**Dual-Layer Spectral CTA for TAVI Planning Using a Split-Phase Protocol and Low-keV Virtual Monoenergetic Images: Improved Image Quality in Comparison with Single-Phase Conventional CTA**

Verbesserte Bildqualität der TAVI-CTA eines Dual-Layer Spektral-CTs unter Verwendung eines Zwei-Phasen-Protokolls und virtuell-monoenergetischer Bilder im Vergleich zu einem konventionellen CT

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**Key words**
transcatheter aortic valve implantation (TAVI), transcatheter aortic valve replacement (TAVR), dual-energy CT, spectral detector CT, aortography, virtual monoenergetic imaging

**Material und Methoden**
75 CTAs des DLCT wurden retrospektiv mit 75 CTAs eines konventionellen CTs verglichen. Mit dem DLCT wurde die CTA ohne EKG-Synchronisation unmittelbar nach einer retrospektiv EKG-gegateten Aufnahme des Herzens und des Aortenbogens durchgeführt. Mit dem SLCT wurde eine einphasige CTA durchgeführt, welche sowohl das Herz als auch die Zugangsfäße in einem retrospektiv EKG-synchronisierten Scan erfasste. Die objektive Bildqualität wurde an verschiedenen Ebenen des arteriellen Zugangsweges verglichen.

**Ergebnisse**
Die virtuell monoenergetischen Bilder des DLCT bei 40 keV zeigten eine signifikant höhere absolute CT-Zahl, SNR und CNR auf allen Ebenen des arteriellen Zugangswegs. Bei den 40 keV-VMI der DLCT betrug das durchschnittliche aortale Gefäßsignal aller 6 gemessenen Regionen 589,6 ± 243 HU im Vergleich zu 492,7 ± 209 HU des SLCT (p < 0,01). Ein ähnlicher Trend konnte für SNR (23,6 ± 18 vs. 18,6 ± 9; p < 0,01) und CNR (21,1 ± 18 vs. 16,4 ± 8; p < 0,01) beobachtet werden. Für das Signalrauschen wurden keine signifikanten Unterschiede beobachtet (27,8 ± 9 HU vs. 28,1 ± 8 HU; p = 0,599).

**Schlussfolgerung**
Bei der TAVI-Planung kann unter Verwendung eines DLCT mit einem Zwei-Phasen-Protokoll und 40 keV-VMI eine höhere objektive Bildqualität im Vergleich zu einem einphasigen Protokoll eines konventionellen CT-Scanners erzielt werden.

**Kernaussagen:**
- Bei Verwendung eines Dual-Layer-CT der ersten Generation kann eine Anpassung der CT-Protokolle zur TAVI-Planung erforderlich sein.
- Die Rekonstruktion virtuell-monoenergetischer Bilder bei 40 keV verbessert die Bildqualität.
- Bei einem Zwei-Phasen-Protokoll ist die Strahlendosis geringer im Vergleich zu einer einphasigen EKG-gegateten CT-Akquisition.

**ABSTRACT**
Purpose Adaptation of computed tomography protocols for transcatheter aortic valve implantation (TAVI) planning is required when a first-generation dual-layer spectral CT scanner (DLCT) is used. The purpose of this study was to evaluate the
Introduction

Dual-energy computed tomography (DECT) has been implemented successfully in clinical practice. There are different technical approaches to acquire spectral imaging, but they all use a high and low mean energy X-ray spectrum from one examination to obtain images. A widespread concept is a dual-source system with two orthogonally positioned X-ray tubes and detectors rotating simultaneously. Another approach is kVp switching, in which an X-ray tube rapidly switches between low and high energy levels at each X-ray projection [1, 2]. A recently developed CT technology is a detector-based DECT using a polychromatic X-ray tube and two layers of detectors – dual-layer detector computed tomography (DLCT). The top layer, an yttrium-based garnet scintillator, and the second gadolinium-oxysulphide-based layer absorb low and high energy photons separately [3, 4].

