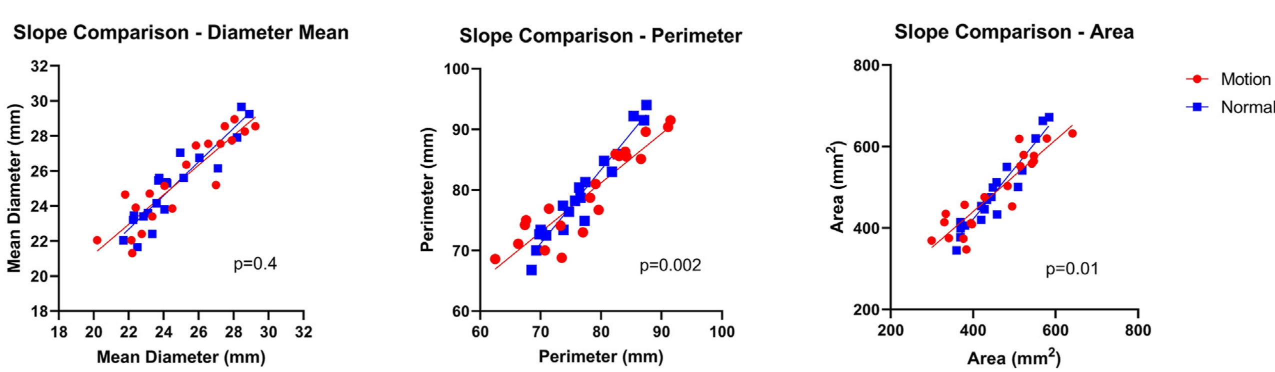

Figure 3. Slope comparison of interobserver variability between Motion and Normal group.

Table 2
Procedural characteristics, in-hospital and 30-d outcomes

Procedural characteristics	All (n = 852)	Motion artifact (n = 46)	Normal (n = 806)	*p* value
Implanted valve				0.38
Sapien 3	151 (17.7%)	11 (23.9%)	140 (17.4%)	
Corevalve/Evolut R/PRO	275 (32.3%)	14 (30.4%)	261 (32.4%)	
ACURATE neo/neo 2	333 (39.1%)	19 (41.3%)	314 (37.0%)	
Allegra	93 (10.9%)	2 (4.4%)	91 (11.3%)	
Procedural duration, min	48 (38-60)	51 (42-59)	48 (38-60)	0.31
Implantation of a second valve	21 (2.4%)	0 (0%)	21 (2.6%)	0.63
In-hospital outcomes				
Mean gradient, mmHg	7.3 ± 4.5	6.3 ± 3.0	7.4 ± 4.6	0.11
Aortic valve area, cm^2	2.1 ± 0.5	2.1 ± 0.6	2.1 ± 0.5	0.57
Paravalvular leak ≥ moderate	19 (2.2%)	0 (0%)	19 (2.4%)	0.62
Median duration of hospitalization, days	6(3-8)	5(3-10)	6(3-8)	0.95
30-d outcomes				
Vascular complications				0.26
None	761 (89.3%)	39 (84.8%)	722 (89.6%)	
Minor vascular complication	34 (4.0%)	4 (8.7%)	30 (3.7%)	
Major vascular complication	57 (6.7%)	3 (6.5%)	54 (6.7%)	
Bleeding				0.25
None	769 (90.3%)	40 (87.0%)	729 (90.5%)	
Minor bleeding	23 (2.7%)	2 (4.4%)	21 (2.6%)	
Major bleeding	35 (4.1%)	1 (2.2%)	34 (4.2%)	
Life-threatening bleeding	25 (2.9%)	3 (6.5%)	22 (2.7%)	
Implantation of a new permanent pacemaker	71 (8.3%)	6 (13.0%)	65 (8.1%)	0.27
Any stroke	29 (3.4%)	1 (2.2%)	28 (3.5%)	1.0
Annular rupture	1 (0.1%)	0 (0%)	1 (0.1%)	1.0
All-cause mortality	12 (1.4%)	0 (0%)	12 (1.5%)	1.0

