Evaluation of patient positioning during digital tomosynthesis and reconstruction algorithms for Ilizarov frames: A phantom study

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Abstract

Aim: After surgery using the Ilizarov method, bone structures are better visualized using tomosynthesis. However, the bone is not always adequately observed because of the shadow created by the metallic bolt. Therefore, we evaluated the ability of tomosynthesis to reduce interference caused by metal artifacts on bone radiographs and developed an optimal image acquisition method for such cases.

Materials & Methods: The Ilizarov frame phantom for tomosynthesis was constructed using bolts placed on the bone. Distances between the bolt and bone and the angle between the bolt and X-ray tube orbit were set at three different levels. Filtered back-projection images were reconstructed using two different features of the reconstruction function: THICKNESS-- (CONTRAST4) and THICKNESS++ (METAL4); the first is suitable for improving contrast and the second is suitable for metal artifacts. The peak signal-to-noise ratio (PSNR) was used during image evaluation to determine the influence of the metallic bolt on bone structure visibility.

Results: The PSNR increased as the angle between the metal bolt and the X-ray tube orbit and the distance between the metallic bolt and bone increased. The PSNR was larger when using THICKNESS-- (CONTRAST4) than when using THICKNESS++ (METAL4).

Conclusion: The optimal reconstruction function and image acquisition determined using the metallic bolt in this study suggest that quality equal to that without the metallic bolt can be obtained.

Clinical Significance: We describe an optimized method for image acquisition without unnecessary acquisition repetition and unreasonable posture changes when the bone cannot be adequately visualized.

Keywords: digital tomosynthesis, metal artifacts, Ilizarov technique, peak signal-to-noise ratio, metallic bolt, laboratory research

Introduction

Digital tomosynthesis (DT) combines the benefits of digital imaging with those of computed tomography to provide three-dimensional (3D) structural information that can be easily implemented in conjunction with radiography using lower radiation doses at a lower cost. In contrast, DT reconstruction also involves inconsistent reconstructed images, which are limited by a low signal-to-noise ratio due to the superposition of several low-exposure projection images.[1]

The Ilizarov method has been established as a powerful technique for the management of various bone diseases and conditions. The evolutionary development of the Ilizarov method for bone lengthening and its current role have considerably improved the quality of life of millions of people worldwide.[2] Control and guidance of the bone shape-forming process remain the basis of the Ilizarov method and its evolution. Before Ilizarov surgery, patients are evaluated by plain radiography; after surgery, they are evaluated at weekly or biweekly intervals by standard plain anteroposterior and lateral radiography with acquisition of additional radiographs of the center of the distraction site.[3] Radiologists need to measure the corticotomy defect and remaining transport distance to provide an estimate of the remaining treatment days. More importantly, radiologists must evaluate the bone formed by distracting the corticotomy site, which is known as the regenerated bone.[4] However, in some cases, the bone cannot be adequately observed on radiography due to a shadow from the metallic bolt. Bone structures can be better visualized using DT during a single session because it is less affected by metal artifacts and enables the acquisition of images at any height parallel to the DT bed.

Nevertheless, even with DT, the visibility of bone structures is affected by shadows from the metallic bolt. No previous studies have reported the optimal acquisition method for such cases. Moreover, a quantitative evaluation of images including metal shadows projected at the imaging site has not yet been conducted, and there are currently no indicators to help determine the optimal imaging and reconstruction methods. Therefore, in the present study, we aimed to evaluate the use of DT for reducing the interference caused by metal artifacts on bone radiographs and to develop the optimal image acquisition method for such cases.

Materials & Methods

Phantom specifications

To evaluate the reduction of metal artifacts, we prepared a prosthetic phantom containing an artificial bone. We evaluated the Ilizarov method using this prosthetic phantom. The phantom was commercially obtained, and it contained a metallic bolt (Ilizarov, Smith & Nephew, London, UK) placed on the bone.

DT system

The DT system (Sonialvision Safire II; Shimadzu Co., Kyoto, Japan) comprises an X-ray tube filter with a 0.6-mm focal spot and a 362.8- × 362.8-mm digital flat-panel detector composed of amorphous selenium. The source-to-isocenter and isocenter-to-detector distances were 980 and 1100 mm, respectively (anti-scatter grid, focused type; grid ratio, 12:1). DT was performed linearly with a total acquisition time of 5.0 s (effective dose: 47 kVp, 1.25 mAs).