The first-generation DLCT scanner is equipped with a detector with a width of 4 cm along the z-axis. The use of a CT scanner with such detector coverage may cause difficulties in ECG synchronous cardiac imaging [5–7]. Due to its special requirements (CT angiography of the vascular access and an ECG-synchronized data set of the aortic root and heart), the scan protocols for TAVI planning have to be adapted when using a scanner with a smaller detector width [6, 8]. At our institution, according to the recommendations for CT scanners with a limited detector coverage, we chose a split-phase protocol for TAVI planning.

After a retrospective ECG-gated scan of the annulus including the heart and the aortic arch, the access vasculature is evaluated in a second scan without ECG synchronization [8]. This split-phase protocol requires a short intermission between the two scans to make scan adjustments and adjust the table position resulting in a late arterial acquisition. Caused by the lower vessel attenuation of the late arterial phase compared to an early arterial phase, this split-phase protocol could lead to a loss of image quality in the evaluation of the arterial access route. However, DLCT allows for increasing vessel attenuation in contrast-enhanced CT scans using virtual monoenergetic image reconstructions (VMI) at lower energy levels to compensate for this effect of suboptimal vessel enhancement [9–12].

The primary objective of this study was to determine the objective image quality of DLCT in CTA for TAVI planning. To this end, we compared low-energy (40 keV) VMI of DLCT with conventional images (CI) obtained with single-layer CT. Absolute CT attenuation values, noise, signal-to-noise ratio (SNR), and contrast-to-noise ratio (CNR) were compared across six levels of the arterial access pathway.

Secondary objectives of this study were to assess the percentage of CTAs with sufficient contrast enhancement and the radiation dose during TAVI planning between DLCT and SLCT. According to recent recommendations, sufficient contrast enhancement was defined as the presence of a CT attenuation value of at least 250 HU across all six levels of the arterial access pathway [5, 8].

Materials and Methods

Study design

Until 2017, an SLCT scanner was used for TAVI planning at our institution. This CT scanner was replaced by a DLCT scanner in December 2017. For our study we included a total of 150 patients who underwent CTA prior to TAVI (75 each for SLCT and DLCT). The included patients were examined in the period from July
2017 to November 2017 (SLCT) and from January to November 2018 (DLCT). Patients that were scanned during these time periods and had incomplete image data or artifacts caused by metal implants were primarily excluded (SLCT: n = 3; DLCT: n = 2).

This retrospective single-center study was approved by our local ethics committee with a waiver of written informed consent (Ref. S-620/2018). This study has been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments.

Image acquisition

SLCT

Conventional CTA was performed using a Philips Brilliance ICT device providing 128 detector rows on a single-layer detector with a width of 8 cm (Philips; Best; The Netherlands). The TAVI planning protocol was an ECG-gated spiral acquisition of the heart and total aorta including the access route. The examination was performed with the following parameters: BMI-dependent tube voltage (100 kVp or 120 kVp) and effective tube current (481 mAs or 499 mAs); rotation time 0.37 s; detector collimation 128 × 0.625 mm; helical pitch value 0.3. Using a flying z-focus, 256 slices were acquired simultaneously. In patients with a BMI > 25 kg/m², the higher tube voltage and effective tube current were chosen. The total scan time was 12.5 s. Bolus tracking was used for image acquisition timing. The acquisition started 11 s after reaching a contrast enhancement threshold of 150 Hounsfield Units (HU) above the baseline attenuation in the descending aorta.

