A new method for radiation dose reduction at cardiac CT with multi-phase data-averaging and non-rigid image registration: preliminary clinical trial

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Purpose

Introduction:

In coronary computed tomography angiography (CTA), prospective ECG triggering scanning can be used in patients with a stable sinus rhythm and a low heart rate [1, 2]. In this technique, the CT scan is usually performed at the center of the mid-diastole phase at around 75% of the R-R interval [3]. As the best phase for diagnosis varies from patient to patient, redundant scan data (padding) centered on mid-diastole are usually acquired [3, 4]. A final image for evaluation of the coronary arteries is reconstructed by selecting the phase with the fewest motion artifacts; data reconstructed from another phase are not used for diagnosis.

Purpose:

We introduce a new method for image noise reduction at coronary CTA that uses the multi-phase images reconstructed from unused redundant scan data. It reduces image noise by averaging multi-phase images transformed by non-rigid image registration. The purpose of our study was to investigate the clinical feasibility of our noise reduction technique at coronary CTA.
Methods and Materials

**Outline of the multi-phase data-averaging technique (Fig. 1):**

In general, multiple data acquisitions of an object and their averaging at CT yields lower image noise than dose single data acquisition [5]. **Our new method uses three different cardiac phase images to reduce image noise.** While coronary CTA with prospective ECG-triggering is usually performed in the center of the mid-diastole phase, data can be acquired at the off-center of the temporal window if redundant scan time (padding) is added. We set the range and center of the phase window at 70-80% and 75% of the R-R interval, respectively.

We first generated three sets of volume data at 70-, 75-, and 80% of the R-R interval. **Next, as images at each phase were spatially misaligned, we applied non-rigid registration to align the 70- and 80% images to the 75% image.** We performed image registration with the Insight Segmentation and Registration Toolkit (ITK; [http://www.itk.org](http://www.itk.org)) and applied the ITK particle analysis tool ([BSplineDeformableRegistration module](http://www.itk.org)). This registration module includes mutual information metric and deformation field-based on the 3rd-order B-Spline function. It can perform non-rigid deformation that includes translation, rotation, and distortion. After running the registration module, the 70- and 80% images were aligned to the shape of the 75% images on a pixel-by-pixel basis.

In the last step we performed weighted averaging of the three images and generated a de-noised image. Linearly weighted averaging was with ImageJ software (National Institutes of Health, Bethesda, MD) ([http://rsb.info.nih.gov/ij](http://rsb.info.nih.gov/ij)). The weighted factor of the 75% image was 0.4; it was 0.3 for the aligned 70% and 80% images. The three multiplied images were summed using the ImageJ particle analysis tool ([ImageCalculator plugin](http://rsb.info.nih.gov/ij)), and a de-noised image was generated (Fig. 2).
Fig. 1: Outline of the multi-phase data-averaging technique. At first, three sets of consecutive volume data at the 70-, 75-, and 80% phase of the R-R interval were prepared. Next, the 70- and 80% images were aligned by non-rigid registration to the 75% image. Finally, weighted averaging of the three images was performed and a de-noised image generated.

References: Diagnostic Radiology, Hiroshima University - Hiroshima/JP
Fig. 2: A 74-year-old man with a body mass index of 26.9 kg/m². A sample transverse CT image of the ascending aorta and left main coronary artery (120 kV, 720 mA) is shown. (a) Conventional 75% image. The ROI shows CT attenuation of 372.0 HU and image noise of 24.8 HU. (b) De-noised image. The ROI shows CT attenuation of 369.2 HU and image noise of 19.2 HU.

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Patients:

Institutional review board approval was obtained for this retrospective study; informed consent was waived. We enrolled 30 patients (25 men, 5 women, median age 68 years, range, 35 - 80 years) who underwent coronary CTA with prospective ECG-triggering. If the patient's resting heart rate exceeded 65 beats per minute (bpm), we orally administered 20-40 mg of metoprolol (Selokeen) 60 min before CT examination. All had normal renal function (serum creatinine level < 1.5 mg/dL), no history of allergy to contrast agents, sinus rhythm, and a left ventricular ejection fraction of more than 40%.
CT scanning:

All coronary CTA examinations were performed using a 64-slice CT scanner (LightSpeed VCT XT scanner, GE Healthcare) with prospective ECG triggering (SnapShot Pulse). The volume of the contrast material was adapted to the patient's body weight; all patients received 0.6 ml/kg of nonionic contrast material (Iomeprol, Iomeron 350 mgI/ml) injected at a fixed duration of 10 sec followed by 20 ml of a 0.9% saline solution injected at the same flow rate as the contrast material.