The reference radiation dose was that generally used in clinical practice (because the clinical task was to assess the Ilizarov method). To sample the projection images during a single tomographic pass (projections, 74; acquisition angle, 40 degrees) and reconstruct tomograms of the desired height, we used a 1024 × 1024 matrix with 32 bits (single-precision floating number) per image (pixel size, 0.279 mm; reconstruction interval, 1 mm).

Image acquisition

Images were evaluated using the distance, angle, and reconstruction function that are assumed by the Ilizarov method. Figure 1a-c shows an example of the distance between the metallic bolt and the bone, which was set at three different levels: 45, 65, and 85 mm. Figure 1d-f shows an example of the angle between the metallic bolt and the X-ray scanning direction, which was also set at three different angles: 10, 25, and 40 degrees. Images were acquired five times under these settings.

Reconstruction function

The reconstruction function of the filtered back-projection (FBP) method of the DT system (Sonialvision Safire II; Shimadzu Co., Kyoto, Japan) can be broadly divided into THICKNESS-- and THICKNESS++. The main difference between these two features is that THICKNESS++ is restricted compared to THICKNESS-- with regard to the position information for the height direction.

THICKNESS-- is available as five types: THICKNESS--, THICKNESS-- (CONTRAST), THICKNESS-- (CONTRAST2), THICKNESS-- (CONTRAST4), and THICKNESS-- (CONTRAST6). THICKNESS++ is also available as five types: THICKNESS++, THICKNESS++ (METAL), THICKNESS++ (METAL2), THICKNESS++ (METAL4), and THICKNESS++ (METAL6). When the number of these features increases (for example, from CONTRAST2 to CONTRAST4), the undershooting artifact around the metallic bolt, which is generated around highly absorbent materials, such as metal, is improved, and the emphasis of the edge is weakened. Therefore, we selected the reconstruction function that best suited our purpose.

THICKNESS-- (CONTRAST4) and THICKNESS++ (METAL4) are actually used clinically in our hospital; therefore, these two features were adopted. The thickness for THICKNESS-- (CONTRAST4) was 4.1 mm, and that for THICKNESS++ (METAL4) was 12.1 mm. Because we wanted to examine how the thickness of the fault affects the image, we compared -- with ++. Even if the values of -- and ++ change, the fault thickness does not change.

Evaluation

The simplest and most widely used full-reference quality metric is the mean squared error (MSE), which is computed by averaging the squared intensity differences of distorted and reference image pixels, along with the related quantity of the peak signal-to-noise ratio (PSNR). MSE and PSNR are appealing because they are simple to calculate, have clear physical meanings, and are mathematically convenient in the context of optimization.[5]

To evaluate the effects and severity of metal artifacts in each image featured in the in-focus plane, we calculated the PSNR. Image data were evaluated using Image J 1.36 (National Institutes of Health, Bethesda, MD, USA). The PSNR and MSE were calculated by the following equations:

$$\mathrm{PSNR[dB]} = 10 \cdot \log_{10} \frac{\mathrm{MAX}^2}{\mathrm{MSE}}$$

$$\mathrm{MSE} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{N} \|\mathrm{X(i)} - \mathrm{X'(i)}\|^2$$

where MAX is the dynamic range of the pixel values (in this case, 65535 for 16-bit grayscale images), i is the pixel number assigned to each pixel position, x(i) is the pixel value in the original image, and X'(i) is the pixel number in the deteriorated image.

In this study, the original image was that of the bone phantom only, and the deteriorated image was that of the bone phantom with a metallic bolt. The size of the region of interest (ROI) during the evaluation of the feature (metal artifact) and background was 10 mm × 10 mm (100 pixels). Therefore, there were 100 i, from 1 to 100.

Figure 1g and 1h shows the measurement point, its enlarged view, and its pixel value in the bone phantom only and in the bone phantom with a metallic bolt, respectively. The PSNR value in Figure 1h, calculated using Figure 1g, is 10.48.

When the difference between the two images is large, the PSNR value decreases. Typically, a PSNR value of ≥40 db makes it difficult to distinguish the deteriorated image from the original image, whereas a value of ≤20 db makes the image unacceptable.[6]

The cross-section measurement was at the center of the radius (85 mm from the top of the examination table). We set the point that split the radius into two (inside and outside, proximal, and distal). A point 30 mm away from the distal end of the radius was considered the center of the ROI.

The effects of metal artifacts on each data set were assessed by a one-way analysis of variance and multiple comparisons test (i.e., the Tukey–Kramer test).

The dependent variable was the PSNR; the independent variables were the reconstruction function, distance, and angle. A total of 15 samples without a metallic bolt and 45 samples with a metallic bolt were evaluated. Statistical analyses were performed using SPSS for Windows (version 22.0; IBM Corp., Armonk, NY, USA). $P<0.05$ was considered statistically significant.

