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# CT venography after knee replacement surgery: comparison of dual-energy CT-based monochromatic imaging and single-energy metal artifact reduction techniques on a 320-row CT scanner

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## Abstract

**Background:** An optimal metal artifact reduction (MAR) technique is needed for a reliable and accurate image-based diagnosis.

**Purpose:** Using a 320-row scanner, we compared the dual-energy computed tomography (CT)-based monochromatic and the single-energy metal artifact reduction (SEMAR) techniques for CT venography (CTV) to identify the better imaging method for diagnosing deep vein thrombosis (DVT) in patients who had undergone knee replacement surgery.

**Material and Methods:** Twenty-three consecutive patients with suspected DVT after unilateral knee replacement surgery underwent dual-energy CT (135/80 kVp). Monochromatic images of 35–135 keV were generated; the monochromatic image with the best signal-to-noise ratio (SNR) of the popliteal vein near the metal prosthesis were selected. The projection data of 80 kVp were reconstructed using MAR algorithm. The mean SNR ON MAR and the best SNR ON monochromatic images were compared. Two radiologists evaluated visualization of the metal artifacts on a four-point scale where 1 = extensive artifacts, 2 = strong artifacts, 3 = mild artifacts, and 4 = minimal artifacts.

**Results:** The mean SNR was significantly higher on the MAR than the monochromatic images ($12.8 \pm 4.7$ versus $7.7 \pm 5.1$, $P < 0.01$) and the visual scores were significantly higher for MAR than monochromatic images ($2.6 \pm 0.8$ versus $1.3 \pm 0.4$, $P < 0.01$).

**Conclusion:** For CTV after knee replacement surgery, the MAR technique is superior to the monochromatic imaging technique.

## Introduction

Computed tomography venography (CTV) is useful for the diagnosis of deep vein thrombosis (DVT), a common problem that may result in life-threatening pulmonary thromboembolism after knee replacement surgery (1–6). Previous studies reported that CTV and CT pulmonary angiography are useful in patients who,

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based on clinical assessment, are at high risk for pulmonary thromboembolism (7,8). However, after knee replacement surgery, metal artifacts limit the usefulness of CTV (9). Therefore, an optimal metal artifact reduction technique that yields artifact-free images or images with the least artifacts possible is needed for a reliable and accurate image-based diagnosis.

Dual-energy CT-based monochromatic imaging and a dedicated metal artifact reduction algorithm are the principal artifact reduction techniques (10,11). Recently, a raw-data-based monochromatic imaging technique was introduced on 320-row CT scanners (12). Previous studies reported that monochromatic high keV images are useful for metal artifact reduction (13,14). The dedicated metal artifact reduction technique, the single-energy metal artifact reduction (SEMAR, Toshiba Medical Systems) algorithm, was also introduced on 320-row CT scanners and studies showed that its application significantly reduced artifacts due to various metallic objects (e.g. dental metals (15,16), metallic coils (17) and hip prostheses (18)).

To identify the best imaging method for CTV on a 320-row CT scanner in patients who had undergone knee replacement surgery we compared the quantitative and qualitative effects of the monochromatic imaging and the SEMAR technique.

## Material and Methods

This study was approved by the ethics committee of our institutions; prior written informed consent was obtained from all patients or their legal representatives.

### Patient population

Between January 2015 and January 2016, we enrolled 23 consecutive patients with suspected DVT after unilateral knee replacement surgery (4 men, 19 women; age range, 56–87 years; mean age, 76 years). Their characteristics are shown in Table 1.

### Data acquisition

Besides conventional routine CTV of the pelvis and lower extremities, sites harboring the knee prosthesis were subjected to dual energy CTV scanning on a 320-detector CT scanner (Aquilion ONE ViSION, Toshiba Medical Systems, Otawara, Japan). The dual-energy mode and a two-rotation kV-mA switching system was used. The scan parameters for dual energy CTV were: sequential acquisition; detector collimation, $320 \times 0.5$ mm; tube rotation time, 0.75 s; tube voltage, 135 and 80 kVp. Exposures of 110 and 630 mA were used because the milliampere ratio on high- and low-energy scans is fixed by the manufacturer and aims at achieving the same signal-to-noise ratio (SNR) in both scans. The displayed CT dose index was 27.7 mGy (135 kVp, 11.7 mGy; 80 kVp, 16 mGy). The scan range, including the knee joint, was 16 cm and adequate for the evaluation of the sites harboring the metal implants. Contrast medium (660 mgI/kg) was delivered over 40 s with a 20- or 22-gauge power injector (Dual Shot GX, Nemotokyorindo, Tokyo, Japan). Scanning was started automatically 240 s after contrast medium injection.