DLCT

Spectral CTA was performed using a Philips iQon device providing 64 detector rows on a dual-layer detector with a width of 4 cm (Philips; Best; The Netherlands). The TAVI planning protocol consisted of a split-phase acquisition of the heart on the one hand and of the total aorta including the access route on the other hand. An ECG-gated spiral acquisition of the heart and aortic arch in caudo-cranial direction was immediately followed by a late arterial non-ECG-gated helical CTA scan from subclavian to femoral arteries in cranio-caudal direction (▶ Fig. 1). The following scanning parameters were used for the late arterial CTA scan: tube voltage 120 kVp; effective tube current 130 mAs; rotation time 0.27 s; detector collimation 64 × 0.625 mm; helical pitch value 1.234. Using a flying z-focus, 128 slices were acquired simultaneously. Bolus tracking was used for image acquisition timing. The ECG-gated acquisition of the heart and annulus was started 6 s after the attenuation reached a contrast enhancement threshold of 110 HU above the baseline in the descending aorta (scan time: 9 seconds). The craniocaudal acquisition of the CTA was started 26 s after reaching the threshold value in the descending aorta. The total acquisition time of the late arterial CTA was 3.2 s.

In ▶ Table 1, the relevant scan parameters of both CT protocols are provided.

Contrast medium

80 ml of the contrast medium Iomeron 400 (400 mg iodine/ml; Bracco Imaging; Konstanz, Germany) was used as the standard volume and was adjusted for obese patients (up to 100 ml; mean BMI: 34 ± 5 kg/m²). The following injection protocol for both scan-
ners was applied using an automated injector: 4.0 ml/s for 10 s (40 ml), followed by 3.0 ml/s for 13 s (40 ml) and a saline chaser flush (50 ml).

**Image reconstruction**

For SLCT, conventional polychromatic images were reconstructed with a slice thickness of 0.67 mm and an increment of 0.3 in axial orientation using a standard soft tissue kernel. The images were reconstructed at 70 % of the R-R interval (during diastole). For late arterial DLCT CTA, virtual monoenergetic images (40 keV-VMI) were reconstructed with a slice thickness of 0.8 mm and an increment of 0.4 mm using a standard soft tissue kernel. For both data sets, an iterative reconstruction algorithm was used as provided by the vendor (SLCT: IMR Level 1; DLCT: iDose4 Level 3).

**Image analysis**

Objective image quality measurements of both groups were performed by one reader using a dedicated image processing workstation (IntelliSpace Portal Version 10; Philips; Best; The Netherlands). In each CTA, a circular region-of-interest (ROI) with a fixed area of 2.0 cm² was placed at the following six levels of the aorto-iliac access: ascending aorta (AA) and descending aorta (DA) at the level of the right pulmonary artery, abdominal aorta at the level of the hiatus (HA) and at the level of the renal arteries (RA), right common iliac artery (RCl) and right distal external iliac artery (REI). For calculating the contrast-to-noise ratio (CNR), a circular ROI was placed over the right psoas muscle. The vessel attenuation was defined by the mean enhancement within the ROI and noise was represented by standard deviation (SD). The signal-to-noise ratio (SNR) was defined as the vessel attenuation divided by noise. The CNR was calculated as follows: \( \text{CNR} = \frac{\text{mean arterial attenuation} - \text{mean muscle attenuation}}{\text{mean arterial noise}} \).

**Statistical analysis**

All data were analyzed using SPSS version 25.0 (SPSS Inc, Chicago, IL, USA). Continuous variables were reported as the mean ± standard deviation (SD), categorical values as proportions. Wilcoxon rank-sum test and two-sample t-test were used to compare continuous variables. All reported p-values are two-sided and a p-value < 0.05 was considered to indicate statistical significance.

**Results**

**Patient characteristics**

150 patients (72 males; mean age: 82 ± 6y; BMI 28 ± 5 kg/m²) who underwent CTA prior to TAVI were included in this study (75 on each CT scanner). Age, BMI, and serum creatinine were assessed using electronic medical records. There were no statistical differences in gender, age, or BMI between these two groups as provided in ▶ Table 2. In the SLCT group, 49 CT acquisitions were performed at 120 kV and 26 CT acquisitions at 100 kV.