absolute difference in sizing is unlikely to be clinically relevant: for mean diameter, the difference was −0.5 mm (−2.7 to 1.7 mm) for Motion and −0.6 mm, (−2.3 to 1.2 mm) for Normal, meaning that the bias between the Motion and Normal group is 0.1 mm, therefore unlikely to sway the valve choice toward a larger (or smaller) THV. Similarly, the difference in bias for perimeter between the Motion and Normal group was 0.9 mm and 0.7 mm^2 for area. Interobserver variability in our sample is similar to that reported previously,[9] with mean diameter being one of the most motion-artifact "resistant." In a previous study, mean diameter and area were the parameters with the best performance in terms of interobserver variability.[10]

The impact of inadvertent inclusion of an artifact-affected or "blurry" part of the annulus is likely to be more pronounced when perimeter or area measurements are performed because more of the "blurry" part might be included as opposed to long/short perimeter derived measurements where only a line might cross into the "blurry" part of the annulus. This is one possible explanation why long/short axis derived mean diameter performs better in patients with motion artifacts.

Implantation of a transcatheter heart valve was technically possible in all patients regardless of the presence of motion artifacts on planning CT, without significant differences in procedural characteristics. Surrogate parameters of an inadequate valve selection did not show any signal toward potential harm. Surrogate parameters for inadvertent oversizing (annular rupture, higher pacemaker-implantation rate), as well as surrogate parameters for inadvertent undersizing (valve embolization or pop-out, PVLs and elevated transvalvular gradients) were similar in patients with and without motion artifacts on TAVI-planning CT. In addition, all-cause mortality during follow-up did not differ between the 2 groups. Univariate and multivariable predictors for all-cause mortality did not include motion artifact and seemed to be tied to patients' baseline comorbidities.

Taken together, our data suggest that (i) in the presence of motion artifact, it is possible to perform accurate, reproducible measurement for valve selection, (ii) long and short axis derived mean annular diameter

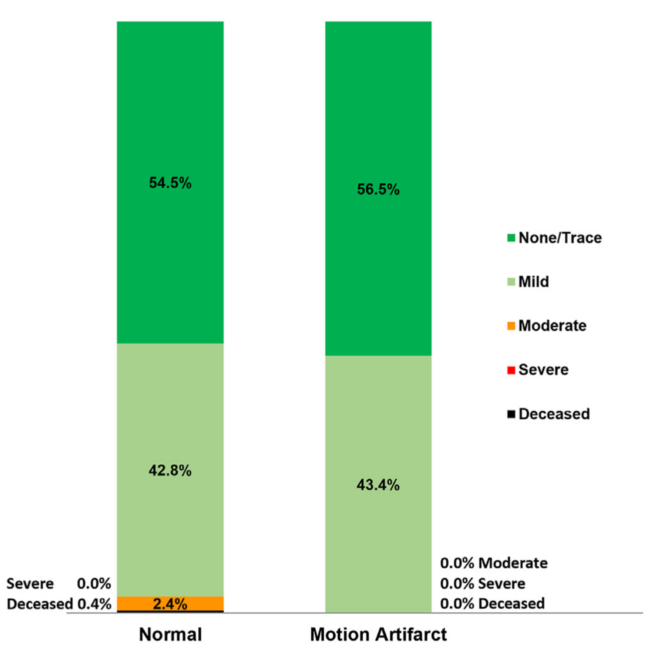

Figure 4. Paravalvular leak on discharge echocardiography.

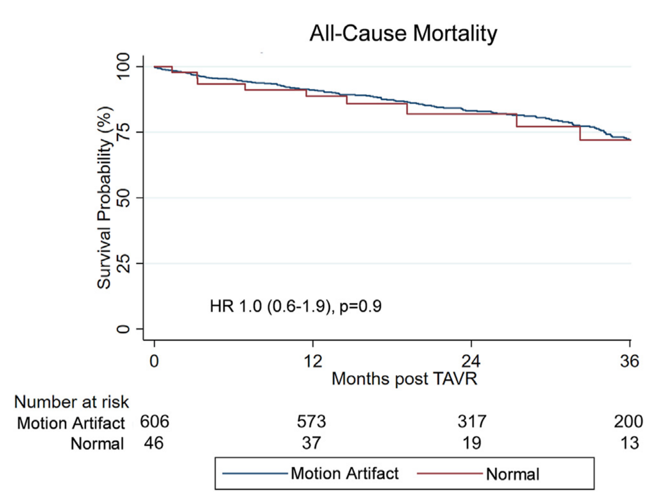

Figure 5. Clinical outcomes. Kaplan-Meier curves for all-cause mortality.