The measurement value depended on the size of the ROI. A larger ROI indicated a larger signal change in the ROI. A smaller ROI indicated a larger measurement error in terms of statistical variation. The method of SNR determination using clinical images (AKIO OGURA)[7] indicated that the position of the ROI was selected for uniformity of the signal intensity area, and that the size of the ROI was more than 7 × 7 pixels. In this study, the diameter of the metallic bolt was 10.0 mm based on the Ilizarov method. The objective was to analyze the point with the highest influence of the shadow of the metallic bolt based on the Ilizarov method. In preliminary experiments, when the ROI size became larger than 10.0 mm, the difference between the PSNR of bone with and without the metallic bolt became smaller. However, this was not the same for a uniform phantom. Therefore, it was necessary to minimize the influence of the positional shift of the measurement point. As a result, 10- × 10-pixel (10.0 mm × 10.0 mm) ROIs were adopted.

Results

As described in the Methods section, we calculated the PSNR values by scanning at specific angles between the X-ray scanning direction and subjects (set at 10, 25, and 40 degrees) using two different phantoms: a bone phantom and a bone phantom with a metallic bolt. The results are shown in Table 1.

Reconstruction function

The PSNR value of the reconstruction function THICKNESS-- (CONTRAST4) was always higher than that of the function THICKNESS++ (METAL4). Even with the same angle and distance, using THICKNESS-- (CONTRAST4) led to more measurement points in which a significant main effect was observed. Table 2 shows the measurement points with no significant difference at an angle and distance of 40 degrees and 85 mm, respectively (40 degrees was the largest angle; 85 mm was the longest distance). Examples of images obtained with THICKNESS-- (CONTRAST4) and THICKNESS++ (METAL4) are shown in Figure 2a and 2b, respectively.

Distance

We found that the PSNR increased as the distance between the metallic bolt and the bone increased. The number of measurement points showing a significant main effect also increased as the distance between the metallic bolt and the bone increased. Table 2 shows the measurement points demonstrating that there was no significant difference in the combination of an 85-mm distance and THICKNESS-- (CONTRAST4) (85 mm was the longest distance). Examples of images obtained with THICKNESS-- (CONTRAST4), a 10-degree angle, and changes in the distance are shown in Figure 2a, 2c, and 2d.

Angle

We found that the PSNR increased as the angle between the metallic bolt and the X-ray scanning direction increased. The number of measurement points showing a significant main effect also increased as the angle between the metallic bolt and the X-ray scanning direction increased. Table 2 shows the measurement points demonstrating no significant difference in the combination of a 40-degree angle and THICKNESS-- (CONTRAST4) (40 degrees was the largest angle). Examples of images obtained with THICKNESS-- (CONTRAST4), a 45-mm distance, and changes in the angle are shown in Figure 2a, 2e, and 2f.

Images of the bone phantom alone and under optimal conditions

The highest PSNR value of the bone phantom with the metallic bolt was 26.39 with the combination of a 40-degree angle, 85-mm distance, and THICKNESS-- (CONTRAST4). Without the metallic bolt, the PSNR value was 26.73 with the combination of a 40-degree angle, no metallic bolt, and THICKNESS-- (CONTRAST4). The Tukey–Kramer test indicated no significant difference between the two combinations ($p \geq 0.05$).

Discussion

Our study showed that the reconstruction function, distance, and angle parameters are critical for obtaining the optimal imaging results for cases involving metallic bolts that cannot be removed from the scanning field.

Optimal reconstruction function

When using the FBP method, the frequency limit is set in the depth direction (Z axis). In our study, THICKNESS++ (METAL4) produced a more restricted frequency range than THICKNESS-- (CONTRAST4), indicating that it is restricted with regard to the positional information of the height direction. The use of a thinner fault thickness with THICKNESS-- (CONTRAST4) (4.1 mm) than with THICKNESS++ (METAL4) (12.1 mm) reduced the size of the high-absorption component (the metallic bolt part). Therefore, the PSNR increased by changing the reconstruction function from THICKNESS++ (METAL4) to THICKNESS-- (CONTRAST4) using the same angle and distance. For cases in which metallic bolts cannot be removed from the scanning field, the bone can be clearly seen by using the reconstruction function THICKNESS-- (CONTRAST4). In contrast, because THICKNESS++ (METAL4) provides a much more restricted frequency range than THICKNESS-- (CONTRAST4), it improves the undershooting artifacts around the metallic bolt.

