Multidetector-row computed tomography imaging of prosthetic heart valves: clinical and experimental aspects
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CHAPTER 10

CT acquisition parameters for transcatheter heart valves: effect of tube voltage and prospective ECG triggering on image quality and stent-induced artifacts

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Submitted
CHAPTER 10 | Transcatheter valves

ABSTRACT

Objectives
To optimize computed tomography (CT) acquisition parameters for imaging of transcatheter heart valves (THV).

Background
THV implantation is a minimally invasive alternative to conventional aortic valve replacement. CT imaging of implanted THV complements echo-Doppler but is hampered by metal-related artifacts. We investigated the effect of ECG gating and tube voltage on image quality.

Methods
Two types of THV (Medtronic CoreValve and Edwards Sapien) were imaged in a static phantom with 256 detector-row CT. Image acquisition was performed using two retrospectively ECG-gated protocols (120kVp/600mAs and 140kVp/600mAs) and two prospectively triggered protocols (120kVp/210mAs and 140kVp/155mAs). Two observers assessed image quality using blinded and randomized image pairs in a two-alternative forced-choice test in two scoring rounds. Image noise was quantified. Hypo- and hyperdense artifacts were measured using <-50HU and >200HU thresholds, respectively.

Results
For the CoreValve, image quality was the most optimal using prospective triggering at 120kVp (39% both rounds) followed by prospective triggering at 140kVp (36 and 38% for round 1 and 2 respectively). Average inter- and intraobserver kappa was good (0.62 both). Prospectively triggered protocols reduced hypodense (p<0.001) but not hyperdense artifacts (p=0.2), whereas protocols using 140kVp reduced hyperdense (p<0.001) but not hypodense artifacts (p=0.06). For the Sapien valve, the best acquisition protocol was prospective triggering at 140kVp (45 and 42% for round 1 and 2 respectively) followed by prospective triggering at 120kVp (30 and 35% for round 1 and 2 respectively). Average inter- and intraobserver kappa was moderate (0.55) and good (0.62), respectively. Hyper- and hypodense artifacts were reduced with protocols using 140kVp (p<0.001) but not by prospectively triggered protocols (p=0.052 and p=0.057 respectively). Prospective triggering lowered image noise for both valves (p<0.001).

Conclusions
In vitro, CT image quality of both the CoreValve and Sapien THV significantly improves by prospective triggering.
INTRODUCTION

Transcatheter heart valve (THV) implantation in the aortic valve annulus is related to complications such as coronary obstruction, periprosthetic leakage and conduction abnormalities.\(^1\,2\) Echocardiography is the primary imaging modality to evaluate prosthetic function. However, multidetector computed tomography (MDCT) has been shown to complement echocardiographic findings by providing detailed imaging of the THV position, and may more optimally provide information on the displacement of native calcified tissue, non-circular prosthetic stent expansion and, possibly, stent migration.\(^3\,4\) A limitation of echocardiography is that the metal stent of the THV causes acoustic shadowing and precludes visualization of large parts of the periprosthetic anatomy. However, little is known about the interaction between MDCT and the metal stent structure of the currently available types of THV and, to our knowledge, no specific recommendations exist for MDCT image acquisition after THV implantation.

Experience with MDCT imaging of normal biological and mechanical valve prostheses has shown that metal valve components caused variable amounts of artifacts.\(^5\,6\) These artifacts depend on the structure and the composition of the metal components. For example, an older prosthesis made of a cobalt chrome alloy (Bjork-Shiley monostrut) is associated severe artifacts whereas bioprostheses and modern mechanical prostheses made of carbon and titanium result in good image quality.\(^5\,7\) Despite these variable artifacts, MDCT could complement echo-Doppler findings. In selected patients, MDCT reveals obstructive masses, false aneurysms and degeneration of biological prostheses that were not found with echocardiography due to acoustic shadowing\(^7\) and the use of MDCT for these indications has recently been found appropriate by an expert panel.\(^10\) Possibly, post-implant MDCT imaging after THV implantation may confer similar advantages. However, the currently used THV are not comparable to normal prostheses due to differences in design. They consist of two types of metal mesh structures: an elongated stent made of nickel titanium alloy (nitinol) stent for the CoreValve (CoreValve Medtronic, Minneapolis, MN) and a short and more bulky cobalt chrome alloy stent for the Sapien XT valve (Edwards Lifesciences Irvine, CA). Because of the structure and composition of these valves, the MDCT imaging characteristics may vary considerably from other (mechanical or biological) prosthetic heart valves and may also vary between the two types of THV.