### Image reconstruction

The SEMAR technique has been reported previously (15). Briefly, an initial image is generated with standard filtered back projection (FBP). The metal devices are then segmented from this image and metal-only data are forward projected to generate a sinogram of metal-only data. The metal data points in the sinogram are replaced with interpolated values. The interpolated sinogram is reconstructed with FBP and the resulting image volume is then classified into several tissues. The classified image data are forward projected and the resulting sinogram is blended with the original sinogram to reduce metal artifacts. An image volume is reconstructed from the blended sinogram. Finally, the last image is blended with the metal devices from the first segmentation.

A flow chart of the study design and image reconstruction is shown in Fig. 1. Specific post-processing was applied to generate monochromatic images at different energy levels. Using 80-kVp and 135-kVp projection data, monochromatic images were generated in 10-keV increments in the range of 35–135 keV. The SEMAR algorithm cannot be used with the monochromatic imaging technique. The 80-kVp projection data were therefore reconstructed with SEMAR (80 kVp + SEMAR); the 135-kVp raw data were not reconstructed because low kVp scanning has been recommended for CTV (5,6,19). For the reconstruction of all axial images the image thickness and interval were 3.0 mm. The adaptive iterative reconstruction technique (AIDR 3D, Toshiba Medical Systems) was also used for reducing the noise on monochromatic and 80 kVp + SEMAR images.

**Table 1.** Patient characteristics.

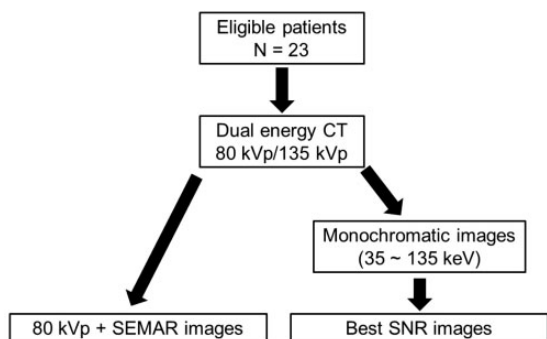| Number | Female : Male ratio | Age (years) | Surgical site Left : Right | Body weight (kg) | Height (cm) |
|---|---|---|---|---|---|
| 23 | 19 : 4 | 76 ± 7 | 13 : 10 | 59 ± 13 | 150 ± 9 |

**Fig. 1.** Flow chart of the study design. After unilateral knee replacement surgery, 23 patients underwent CTV in dual-energy mode with a two-rotation kV switching system (80 kVp and 135 kVp). The projection data of 80 kVp were reconstructed using SEMAR algorithms. Monochromatic images were generated by using 80-kVp and 135-kVp projection data.

## Quantitative evaluation

Regions of interest (ROIs) were placed in the popliteal vein near the knee prosthesis in the center of the 16-cm scan range along the z-axis. Two board-certified radiologists consensually recorded the CT attenuation (in Hounsfield units [HU]) in a circular ROI. Image noise was defined as the standard deviation (SD) in HU. The ROI placement was consistent on monochromatic- and 80 kVp + SEMAR images. The SNR of each ROI was calculated as:

$$SNR = \text{(absolute value of the CT numbers in each ROI)} / \text{image noise}$$