The reduction of artifacts is a distinctive advantage of our method. When using DT, artifacts occur as very low signals along the scanning direction around the edges of highly attenuating materials, such as metal prostheses or osteosynthetic materials. These artifacts are predominantly caused by a mismatch between the assumptions of the reconstruction algorithm (ideal monochromatic beam) and reality (wide spectral range). The limited scanning angle (in this study, 40 degrees) also contributes to this effect, but to a much lesser extent. When observing the area around the metallic bolt, a clearer image was obtained using THICKNESS++ (METAL 4) rather than THICKNESS-- (CONTRAST4). With DT, images of various reconstruction functions can be obtained from the imaged data, and it is unnecessary to repeat the acquisition. Therefore, when bolts cannot be placed outside the scanning field, the images should be reconstructed using THICKNESS-- (CONTRAST4). However, when the observation is performed near the metallic bolt, the images should be reconstructed using THICKNESS++ (METAL4).

Optimal image acquisition

The degradation of CT images occurs due to the interaction between the polyenergetic X-ray beam and dense structures, thus creating two distinctive effects. The first effect is generalized noise proportional to the overall amount of metal present on the axial slice. It is seen as a fine, dark, bright streak on the image. In this case, the artifact is distributed fairly and proportionately across the image. The second effect, which is due to pairing between the rods and struts, causes a more noticeable broad dark streak with surrounding bright edges and is a function of the helical manner in which the scan is acquired.

Figure 3a shows the relationship among the X-ray tube, external fixture, and X-ray detector for helical CT, and an example of metallic bolt projection on a helical CT image. During the CT scanning process, the source completes a full rotation because it must scan the metallic bolt.[8] Therefore, the bone cannot be adequately observed because of the shadows created by the metallic bolt.

DT image quality depends on numerous factors, such as the size, shape, density, atomic number, and position of the metal objects, as well as the size and shape of the object's cross-section. Particularly for implants manufactured from metals (e.g., titanium), the effects of beam hardening and scatter are high; hence, noise-induced streaking artifacts primarily affect image quality. During image acquisition with DT, the acquisition angle is 40 degrees. If bolts cannot be removed from the scanning field, then the DT scan enables one to observe the bone without metal artifacts (Figure 3b). Nevertheless, even with DT, the visibility of bone structures is affected by artifacts from the metallic bolt, thereby adversely affecting image quality. In these cases, dispersing the influence of the metallic bolt appears to be a promising approach to reducing artifacts stemming from metals with a relatively high atomic number.

In our study, when the distance between the metallic bolt and bone increased, the metal bolt artifact was dispersed in the vertical direction (X-ray scanning direction) as the angle between the metallic bolt and X-ray scanning direction increased. As a result, the metal artifact was reduced and the PSNR increased.

Therefore, the metal shadows dispersed and the PSNR increased when the distance between the metallic bolt and bone increased, and when the angle between the metallic bolt and X-ray tube orbit increased. The angle between the metallic bolt and X-ray scanning direction should be larger, even in actual clinical practice; however, it is usually limited. In the case of the Ilizarov method used for the lower leg, considering the bed width in the present study, an angle of 40 degrees was a limitation.

Conclusions

In the case of phantoms with metallic bolts, the PSNR was highest (26.39) with the following conditions: THICKNESS-- (CONTRAST4), 85-mm distance, and 40-degree angle. Using the function THICKNESS-- (CONTRAST4), the PSNR without a metallic bolt was 26.73.

The Tukey–Kramer test showed no significant differences between the following conditions: [THICKNESS-- (CONTRAST4)/no metallic bolt/40-degree angle] and [THICKNESS-- (CONTRAST4)/85-mm distance/40-degree angle] ($p < 0.05$). Therefore, to accurately describe findings and identify potential obstacles that arise during treatment, it is suggested that one should maintain the same quality without the metallic bolt. For external fixation with the Ilizarov method, radiologists do not need to perform repeated imaging because one-time imaging with DT may provide an optimal image. Because DT is based on the angle, using angles such as pronation or supination in the reference line or the angle of the measurement site with respect to the DT bed can lower the risk of interference caused by the skills of the radiologist. This suggests that images with high reproducibility can always be obtained as an output.

One limitation of our study was the image quality assessment. Sometimes, the PSNR is not very well-matched to the perceived visual quality.[9–12] Although efforts are being made to produce an objective scoring system to assess the quality of digital images in general, to our knowledge, no such score currently exists for radiography. Therefore, we performed an evaluation using the PSNR, which is, at present, considered an optimal full-reference quality metric.