Metal-related artifacts are ubiquitous in MDCT imaging and the interactions of metal and the X-ray beam have been widely studied. These artifacts primarily depend on physics-based interactions and can be modified by adjusting the acquisition parameters.\(^11\,13\) For example, the adjustment of acquisition parameters such as an increase in tube current or tube voltage may reduce the photon deflections (e.g. scatter and noise) caused by the metal and increase photon energy to allow more photons to pass through the metal structures (e.g. reduce photon starvation). The effectiveness of such strategies has been shown to depend on the size and composition of the metal object studied.\(^11\,13\)
The aim of our study was to assess various acquisition parameters for two THV in order to optimize acquisition parameters for these valves in a clinical setting and improve the MDCT imaging quality of the periprosthetic anatomy. Specifically, we evaluated whether 1) increasing the photon energy with the use of the higher tube voltage and 2) using axial image acquisition (in contrast to helical acquisition with retrospective ECG gating) improved image quality.

METHODS

Two THV (Medtronic Corevalve 26 mm, Medtronic, Minneapolis, MN, and Edwards Sapien XT 26 mm, Edwards Lifesciences, Irvine, CA.) were inserted in a polymethylmethacrylate (PMMA) valve chamber filled with water which has been described before. Image acquisition was done with a 256 detector-row CT system (iCT, Philips Healthcare, Best, the Netherlands) in a static position using four different acquisition protocols. An artificial ECG signal set at 75/min was used for ECG-gating. Acquisition parameters are presented in Table 1.

TABLE 1 | Scan settings

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECG</td>
<td>Retrospective</td>
<td>Retrospective</td>
<td>Prospective</td>
</tr>
<tr>
<td>kVp</td>
<td>120</td>
<td>140</td>
<td>120</td>
</tr>
<tr>
<td>mAs</td>
<td>600</td>
<td>600</td>
<td>210</td>
</tr>
<tr>
<td>Pitch</td>
<td>0.2</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>Collimation</td>
<td>128 x 0.625 mm</td>
<td>128 x 0.625 mm</td>
<td>128 x 0.625 mm</td>
</tr>
<tr>
<td>Rotation time (ms)</td>
<td>270 ms</td>
<td>270 ms</td>
<td>270 ms</td>
</tr>
<tr>
<td>Filter</td>
<td>Cardiac B</td>
<td>Cardiac B</td>
<td>Cardiac B</td>
</tr>
<tr>
<td>Anatomical length (mm)</td>
<td>80.1</td>
<td>80.1</td>
<td>80.0</td>
</tr>
<tr>
<td>CTDIvol (mGy) ‡</td>
<td>39.9</td>
<td>58.8</td>
<td>13.9</td>
</tr>
<tr>
<td>DLP (mGy*cm) §</td>
<td>512.8</td>
<td>753.4</td>
<td>111.4</td>
</tr>
</tbody>
</table>

Retrospective gating was performed with either 120 kVp / 600 mAs or 140 kVp / 600 mAs at a pitch of 0.2. We chose the smallest possible scan range (80.1 mm) that could be covered with the use of retrospective gating. Prospective triggering was performed with either 120 kVp / 210 mAs or 140 kVp / 155 mAs and axial scanning (i.e. no table
movement) and 8 cm exposed at the center of the gantry. The maximal range that could be reconstructed from this data was 70 mm. For prospective triggering at 140 kVp, the highest possible tube current was 155 mAs. No padding was used. Ten acquisitions were done for each of the four protocols under static conditions without valve movement.