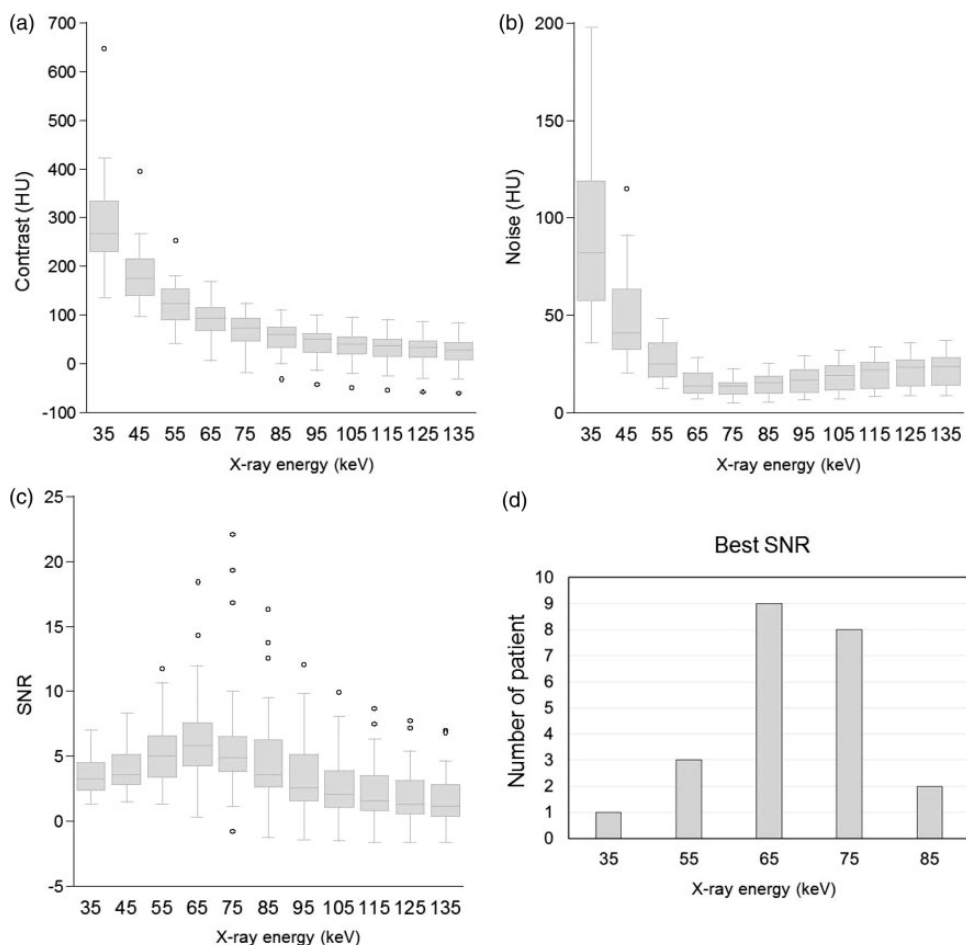To evaluate the vascular image quality, the SNR on the best 35–135 keV monochromatic image was



**Fig. 2.** (a) Graph showing the average image contrast of the popliteal vein for all patients. The mean contrast decreased as the keV value decreased. (b) Graph showing the average image noise of the popliteal vein for all patients. In the 35–75 keV range the curve sharply increased as keV decreased. Between 75 and 135 keV the curve was distributed in the bottom area and the values were relatively low. (c) Graph showing the average SNR of the popliteal vein for all patients. The highest SNR was observed at 65 keV. (d) Images with the best SNR were obtained between 35 and 85 keV; in 17 of 23 patients (73.9%) it was acquired at 65 and 75 keV.
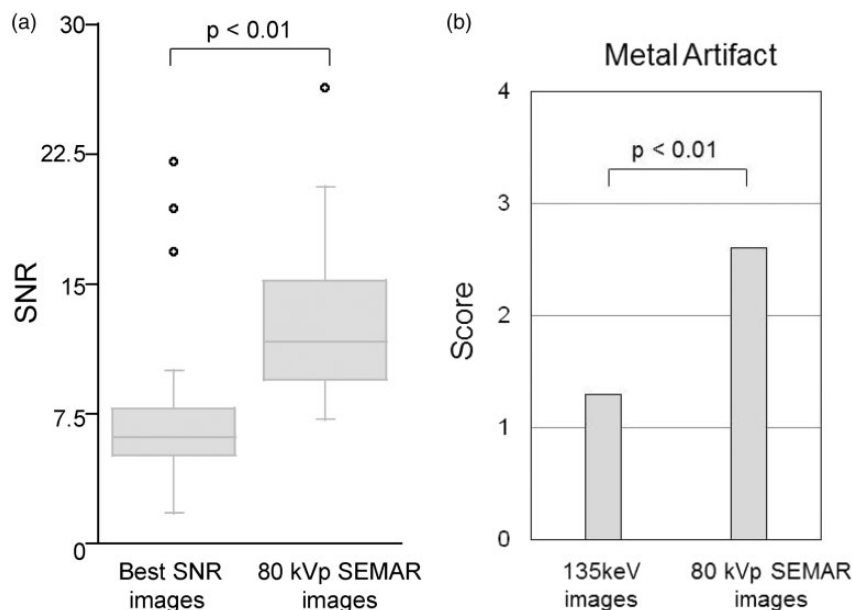
**Fig. 3.** (a) Box-and-whisker plot showing the results of our quantitative image analysis. The SNR was significantly higher on SEMAR than monochromatic images ($12.8 \pm 4.7$ vs. $7.7 \pm 5.1$, $P < 0.01$). (b) Graph showing the results of our qualitative image analysis. Better visual scores were obtained with SEMAR than monochromatic imaging ($2.6 \pm 0.8$ vs. $1.3 \pm 0.4$, $P < 0.01$).