Clinical Significance

Because our method was based on the measurement of the distance between the metallic bolt and bone using a plain radiograph, it helped to set the angle between the metallic bolt and X-ray scanning direction, which enabled us to obtain an image equivalent to the one without the metallic bolt. The use of this method can provide optimal images without positional changes, without unreasonable posture changes, and during a single acquisition session (without unnecessary repetition of image acquisition), which can greatly benefit patients.

Conflict of interest

There are no conflicts of interest to declare.

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Figures and legends

Fig. 1: Phantom setup and determination of regions of interest.

a-c Lateral view of the examination table. The distance between the metallic bolt and bone was set at 45 mm (**a**), 65 mm (**b**), and 85 mm (**c**). **d-f** Vertical view of the examination table. The angle between the metallic bolt and X-ray scanning direction was set at 10 degrees (**d**), 25 degrees (**e**), and 40 degrees (**f**). The measurement point, its enlarged view, and corresponding pixel value in the case of the bone phantom only (**g**). The bone phantom with a metallic bolt and the PSNR value (calculated using **g**) is 10.48 (**h**). ROI, region of interest.

Fig. 2: Examples of digital tomosynthesis images

(**a**) Images acquired at a 10-degree angle and 45-mm distance using THICKNESS-- (CONTRAST4). The peak signal-to-noise ratio (PSNR) was 12.55. (**b**) Image acquired at a 10-degree angle and 45-mm distance using THICKNESS++ (METAL4). The PSNR was 10.48. (**c**) Image acquired at a 10-degree angle and 65-mm distance using THICKNESS-- (CONTRAST4). The PSNR was 17.11. (**d**) Image acquired at a 10-degree angle and 85-mm distance using THICKNESS-- (CONTRAST4). The PSNR was 19.82. (**e**) Image acquired at a 25-degree angle and 45-mm distance using THICKNESS-- (CONTRAST4). The PSNR was 17.01. (**f**) Image acquired at a 40-degree angle and 45-mm distance using THICKNESS-- (CONTRAST4). The PSNR was 20.07.

Fig. 3: (**a**) Helical nature of the computed tomography scanning process. (**b**) Digital tomosynthesis scanning process.

Tables

Table 1: Average peak signal-to-noise ratio values obtained using digital tomosynthesis reconstruction algorithms

10-degree angle between the metallic bolt and X-ray scanning direction		
Distance/reconstruction function	THICKNESS-- (CONTRAST4)	THICKNESS++ (METAL4)
Only phantom	27.90	32.02
45 mm	12.22	8.73
65 mm	17.03	12.07
85 mm	19.64	15.12
25-degree angle between the metallic bolt and X-ray scanning direction		
Distance/reconstruction function	THICKNESS-- (CONTRAST4)	THICKNESS++ (METAL4)
Only phantom	25.09	29.24
45 mm	16.63	13.06
65 mm	19.01	16.35
85 mm	23.24	22.90
40-degree angle between the metallic bolt and X-ray scanning direction		
Distance/reconstruction function	THICKNESS-- (CONTRAST4)	THICKNESS++ (METAL4)
Only phantom	26.73	32.79
45 mm	19.59	17.63
65 mm	23.10	22.45
85 mm	26.39	24.14