Artifact quantification

All image sets were transferred to a dedicated workstation for analysis (Extended Brilliance Workstation, Philips Healthcare, Best, the Netherlands). Hyper- and hypodense artifact volumes were quantified in 3D volume rendered images using two thresholds based on the densities of the surrounding structures according to a methodology described before.\textsuperscript{13,14} Thresholds were determined from the CT density of the surrounding structures such as the PMMA in the valve chamber and water. We chose threshold values that were approximately three standard deviations (SD) above the Hounsfield Units (HU) of PMMA (measured in a zone without artifacts) and below the HU of water, respectively. The chosen thresholds were 200 HU for hyperdense artifacts and -50 HU for hypodense artifacts. Because the 200 HU threshold included the radiopaque components of the metal stents of the valves, the change in hyperdense volume underestimates the actual change in artifacts.\textsuperscript{14} Areas outside the valve chamber and other unrelated sources of artifacts were digitally excised in an identical manner for all scans.

Image noise (defined as the SD of CT attenuation) was measured in all images using a circular region of interest (diameter 1 cm) that was placed in an identical section of the PMMA structure of the valve chamber.

Visual assessment

Data evaluation was performed on a research workstation (iX Viewer, Images Sciences Institute, University Medical Center Utrecht, the Netherlands) that allowed for scrolling through the data sets using interactive multiplanar reformatting. A two-alternative forced choice method was used. Two observers (PS, LdH) were individually presented with random and blinded pairs of the four acquisition protocols of the same THV type. All possible pair wise comparisons of the four acquisition protocols for each series were presented to the observers (i.e. six comparisons for each series, 10 series per valve, two valve types, resulting in 120 pairs). The sequence in which the image pairs were presented was randomized with respect to series and acquisition protocol. To determine intra-observer variability, these 120 pairs were presented twice to the observers after a four week interval and with new randomization.

Image quality was graded according to the 1) detail of the peri-prosthetic structures, 2) the amount of artifacts and 3) the detail of the prosthetic stent. Observers were required to choose the image with superior image quality.
Statistical analysis

Data were analyzed using SPSS software (SPSS Statistics Version 16.0, SPSS Inc, Chicago, IL). Parametric data are presented as means ± SD and non-parametric data as medians with interquartile range (IQR). For each valve, a Kruskall Wallis test was used to detect differences between acquisition protocols for every artifact type and for image noise. A Mann Whitney U test with Bonferroni correction was used to detect differences between protocols. Statistical significance was defined as p<0.05.

For the visual assessment, observer scores were expressed as the overall percentage of cases in which one acquisition protocol was found to be better or worse compared to the other protocols. Inter- and intra-observer agreement was determined using kappa (κ) statistics with correction for equal probability. Inter- and intra-observer agreement were expressed as mean κ value with standard error (SE) between observers for each scoring round and for individual observers. A κ value of 0.81-1.00 indicated very good agreement; 0.61—0.80, good agreement; 0.41—0.60, moderate agreement; 0.21—0.40, fair agreement; and 0.20 or lower, poor agreement.13

RESULTS

Visual scoring results of the two-alternative forced choice test per scoring round are summarized in Figure 1 and 2.

For the CoreValve, the average scores of both scoring rounds for the side-by-side comparison of image quality resulted in the best image quality for the prospectively triggered protocol at 120 kVp (39% both scoring rounds) followed by prospective triggering at 140 kVp (36% and 38% for the first and second scoring round respectively) and by retrospective gating at 120 kVp (16% and 14% for the first and second scoring round respectively) and at 140 kVp (9% for both scoring rounds). Differences between 120 and 140 kVp were small, and 140 kVp conferred no advantage for image quality. Inter-observer kappa was 0.53 (SE 0.11) for round 1 and 0.7 (SE 0.09) for round 2 indicating moderate and good agreement respectively. Intra-observer kappa was 0.67 (SE 0.10) and 0.57 (SE 0.11) for the two observers indicating good and moderate agreement, respectively. For the Sapien valve, image quality was best for the prospectively triggered protocol at 140 kVp (45% and 42% for the first and second scoring round respectively), followed by prospectively triggered at 120 kVp (30% and 35% for the first and second scoring round respectively), retrospective gating at 140 kVp (15% and 18% for the first and second scoring round respectively) and at 120 kVp (10% and 5% for the first and second scoring round respectively). Inter-observer kappa for round one and two was 0.57 (SE 0.11) and 0.53 (SE 0.11), respectively, indicating moderate agreement. Intra-
FIGURE 1  |  CoreValve image quality results per scoring round from visual assessment of image quality. The bars represent the percentage in which one acquisition protocol was found to be superior to the other protocols.