compared with the highest SNR with the SNR on $80 \, kVp + SEMAR$ images.

## Qualitative evaluation

We visually compared $135 \, keV$– and $80 \, kVp + SEMAR$ images to assess metal artifact reduction. From among the dual-energy based monochromatic images, 135-keV images were chosen because monochromatic high keV images were reported to be useful for metal artifact reduction (13,14). All images were reviewed on an image processing workstation (Vitrea ver. 6.4, Toshiba Medical Systems) by two board-certified radiologists with 15 and 8 years of experience, respectively. We intermixed the $135 \, keV$ and the $80 \, kVp + SEMAR$ images; the readers were blinded to the reconstruction methods and the identity of the patients. Visual assessment of metal artifacts and the depiction of adjacent structures was graded as: 4 (excellent) = minimal artifacts, excellent depiction of adjacent structures, very useful diagnostic information; 3 (good) = mild artifacts, good depiction of adjacent structures, sufficient diagnostic information; 2 (fair) = strong artifacts, faint depiction of adjacent structures, limited diagnostic information; and 1 (poor) = extensive artifacts, no depiction of adjacent structures. Disagreement between the two readers was settled by a consensus review that included a third senior radiologist with 33 years of experience.

## Statistical analysis

All data are reported as the mean $\pm$ SD. The quantitative and visual evaluation results were compared using the paired Student's *t*-test and the McNemar test, respectively. The degree of agreement between the two observers performing the visual evaluation was measured using kappa statistics. All statistical analyses were carried out using the statistical software package JMP 9.0.2 (SAS Institute, Cary, NC, USA). A *P* value of $< 0.05$ was considered to be statistically significant.