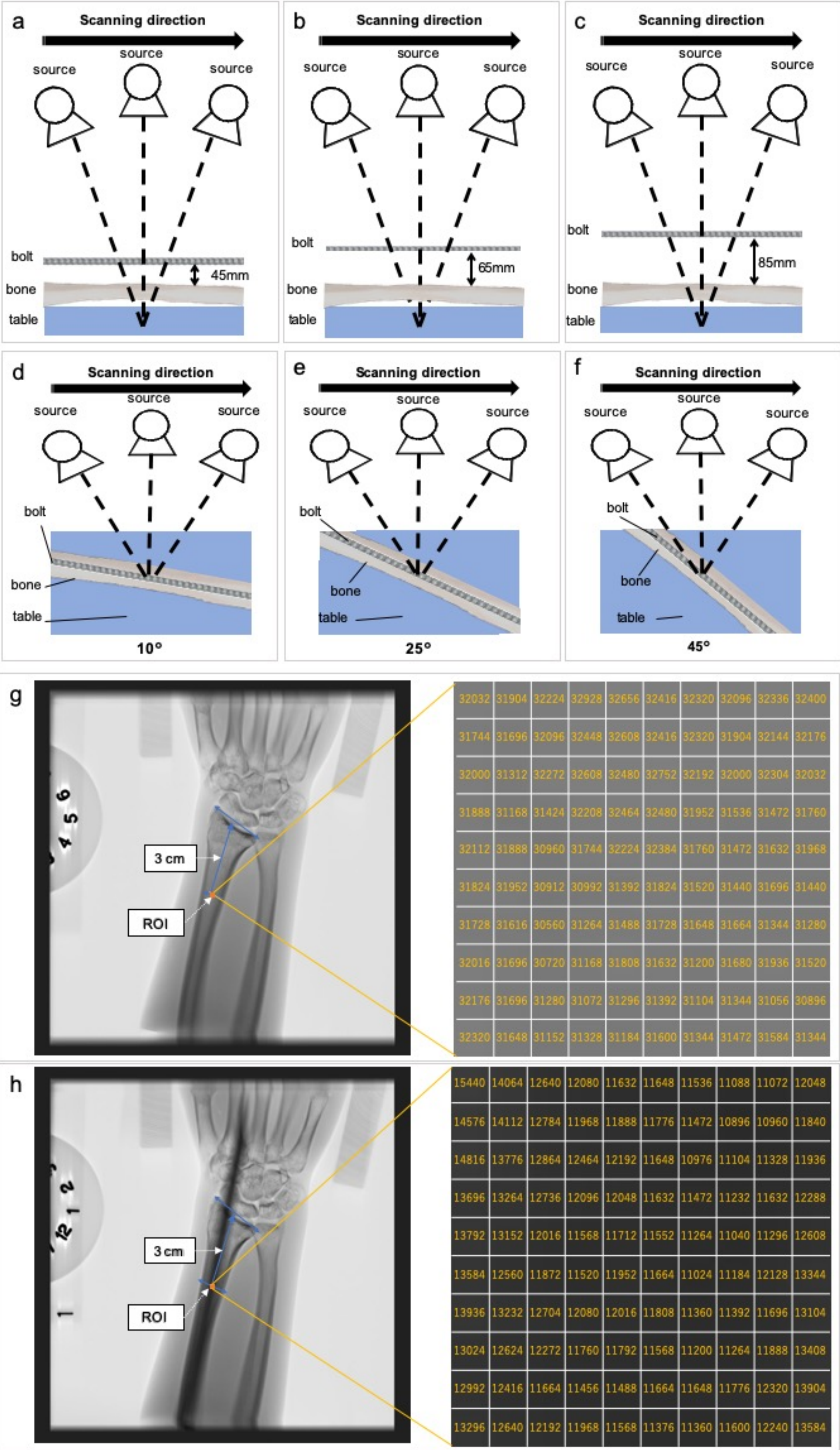
Table 2: Results of the multiple comparison analysis (Tukey–Kramer method)

	40 degrees, 85 mm, THICKNESS-- (CONTRAST4)	40 degrees, 85 mm, THICKNESS++ (METAL4)	40 degrees, 65 mm, THICKNESS-- (CONTRAST4)	25 degrees, 85 mm, THICKNESS-- (CONTRAST4)
10 degrees, 85 mm, THICKNESS-- (CONTRAST4)	[a]	[a]	n.s.	n.s.
25 degrees, 65 mm, THICKNESS-- (CONTRAST4)	[a]	[a]	n.s.	n.s.
25 degrees, 85 mm, THICKNESS-- (CONTRAST4)	n.s.	n.s.	n.s.	—

40 degrees, 45 mm, THICKNESS-- (CONTRAST4)	a	a	n.s.	n.s.
40 degrees, 65 mm, THICKNESS-- (CONTRAST4)	n.s.	n.s.	—	n.s.
40 degrees, 85 mm, THICKNESS-- (CONTRAST4)	n.s.	—	n.s.	n.s.
25 degrees, 85 mm, THICKNESS++ (METAL4)	a	n.s.	n.s.	n.s.

40 degrees, 65 mm, THICKNESS++ (METAL4)	n.s.	n.s.	n.s.	n.s.
40 degrees, 85 mm, THICKNESS++ (METAL4)	n.s.	—	n.s.	n.s.

n.s.: no significant difference. [a]$p < 0.05$.