FIGURE 2  |  Sapien image quality results per scoring round from visual assessment of image quality. The bars represent the percentage in which one acquisition protocol was found to be superior to the other protocols.
observer kappa was 0.63 (SE 0.10) and 0.6 (SE 0.10) indicating good and moderate agreement respectively. Representative valve images for each acquisition protocol are presented in Figure 3.

**FIGURE 3** | CT image reconstructions of the CoreValve and the Sapien transcatheter valve with the use of the different acquisition protocols.
Significant differences in hypo- and hyperdense artifact volumes were found between the four protocols for the CoreValve (both p<0.001) and the Sapien valve (p=0.013 and p<0.001 for hypo- and hyperdense artifacts respectively). For the CoreValve, prospective triggering reduced hypodense (p<0.001) but not hyperdense artifacts (p=0.2, see Table 2).

**TABLE 2 |** Artifacts and image noise for the CoreValve prosthesis. Values represent median and interquartile range (IQR).

<table>
<thead>
<tr>
<th>Protocol</th>
<th>A Retrospective 120 kVp</th>
<th>B Retrospective 140 kVp</th>
<th>C Prospective 120 kVp</th>
<th>D Prospective 140 kVp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypodense artifacts (mm³)</td>
<td>670 (593-739)</td>
<td>860 (585-1090)</td>
<td>383 (374-465)</td>
<td>437 (317-629)</td>
</tr>
<tr>
<td>Hyperdense artifacts (mm³)</td>
<td>5600 (5600-5625)</td>
<td>5100 (5100-5200)</td>
<td>5300 (5300-5300)</td>
<td>5100 (5100-5100)</td>
</tr>
<tr>
<td>Image noise (HU)</td>
<td>14.0 (13.1-16.3)</td>
<td>13.0 (12.3-14.4)</td>
<td>11.4 (10.5-12.3)</td>
<td>11.9 (11.5-12.7)</td>
</tr>
</tbody>
</table>

Conversely, 140 kVp did not affect hypodense artifacts (p=0.06) but resulted in less hyperdense artifacts (p<0.001). Compared to other protocols, prospective triggering performed better at 120 kVp and 140 kVp for hypodense and hyperdense artifacts respectively (both p<0.001).

For the Sapien valve, 140 kVp was effective in reducing hypo- and hyperdense artifacts (p<0.002 and p<0.001 respectively, see Table 3). A trend for reduction was found for prospective triggering (p=0.057 and p=0.052 for hypo- and hyperdense artifacts respectively). The protocol with the least artifacts was 140 kVp prospectively triggered.

**TABLE 3 |** Artifacts and image noise for the Sapien prosthesis. Values represent median and interquartile range (IQR).

<table>
<thead>
<tr>
<th>Protocol</th>
<th>A Retrospective 120 kVp</th>
<th>B Retrospective 140 kVp</th>
<th>C Prospective 120 kVp</th>
<th>D Prospective 140 kVp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypodense artifacts (mm³)</td>
<td>2009 (1924-2301)</td>
<td>1922 (1689-2172)</td>
<td>2051 (2024-2126)</td>
<td>1855 (1764-1932)</td>
</tr>
<tr>
<td>Hyperdense artifacts (mm³)</td>
<td>3845 (3647-4065)</td>
<td>3174 (3072-3557)</td>
<td>3357 (3312-3487)</td>
<td>3182 (3086-3315)</td>
</tr>
<tr>
<td>Image noise (HU)</td>
<td>15.8 (15.1-17.5)</td>
<td>13.4 (12.7-14.0)</td>
<td>10.8 (10.5-11.7)</td>
<td>10.3 (10.1-10.9)</td>
</tr>
</tbody>
</table>

Significant differences in image noise existed between the four acquisition protocols (p=0.023, Tables 2 and 3). Posthoc testing revealed significant differences between the prospectively triggered and retrospectively gated protocols (p<0.001 for all comparisons). No significant differences in image noise existed between protocols with 120 kVp and 140 kVp (p=0.62 for retrospective gating and p=0.92 for prospective triggering).
DISCUSSION

In vitro, the best MDCT imaging results for THV were achieved by prospective triggering at 120 kVp for the CoreValve and by prospective triggering at 140 kVp for the Sapien valve. The acquisition parameters commonly used for retrospectively gated coronary CT angiography (e.g. at 120 kVp and 600 mAs) may therefore be inadequate for optimal imaging results.