## Results

### Quantitative evaluation

Among the $35–135 \, keV$ monochromatic images, the image contrast was highest on $35 \, keV–$ ($287.1 \pm 104.3$), the image noise was lowest on $75 \, keV–$ ($13.3 \pm 5.2$), and the SNR was highest on $65 \, keV$ monochromatic images (Fig. 2a–c). The highest SNR was observed on images acquired between 35 and $85 \, keV$; in 17 of the 23 patients (73.9%) the best SNR was obtained at 65 or $75 \, keV$ (Fig. 2d). The mean SNR on monochromatic images with the highest SNR was $7.7 \pm 5.1$; on $80 \, kVp + SEMAR$ images it was $12.8 \pm 4.7$ ($P < 0.01$) (Fig. 3a).
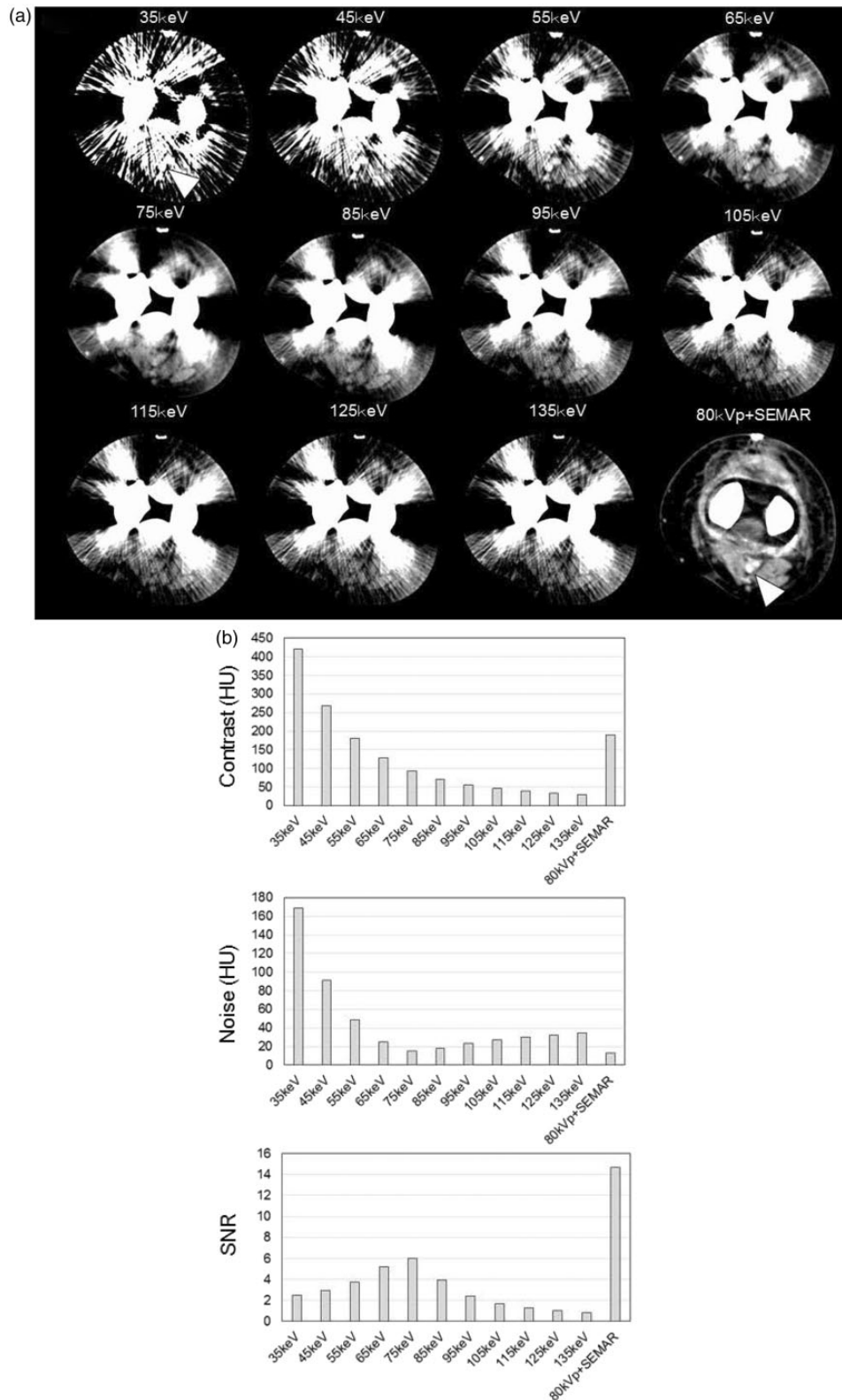
**Fig. 4.** (a) A 56-year-old woman with total knee replacement (left). Lower keV images yielded high venous contrast enhancement but at the cost of increased