**Quantitative assessment**

Representative images of 40 keV VMI of DLCT and conventional images of SLCT are seen in ▶ Fig. 2. 40 keV VMI of DLCT showed a significantly higher mean vessel attenuation at all six levels of the arterial access route (▶ Table 3; ▶ Fig. 3). The overall mean aortic attenuation of all six measured regions was 589.6 ± 243 for DLCT and 492.7 ± 209 for SLCT (p < 0.01). Similar observations were found for SNR and CNR (▶ Table 4). The overall mean SNR was 23.6 ± 18 for DLCT and 18.6 ± 9 for SLCT (p < 0.01). The CNR across all segments was 21.1 ± 18 for DLCT and 16.4 ± 8 for SLCT (p < 0.01). No deterioration was found for vessel noise using DLCT (▶ Table 5). Sufficient aortic enhancement at all segments of the access route was achieved in 93 % with DLCT and 89 % with SLCT.
In the separate comparison of the DLCT group with the SLCT group at 100 kV and 120 kV, similar trends were observed without reaching the level of statistical significance (▶ Table 6). Between the two SLCT groups, the measured values for attenuation, SNR and CNR were higher when using 100 kV.

Radiation dose
The total dose length product of the complete TAVI planning examination was significantly lower in the DLCT group (1994 ± 367 mGy·cm, including the ECG-gated acquisition of the heart) compared to the SLCT group (2439 ± 703 mGy·cm; p < 0.01). The same tendencies were found in the two subgroups of patients with a BMI below and above 25 kg/m² with significantly lower total dose length products in both DLCT groups (BMI< 25: 1864 ± 293 mGy·cm vs. 2363 ± 694 mGy·cm; p < 0.01; BMI> 25: 2093 ± 393 mGy·cm vs. 2720 ± 610 mGy·cm; p < 0.001).

The volume CT dose index (CTDIvol) of the SLCT group was 3.3 ± 9 mGy. The CTDIvol in the DLCT group was 48.2 ± 9 mGy for the ECG-gated heart imaging and 10.9 ± 3 mGy for the non-ECG-gated high-pitch spiral CTA.

In the separate comparison of the DLCT group with the SLCT group at 100 kV and 120 kV, similar trends were observed without reaching the level of statistical significance (▶ Table 6). Between

<table>
<thead>
<tr>
<th>Attenuation</th>
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<th>SLCT</th>
<th>p-value</th>
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<tr>
<td>AA</td>
<td>537.5 ± 184</td>
<td>469.8 ± 168</td>
<td>&lt;0.01</td>
</tr>
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<td>AD</td>
<td>583.4 ± 205</td>
<td>503.8 ± 183</td>
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<td>HA</td>
<td>572.5 ± 224</td>
<td>475.4 ± 191</td>
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<td>RA</td>
<td>606.9 ± 244</td>
<td>499.2 ± 215</td>
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<td>RCI</td>
<td>616.2 ± 282</td>
<td>499.2 ± 232</td>
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<td>REI</td>
<td>656.2 ± 306</td>
<td>532.2 ± 271</td>
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<td>Total</td>
<td>596.6 ± 243</td>
<td>492.7 ± 209</td>
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<tr>
<td>AA</td>
<td>26.3 ± 11</td>
<td>21.6 ± 9</td>
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<tr>
<td>AD</td>
<td>29.1 ± 11</td>
<td>23.5 ± 10</td>
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<tr>
<td>HA</td>
<td>18.3 ± 7</td>
<td>15.5 ± 6</td>
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<tr>
<td>RA</td>
<td>21.6 ± 9</td>
<td>18.0 ± 8</td>
<td>&lt;0.01</td>
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<tr>
<td>RCI</td>
<td>21.2 ± 10</td>
<td>16.7 ± 7</td>
<td>&lt;0.01</td>
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<tr>
<td>REI</td>
<td>28.8 ± 38</td>
<td>18.7 ± 9</td>
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<tr>
<td>Total</td>
<td>23.6 ± 18</td>
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<th>SLCT</th>
<th>p-value</th>
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<tr>
<td>AA</td>
<td>23.1 ± 10</td>
<td>21.6 ± 9</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>AD</td>
<td>25.9 ± 10</td>
<td>20.8 ± 9</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>HA</td>
<td>16.2 ± 7</td>
<td>13.6 ± 6</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>RA</td>
<td>19.3 ± 9</td>
<td>15.9 ± 7</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>RCI</td>
<td>19.0 ± 10</td>
<td>14.8 ± 7</td>
<td>&lt;0.01</td>
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<tr>
<td>REI</td>
<td>26.5 ± 38</td>
<td>16.5 ± 9</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Total</td>
<td>21.1 ± 18</td>
<td>16.4 ± 8</td>
<td>&lt;0.01</td>
</tr>
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</table>