The image quality results obtained with visual assessment found prospective triggering to be superior for both valve prostheses. Artifact measurement demonstrated merely a trend with prospective triggering for the Sapien valve. In addition, the reduction of hyperdense artifacts using 140 kVp did not seem to translate in better image quality for the CoreValve when scored visually. These discrepancies reflect the different factors that influence image quality. In our experiments, the reduction of noise with prospective triggering resulted in a better detail of the periprosthetic structure despite an unchanged amount of artifacts.

The differences between the two valves may be explained by the differences in constituent metal and valve design. For example, the CoreValve is made of Nitinol, a titanium nickel alloy compared to the cobalt chromium alloy of the Sapien valve. Furthermore, the stent structure of the CoreValve is much finer and more elongated than the short bulkier stent of the Sapien valve. The differences in artifact formation between different metals has been described for mechanical prosthetic valves and neurovascular clips.5,13 These results also suggest that for the two THV, different acquisition protocols may be required to optimize CT imaging results.

The mechanisms by which the increased tube voltage (140 kVp) and prospective triggering may improve image quality may be due to physics-based interactions between the photons and the metal structure. A photon beam which is emitted by the tube may have too little energy to pass through heavy metal structures causing a loss of photons at the detector side (photon starvation). The paucity of photons reaching the detector consequently results in hyper- and hypodense artifacts when the image is reconstructed. One way to reduce this problem is to increase the energy (kVp) of the photons. In our experiment increasing photon energy was only effective for the Sapien valve which may be explained by the thicker struts of the cobalt chromium stent while the finer mesh structure of the CoreValve probably does not cause any photon starvation. Similar effectiveness of 140 kVp for the improvement of image quality has been reported for cobalt containing neurovascular clips.13 Another physics-based interaction between photons and metal is photon deflection and scatter which causes an increased image noise5 and which can be reduced by emitting more photons. The lower image noise associated with prospective triggering may be explained by the more efficient use of the emitted photons for image reconstruction. In our experiment, close to the full dose (210 mAs, ~100%) was used for image reconstruction with prospective
triggering compared to about 16% (100 mAs) with retrospective gating. Therefore, despite a much larger radiation exposure an inferior image quality is achieved. In our experiments prospective triggering improved image quality which may be explained by a reduction of scatter and image noise which provide for a crisper image of the directly adjacent periprosthetic structures.

Our study has several limitations. For one, our in-vitro model did not simulate cardiac motion. Motion is known to exacerbate metal-related artifacts. Although little is known about the velocities of the valve during the cardiac cycle, motion is invariably present and experience with MDCT imaging of normal prosthetic valves has shown that artifacts and image quality vary importantly during the cardiac cycle. The results obtained in our in-vitro model without any motion may underestimate the amount of artifacts found clinically. Our experiments were tailored to compare the effect of CT acquisition protocols on image quality and artifacts without other confounding factors. Specifically for the clinical situation, such an increase in artifacts due to motion further stresses the need for appropriate acquisition protocols.

Second, prospective triggering, which would be recommended on the basis of our findings, probably works best in stable low heart rates while many patients with THV may have atrial fibrillation and other irregular rhythms that may compromise both prospective triggering and retrospective gating. In addition, prospective triggering requires correct timing relative to the cardiac cycle and is limited to only one cardiac phase. Because the radiation exposure associated with prospective triggering is much lower, image acquisition may be repeated fourfold before equalling the dose related to retrospective triggering.

Third, we did not use contrast for our study. Because contrast material is optimized for 120 kVp, the density of contrast changes with 140 kVp which could act as a confounder for our artifact measurements which are based on predefined thresholds. Finally, by using water, we were not able to obtain detailed images of the leaflets. Leaflet imaging, however, was not the focus of our study.

Fourth, we investigated only two THV devices. The earlier generation Sapien THV and the newer investigational devices may behave differently in the same experimental conditions.

In conclusion, our in vitro results suggest that, based on artifact measurement and a two-alternative forced choice image quality test, prospective triggering is superior for MDCT imaging of THV. For the Edwards Sapien THV, an increased tube voltage may also be effective.
REFERENCES