The scanning parameters were as follows: detector configuration of 64 × 0.625 mm, gantry rotation time of 350 msec, tube voltage of 120 kV, and tube current of 400-750 mA. In all patients the phase window during which the patient was exposed was limited to 70-80% of the R-R interval. Axial images were reconstructed with a slice thickness and a reconstruction interval of 0.625 mm using a medium soft-tissue convolution kernel (standard).

We prepared three sets of consecutive volume data at 70-, 75-, and 80% of the R-R interval and performed multi-phase data-averaging (Fig. 1). The effective radiation dose of CTA was calculated as the product of the dose-length product (DLP) multiplied by a conversion coefficient for the chest (k = 0.017 mSv/mGycm) [6].

Quantitative analysis:

One board-certified radiologist with 8 years of experience in cardiovascular radiology calculated the contrast-to-noise ratio (CNR) in the proximal right (RCA) and left main (LMA) coronary arteries using these steps: First, attenuation in a region of interest (ROI) in the proximal RCA and the LMA was measured. The vessel contrast was calculated as the difference in mean attenuation between the contrast-enhanced vessel lumen and the adjacent perivascular tissue. Second, image noise was determined as the standard deviation (SD) of the attenuation value in an ROI placed in the ascending aorta. The CNR was calculated as the ratio of vessel contrast over noise.

Qualitative Analysis:

Two board-certified radiologists (with 8 and 17 years of experience in cardiac radiology, respectively) assessed overall image quality for each major branch of the coronary
arteries (right coronary-, left anterior descending coronary-, and left circumflex coronary artery [RCA, LAD, LCX]). If their data analysis disagreed a final decision was reached by consensus. The overall image quality of each coronary artery segment was rated on a 5-point score where 5 = excellent (no motion artifacts or noise-related blurring and excellent vessel opacification), 4 = good (minor motion artifacts or noise-related blurring, good vessel opacification); 3 = acceptable (some motion artifacts or noise-related blurring, fair vessel opacification), 2 = suboptimal (marked motion artifact or noise-related blurring, poor vessel opacification), and 1 = nondiagnostic. Images with a score of 3 or higher were considered diagnostic.

**Statistical analyses:**

We compared conventional 75%- and de-noised images for differences in our image quality parameters (image noise, CNR) using the paired t-test. The image quality score of the coronary arteries on the two image data sets was compared with the Wilcoxon signed-rank test. We looked for a linear relationship between the noise reduction rate (%) and the time (msec) for the R-R interval during the acquisition of the CT scans using the Pearson correlation coefficient. Differences were considered to be statistically significant at $p < 0.05$. 
Fig. 1: Outline of the multi-phase data-averaging technique. At first, three sets of consecutive volume data at the 70-, 75-, and 80% phase of the R-R interval were prepared. Next, the 70- and 80% images were aligned by non-rigid registration to the 75% image. Finally, weighted averaging of the three images was performed and a de-noised image generated.
**Fig. 2:** A 74-year-old man with a body mass index of 26.9 kg/m². A sample transverse CT image of the ascending aorta and left main coronary artery (120 kV, 720 mA) is shown. (a) Conventional 75% image. The ROI shows CT attenuation of 372.0 HU and image noise of 24.8 HU. (b) De-noised image. The ROI shows CT attenuation of 369.2 HU and image noise of 19.2 HU.

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Results

The mean heart rate during the acquisition of CT scans was 51.9 ± 5.1 bpm (range 45 - 63 bpm); the mean effective radiation dose was 4.9 ± 1.1 mSv.

Our quantitative image quality parameters are shown in Table 1. The mean image noise on the de-noised images was significantly lower than on conventional 75% images ($P < 0.01$). The CNR in the proximal coronary arteries was significantly higher on de-noised-than conventional 75% images ($P < 0.01$). With our method, image noise was reduced by $20.6 \pm 3.6\%$ and CNR was increased by $24.4 \pm 6.4\%$ in the proximal RCA and by $25.4 \pm 6.4\%$ in the LMA over conventional 75% images.