▶ Fig. 3 Attenuation of 40 keV-VMI of DLCT across the arterial segments compared with conventional SLCT images (AA: ascending aorta at the level of the right pulmonary artery; DA: descending aorta at the level of the right pulmonary artery; HA: aorta at the level of hiatus; RA: aorta at the level of the renal arteries; RCI: right common iliac artery; REI: distal right external iliac artery).


▶ Table 4 Signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) of 40 keV-VMI of DLCT and SLCT (AA: ascending aorta at the level of the right pulmonary artery; DA: descending aorta at the level of the right pulmonary artery; HA: aorta at the level of hiatus; RA: aorta at the level of the renal arteries; RCI: right common iliac artery; REI: distal right external iliac artery).
CT scan. A study by Hickethier and colleagues demonstrated that, with the help of monoenergetic image reconstruction, even the contrast in a venous contrast phase is sufficient to allow adequate vascular assessment of abdominal arteries [11]. Weiss and colleagues demonstrated the improvement of monoenergetic image reconstructions for the detection of incidental pulmonary embolism in scans during the portal-venous phase [14].

Our study results suggest that a TAVI planning protocol with a reduced contrast dose also seems possible with DLCT. A promising approach is offered by the prospective SPECTACULAR study by Cavallero and colleagues [15].

In their study, a low-dose contrast agent protocol and 40 keV-VMI of DLCT were chosen for TAVI planning. They also chose a split protocol, but with an abdominal acquisition during an arteriovenous mixed phase following a retrospective ECG-triggered chest scan during an arterial phase [15]. Adequate results in terms of image quality and aortic root measurements were obtained with only 50 ml of contrast medium [15]. However, most of their conclusions were based on the comparison with conventional images at 120 kV of the same scan. Using this method, the improvement of image quality with 40 keV-VMI is well established in the literature and is in line with our results [11, 12, 16].

We also achieved a 17% reduction in radiation dose when comparing these two scanners and protocols. This demonstrates that low radiation dose can be achieved even with DLCT when adapted examination protocols are used. It should be mentioned that we had chosen a radiation-intensive protocol with SLCT, which was considered in the guidelines at that time, but is no longer recommended in the current guidelines [6, 8].

There are other studies on differing examination protocols, such as the 3-phase protocol, that have achieved promising results regarding radiation and contrast agent reduction [17, 18].

There are several limitations to this study. First, the slice thickness and increment were not identical between SLCT and DLCT image data sets. The slice thickness affects image noise and, thus, calculation of the SNR. If SLCT would have been reconstructed with the same slice thickness as DLCT, image noise would decrease to some degree. However, since the calculation of the CNR is unaffected by variations in image noise within the same data set, and the CNR of DLCT was superior to SLCT in our study, the impact of the inequality of slice thicknesses on the results is considered marginal. Second, the algorithm of iterative image reconstruction was not identical between the SLCT and DLCT image data sets. SLCT image data were reconstructed using IMR. DLCT spectral data had to be reconstructed using iDose4, as provided by the vendor. Other studies have shown that IMR may be more effective in noise reduction than iDose4 [19–21]. Thus, this discrepancy will tend to result in an underestimation of the superiority of DLCT concerning the SNR. Third, we focused on assessing parameters of objective image quality of the aortic CTA. Subjective image quality included assessment of the general evaluability of the aortic CTA, assessment of the heart and the left ventricular outflow tract as well as assessment of the presence and severity of stenoses along the iliac access route. In this regard it has to be acknowledged that low-keV image reconstructions may lead to overestimation of calcified stenoses. Fourth, we limited the study to the assessment of VMI at an energy level of 40 keV, because this has been previously shown to be best for