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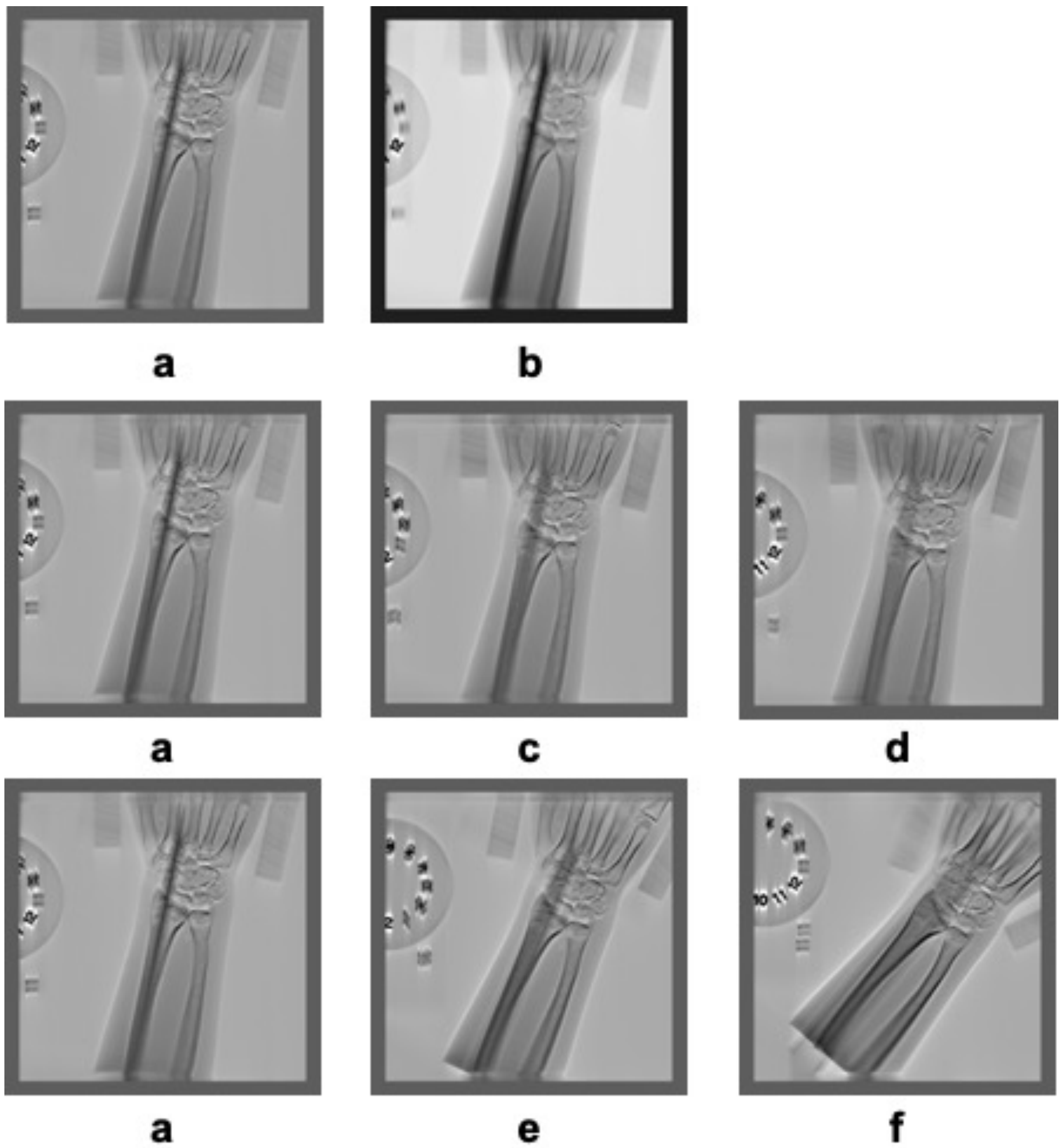
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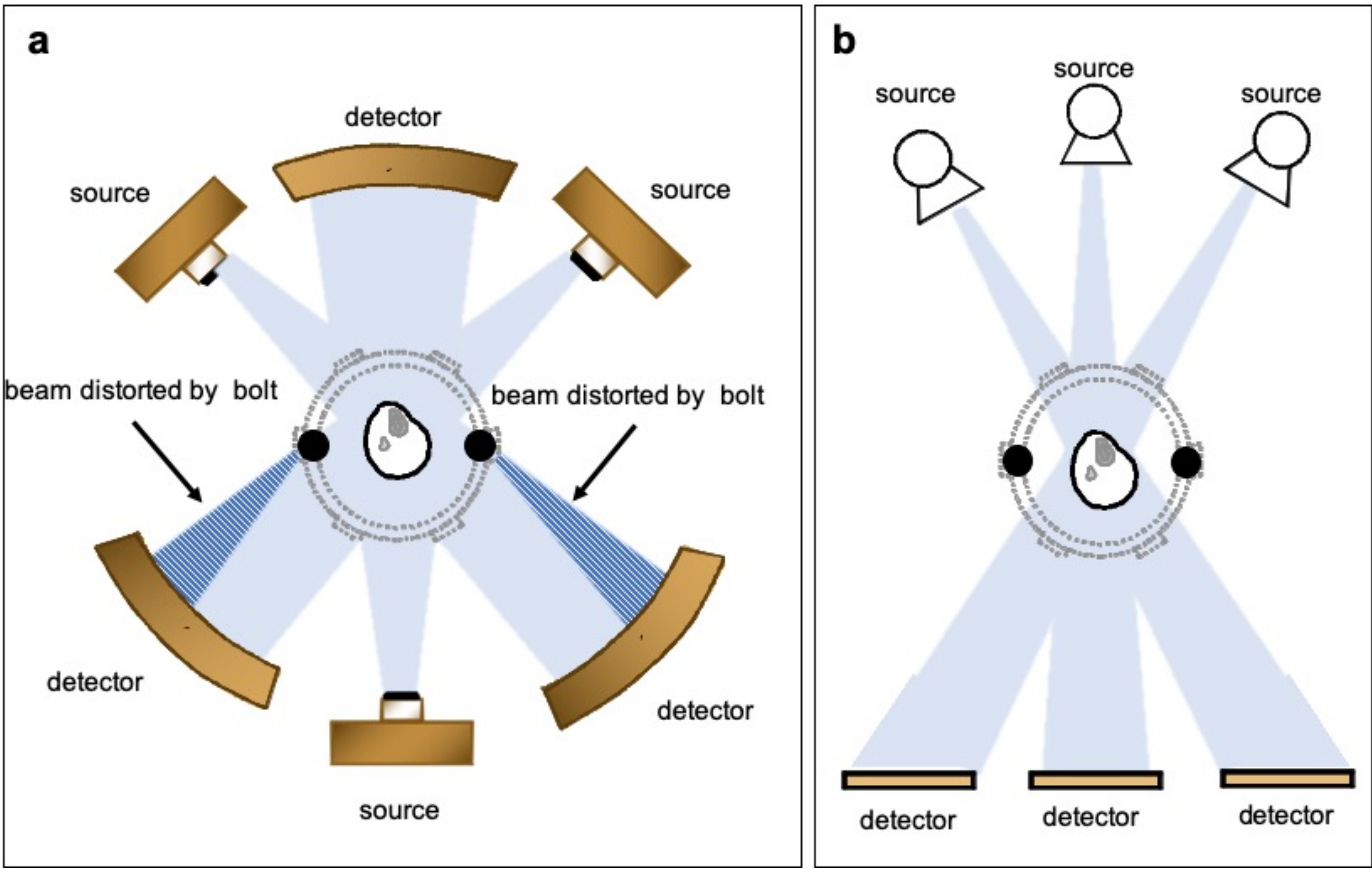
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Figure Legends