### Table 1. Quantitative image quality parameters

<table>
<thead>
<tr>
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<th>Conventional 75% images</th>
<th>De-noised images</th>
<th>$P$</th>
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<tbody>
<tr>
<td>Image noise (HU)</td>
<td>22.9 ± 3.0</td>
<td>18.1 ± 2.2</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>CNR in the RCA</td>
<td>18.1 ± 3.3</td>
<td>22.4 ± 3.8</td>
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<td>CNR in the LMA</td>
<td>18.0 ± 2.7</td>
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Data are the mean ± standard deviation.

RCA: right coronary artery, LMA: left main artery

Table 1

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The noise reduction rate (%) increased proportionally with the time for the R-R interval (msec) (Pearson correlation $r = 0.42$, $P = 0.02$) (Fig. 3).

**Fig. 3**: Noise reduction rate (%) increased in proportion to the time for the R-R interval (msec) (Pearson correlation, $r = 0.42$, $P = 0.02$). Since the noise reduction rate increased in proportion to the time for the R-R interval, we suggest that our method is applicable in patients with a lower heart rate.

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The mean image quality score for conventional 75%- and de-noised images was 3.9 and 4.4, respectively; the difference was significant ($P < 0.01$) (Fig. 4-6). There was substantial interobserver agreement with respect to overall image quality ($# = 0.74$). Representative cases are shown in Figs. 7 and 8.
**Fig. 7:** A 51-year-old man with a body mass index of 22.0 kg/m² who was referred for noninvasive assessment of coronary artery stent patency. The images are curved multiplanar reconstructions of the left anterior descending coronary artery. (a) Conventional 75% image. The image noise was 22.3 HU and CNR in the left main coronary artery was 19.4 and the image quality was rated as good. (b) De-noised image. The image noise was 17.4 HU and CNR in the left main coronary artery was 24.5 and the image quality was rated as excellent.

**References:** Diagnostic Radiology, Hiroshima University - Hiroshima/JP
**Fig. 8:** A 76-year-old man with atypical chest pain and risk factors for coronary artery disease. The curved multiplanar reformation shows about 75% stenosis of the proximal left anterior descending coronary artery due to atherosclerotic plaque. (a) Conventional 75% image. The image noise was 25.2 HU and CNR in the left main coronary artery was 16.3 and the image quality was rated as good. (b) De-noised image. The image noise was 20.5 HU and the CNR in the left main coronary artery was 20.1 and the image quality was rated as excellent.

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Fig. 3: Noise reduction rate (%) increased in proportion to the time for the R-R interval (msec) (Pearson correlation, $r = 0.42$, $P = 0.02$). Since the noise reduction rate increased in proportion to the time for the R-R interval, we suggest that our method is applicable in patients with a lower heart rate.
Fig. 4: Image quality score for the right coronary artery (RCA).

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Fig. 5: Image quality score for the left anterior descending coronary artery (LAD).

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Fig. 6: Image quality score for the left circumflex coronary artery (LCX).

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Conclusion

In our study, the noise reduction rate increased in proportion to the time for the R-R interval. Because a redundant temporal window (padding) was acquired in a very short time-width (70-80% of the R-R interval), there was substantial overlapping among the three data sets of 70-, 75-, and 80% images. We posit that the time width in the 70-80% of the R-R interval correlates with the extent of overlap among the three images. **When the time width in the padding was long, the overlap was small. The lower the degree of overlap, the higher was the noise reduction rate,** thus validating our results.

Our study was limited to patients with a heart rate lower than 63 bpm and in all studies we used prospective ECG-triggering. Since the noise reduction rate increased in proportion to the time for the R-R interval, **we suggest that our method is applicable in patients with a lower heart rate.** While it is feasible for patients whose heart rate is 64 bpm or higher, the noise reduction rate would be lower.

As our method facilitated an image noise reduction of approximately 20% with improved image quality, it may also allow for a radiation dose reduction at coronary CTA. Because the image noise is inversely related to the square root of the tube current [7], theoretically, **it may be possible to reduce the radiation exposure by 36% at coronary CTA with prospective ECG-triggering.**

**Limitation:**

We did not confirm the diagnostic accuracy of our coronary CTA images by comparing our findings with the reference standard, invasive coronary angiography.
References


Personal Information

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