### Discussion

To our knowledge, this is the first study to compare the objective image quality of CTA prior to TAVI between a first-generation dual-layer spectral CT scanner and a conventional single-layer CT scanner. In this study, we demonstrated that not only using DLCT is feasible for TAVI planning but also provides in general higher objective image quality and lower radiation dose compared with SLCT.

These results were achieved despite the late arterial phase caused by the limited detector width of the first generation DLCT. A narrow detector width requires a split-phase protocol for TAVI imaging with a short delay between these two scans. As discussed in the introduction section, the delayed second scan and the resulting late arterial phase affects the image quality and results in a loss of vessel enhancement. However, reconstruction of VMI at 40 keV is known to increase vessel attenuation and this approach was chosen in our study [10–13]. By using VMI at a low keV level near the k-edge of iodine (33 keV), we observed a significant increase in vessel attenuation, SNR, and CNR compared with SLCT. This observation is especially valid regarding the comparison with the SLCT acquisitions performed at 120 kV. Concerning the small subgroup of SLCT acquisitions performed at 100 kV, the superiority of low-keV VMI was generally not statistically significant. This is supposed to result from the fact that reducing the tube voltage from 120 kV to 100 kV already leads to a relevant increase in iodine-induced CT attenuation. Our results are in line with numerous other studies that have shown the benefits of DLCT and monoenergetic imaging [10, 11].

Especially in examinations with poor vascular contrast, DLCT has advantages, since the spectral data set is available in every CT scan. A study by Hickethier and colleagues demonstrated

### Table 5 Noise across the arterial segments of 40 keV-VMI of DLCT and SLCT (AA: ascending aorta at the level of the right pulmonary artery; DA: descending aorta at the level of the right pulmonary artery; HA: aorta at the level of hiatus; RA: aorta at the level of the renal arteries; RCI: right common iliac artery; REI: distal right external iliac artery).

<table>
<thead>
<tr>
<th>Vessels</th>
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<tr>
<td>AA</td>
<td>21.6 ± 6</td>
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<td>AD</td>
<td>20.7 ± 5</td>
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<td>HA</td>
<td>32.3 ± 7</td>
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<td>RA</td>
<td>29.5 ± 8</td>
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<td>RCI</td>
<td>30.9 ± 8</td>
<td>30.5 ± 7</td>
<td>0.763</td>
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<tr>
<td>REI</td>
<td>29.3 ± 9</td>
<td>28.7 ± 9</td>
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<tr>
<td>Total</td>
<td>27.8 ± 9</td>
<td>28.1 ± 8</td>
<td>0.599</td>
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the contrast and visualization of vascular structures [10, 11]. Finally, this was a retrospective study with image quality assessments performed by a single reader. A multi-reader analysis may have fortified the robustness of the study results.

**Conclusion**

In conclusion, performing TAVI planning with a dual-layer spectral detector CT scanner using a split-phase protocol is feasible when using low-energy VMI at 40 keV for late arterial aortic CTA. Higher objective image quality with a lower radiation dose was obtained compared to ECG-synchronized CTA of the whole aorta performed with conventional CT.

Further research is required to evaluate if contrast volume reduction using DLCT with reconstruction of low-energy images is feasible without hampering image quality.

**Conflict of Interest**

The authors declare that they have no conflict of interest.
References