noise and metal artifacts (arrow head: popliteal vein). On higher keV images the metal artifact was decreased slightly; venous contrast enhancement is weak. The 80 kVp + SEMAR technique yielded metal artifact reduction and high venous contrast enhancement. (b) The results of quantitative image analysis. The highest SNR was recorded for 80 kVp + SEMAR images (14.7), followed by 75 keV reconstructions (6.0).
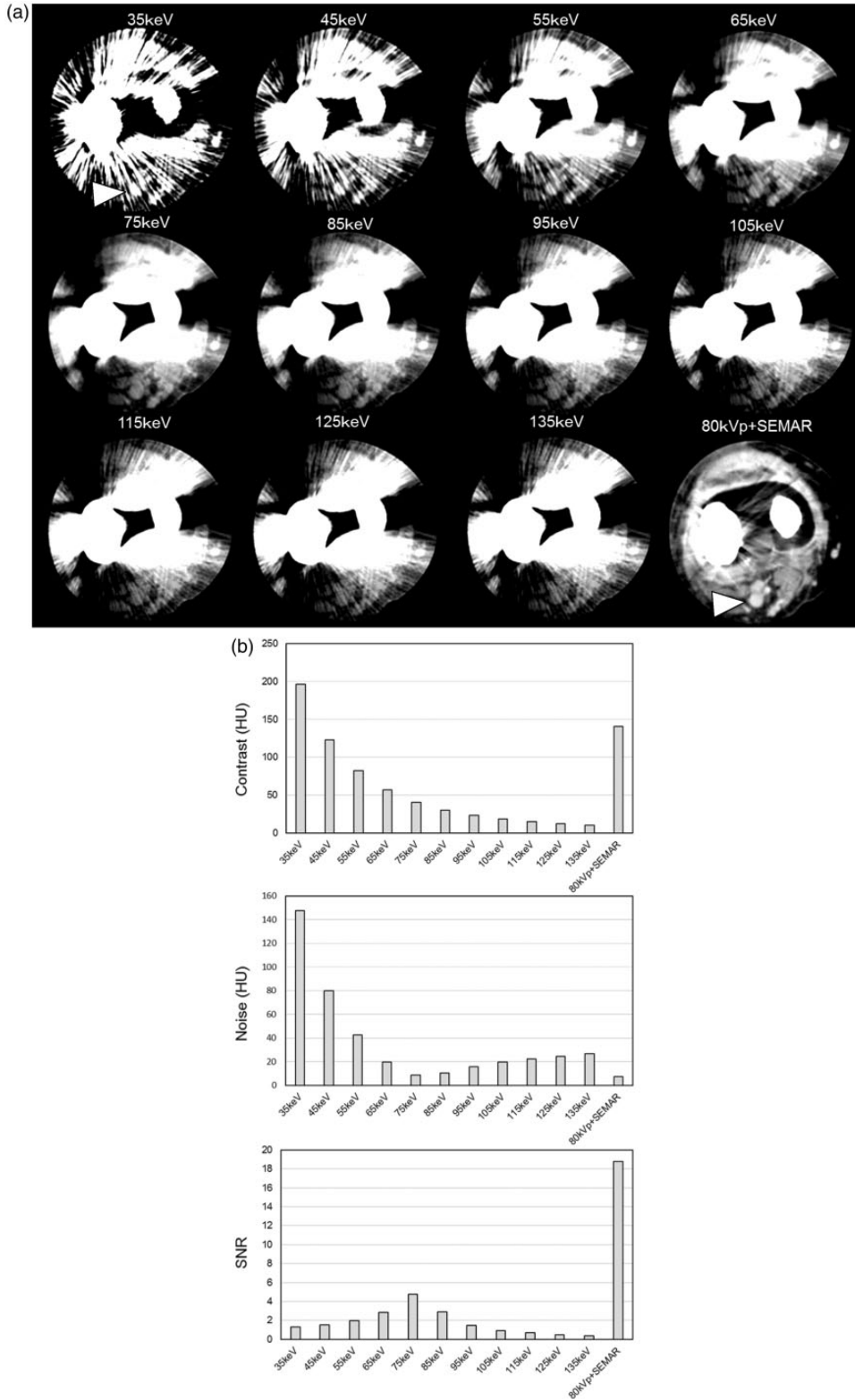
**Fig. 5.** (a) A 77-year-old woman with total knee replacement (arrow head: popliteal vein). The 80 kVp + SEMAR technique yielded metal artifact reduction and high venous contrast enhancement. (b) The results of quantitative image analysis. The highest SNR was recorded for 80 kVp + SEMAR images (SNR = 18.8), followed by 75 keV reconstructions (SNR = 4.8).