Table 3
Univariate and multivariable predictors for all-cause mortality

Variable	Univariate HR (95% CI)	*p* value	Multivariable HR (95% CI)	*p* value
Motion artifact	1.01 (0.55-1.87)	0.952	-	
Age, per year	1.03 (1.01-1.06)	**0.011**	1.01 (0.99-1.04)	0.297
Female sex	0.71 (0.54-0.95)	**0.021**	0.62 (0.46-0.84)	**0.002**
Diabetes	1.23 (0.90-1.70)	0.192	-	
Hypertension	1.15 (0.80-1.66)	0.453	-	
Prior stroke/TIA	1.38 (0.94-2.02)	0.100	-	
Coronary artery disease	0.97 (0.74-1.28)	0.840	-	
Heart failure	2.27 (1.71-3.01)	**<0.001**	1.71 (1.24-2.37)	**0.001**
Atrial fibrillation	1.71 (1.28-2.30)	**<0.001**	1.30 (1.05-1.78)	**0.01**
Peripheral arterial disease	1.69 (1.23-2.33)	**0.001**	1.19 (0.82-1.70)	0.335
COPD	1.26 (0.87-1.83)	0.219	-	
eGFR (ml/min)	0.98 (0.98-0.99)	**<0.001**	0.99 (0.98-0.99)	**0.030**
STS PROM	1.08 (1.05-1.12)	**<0.001**	1.02 (0.98-1.07)	0.200

Notes. Bold values indicate statistical significant ($p < 0.05$).
Abbreviations: COPD, chronic obstructive pulmonary disease; eGFR, estimated glomerular filtration rate; STS PROM, society of thoracic surgeons Predicted Risk of Morbidity and Mortality; TIA, transient ischemic attack.

may be used instead of perimeter or area in such patients, (iii) there is no signal toward higher procedural complications in patients with motion artifacts, (iv) the hemodynamic result is comparable to patients without motion artifact, and (v) there is no survival disadvantage during long-term follow-up.

Limitations

There are several limitations that need to be considered when interpreting the results from our study. First, all limitations inherent to the retrospective, single-center nature of the study apply. Second, the number of patients with motion artifacts is low. This might partly be due to the use of second-generation dual source "flash" scanners, which have a higher temporal resolution than single source scanners and therefore lead to less artifacts. This, of course, limits the generalizability of our findings. Third, this study represents consecutive patients at a single institution, where although 2 operators and 1 radiologist perform the measurements independently for every patient, the program director is involved in every patient's measurement and valve selection process: this lowers the degree of operator-to-operator variability in the measurement process required for valve selection by introducing a certain continuity and standard in measurement and valve selection. This limits the generalizability to other institutions or programs with several operators performing valve selection independently.

Furthermore, it is well-known that several other factors in addition to annular measurements play a role in valve choice (type of valve as well as valve size): extent and degree of valve calcification, left vetricular outflow tract calcification, leaflet symmetry, coronary height, sinotubular junction diameter, and presence of a "horizontal aorta" being the most prominent. These factors might have affected valve choice, and in the setting of a "borderline measurement" might have "swayed" sizing toward a smaller or larger size. Correction for these factors was not possible in our study.

Conclusions

Motion artifacts on TAVI-planning CT affect about 5% of patients. The presence of motion artifacts allows accurate and reproducible valve selection using long and short axis derived mean annular diameter and does not affect procedural, hemodynamic, or clinical outcomes. These findings suggest that the presence of motion artifact does not warrant repeat CT.

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Ethics Statement

The research reported adhered to the local and institutional ethical guidelines.

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Disclosure Statement

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Central Illustration was created using Servier Medical Art (www.servier.com).

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