Fig. 1: Phantom setup and determination of regions of interest.

a-c Lateral view of the examination table. The distance between the metallic bolt and bone was set at 45 mm (**a**), 65 mm (**b**), and 85 mm (**c**). **d-f** Vertical view of the examination table. The angle between the metallic bolt and X-ray scanning direction was set at 10 degrees (**d**), 25 degrees (**e**), and 40 degrees (**f**). The measurement point, its enlarged view, and corresponding pixel value in the case of the bone phantom only (**g**). The bone phantom with a metallic bolt and the PSNR value (calculated using **g**) is 10.48 (**h**). ROI, region of interest.

Fig. 2: Examples of digital tomosynthesis images

(**a**) Images acquired at a 10-degree angle and 45-mm distance using THICKNESS-- (CONTRAST4). The peak signal-to-noise ratio (PSNR) was 12.55. (**b**) Image acquired at a 10-degree angle and 45-mm distance using THICKNESS++ (METAL4). The PSNR was 10.48. (**c**) Image acquired at a 10-degree angle and 65-mm distance using THICKNESS-- (CONTRAST4). The PSNR was 17.11. (**d**) Image acquired at a 10-degree angle and 85-mm distance using THICKNESS-- (CONTRAST4). The PSNR was 19.82. (**e**) Image acquired at a 25-degree angle and 45-mm distance using THICKNESS-- (CONTRAST4). The PSNR was 17.01. (**f**) Image acquired at a 40-degree angle and 45-mm distance using THICKNESS-- (CONTRAST4). The PSNR was 20.07.

Fig. 3: (**a**) Helical nature of the computed tomography scanning process. (**b**) Digital tomosynthesis scanning process.