## Qualitative evaluation

Inter-observer agreement for the visual evaluation of metal artifacts was strong (kappa value $= 0.71$). The visual scores were significantly higher for SEMAR- than monochromatic images ($2.6 \pm 0.8$ versus $1.3 \pm 0.4$, $P < 0.01$) (Fig. 3b).

A representative case is shown in Figs. 4 and 5.

## Discussion

Our quantitative and qualitative image analysis showed that SEMAR is a better metal artifact reduction strategy for CTV on a 320-row CT scanner in patients with knee replacement surgery. The mean SNR was significantly higher on $80 \, \text{kVp} + \text{SEMAR}$ images than on the best monochromatic images and the visual scores for SEMAR imaging were also higher.

Monochromatic imaging may not effectively reduce metal artifacts after total knee replacement. The severity of metal artifacts depends on the thickness, density, composition, orientation, and geometry of the prosthesis [20]. A previous study reported that monochromatic imaging failed to reduce metal artifacts elicited by titanium prostheses, although it was useful for the visualization of stainless steel prostheses [21]. As artifacts from large metal masses tend to be too strong for compensation by mono-energy reconstruction of dual-energy CT images [22], the metal artifact-reducing effect of monochromatic imaging is lower in patients with large prostheses such as total knee arthroplasty or the femoral stem of total hip arthroplasty.

We found that the SNR was not better on monochromatic than $80 \, \text{kVp} + \text{SEMAR}$ images. At low keV levels, higher venous contrast enhancement can be achieved; however, this is at the cost of higher image noise and stronger metal artifacts. At high keV levels, metal artifacts can be reduced, but there is a simultaneous reduction in the signal from the iodine contrast medium. This renders a vascular diagnosis difficult. On the other hand, $80 \, \text{kVp} + \text{SEMAR}$ imaging yields a reduction in metal artifacts and high venous contrast enhancement resulting in a better SNR compared with monochromatic imaging. Recently, the monochromatic reconstruction algorithm has been modified and an advanced monoenergetic (Mono+) technique was introduced on a dual-source CT system [23,24]. It includes a regional spatial, frequency-based recombination of the high signal at lower energies and the superior noise properties at medium energies to avoid a noise increase at lower calculated energies, a drawback of virtual monoenergetic images acquired at low keV levels [24,25]. While this algorithm is not available on 320-row CT scanners, if an advanced monoenergetic technique increases the SNR on low keV images, the monochromatic imaging technique may potentially become an effective strategy for CTV in patients who had undergone knee replacement surgery.

Clinically, the $80 \, \text{kVp} + \text{SEMAR}-$ is more suitable than the dual energy technique because the latter requires a CT system capable of dual-energy acquisition and careful pre-scan planning. There is currently no consensus regarding the optimal scan parameters (such as kVp) for dual-energy metal artifact reduction protocols. Different from the dual energy technique, the radiation dose would not increase by adopting $80 \, \text{kVp} + \text{SEMAR}$ imaging. In our study, the total CT dose index for dual energy scanning was $27.7 \, \text{mGy}$ ($135 \, \text{kVp}$, $11.7 \, \text{mGy}$; $80 \, \text{kVp}$, $16 \, \text{mGy}$). By adopting the $80 \, \text{kVp} + \text{SEMAR}$ technique, the radiation dose can be reduced by 42% ($[27.7–11.7] \times 100)/27.7$.

Our study has some limitations. First, we cannot compare the diagnostic accuracy of SEMAR with monochromatic imaging because none of our patients presented with thrombosis in popliteal veins. Rather, we compared the quality of images obtained with the different techniques. Second, we did not compare the SEMAR- with images obtained with a different imaging modality such as magnetic resonance imaging or ultrasonography. Third, SEMAR and monochromatic imaging on 320-row CT scanners are vendor-specific technologies. The SNR of $80 \, \text{kVp}-$ and monochromatic images may vary among vendors and with the generation of reconstruction algorithms. Therefore, our findings cannot be extrapolated to instruments from different vendors. Finally, complete blinding of the readers to the image type was not possible because the contrast characteristics are typical.

In conclusion, with respect to 320-row CT scanners, SEMAR is a better metal artifact reduction strategy for CTV after knee replacement surgery than dual-energy CT-based monochromatic imaging.

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