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FULL PAPER

Tomosynthesis can facilitate accurate measurement of joint space width under the condition of the oblique incidence of X-rays in patients with rheumatoid arthritis

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Objective: Accurate evaluation of joint space width (JSW) is important in the assessment of rheumatoid arthritis (RA). In clinical radiography of bilateral hands, the oblique incidence of X-rays is unavoidable, which may cause perceptional or measurement error of JSW. The objective of this study was to examine whether tomosynthesis, a recently developed modality, can facilitate a more accurate evaluation of JSW than radiography under the condition of oblique incidence of X-rays.
Methods: We investigated quantitative errors derived from the oblique incidence of X-rays by imaging phantoms simulating various finger joint spaces using radiographs and tomosynthesis images. We then compared the qualitative results of the modified total Sharp score of a total of 320 joints from 20 patients with RA between these modalities.
Results: A quantitative error was prominent when the location of the phantom was shifted along the JSW direction. Modified total Sharp scores of tomosynthesis images were significantly higher than those of radiography, that is to say JSW was regarded as narrower in tomosynthesis than in radiography when finger joints were located where the oblique incidence of X-rays is expected in the JSW direction.
Conclusion: Tomosynthesis can facilitate accurate evaluation of JSW in finger joints of patients with RA, even with oblique incidence of X-rays.
Advances in knowledge: Accurate evaluation of JSW is necessary for the management of patients with RA. Through phantom and clinical studies, we demonstrate that tomosynthesis may achieve more accurate evaluation of JSW.

INTRODUCTION

Rheumatoid arthritis (RA) is a chronic inflammatory disorder caused by autoimmunity. RA causes progressive joint damage of the affected joint. Cartilage thinning is one effect of this progressive joint damage.[1,2] Although cartilage thinning is revealed as joint space narrowing (JSN) in diagnostic imaging, the first radiographic sign of RA in relation to joint space width (JSW) is widening. JSW can therefore be an indirect index used to assess the degree of cartilage damage and hence the progression of RA.[3–5] The accurate detection of JSW is thus very important and is linked to an accurate evaluation of the progression of RA, which leads to correct diagnosis and proper treatment of RA in each patient.

The evaluation of joint destruction such as JSN in patients with RA has traditionally been performed using radiography. However, radiography has low sensitivity for the detection of early joint destruction because the three-dimensional joint structure is projected onto a two-dimensional image. CT is used for more accurate evaluation of joint destruction but has disadvantages

such as high exposure of radiation.[6–8] CT, therefore, is not a first-line examination, and although the continued use of radiographs in RA is debated, it is still recommended to acquire a baseline radiograph. Because tomosynthesis, a recently developed modality, is superior to radiography for the evaluation of overlapping structure such as intercarpal joints with lower radiation exposure than CT, it is expected to be applied to joint destruction evaluation,[9–12] although the accuracy of measurement of JSN with tomosynthesis has not yet been validated.

In the clinical evaluation of JSN caused by RA using radiography or tomosynthesis, bilateral hand joints are exposed simultaneously.[13] It is therefore impossible to match all the affected joints to the centre of the incident X-ray beam in a patient with RA with multiple affected joints. When the centre of the incident X-ray beam does not coincide with the target joint, detected JSW in the projected image contains perceptional or measured errors caused by bony overlap resulting from the oblique incidence of the X-rays.[14,15] Although this phenomenon is unavoidable clinically, to the best of our knowledge, the assessment of the effects caused by the oblique incidence of X-rays has not yet been performed. We therefore performed an assessment using phantoms simulating joints for radiography and tomosynthesis.

Firstly, concerning the effect of phantom position against the centre of the incident X-ray beam in terms of error, is the error more prominent when the phantom is shifted parallel or vertical to the JSW direction? Secondly, concerning the errors caused by the oblique incidence of X-rays, which modality is more correct? And, is the measured value overestimated or underestimated when the phantom is located at a distance from the centre of the incident X-ray beam?

Clinical images of patients with RA are scored by rheumatologists or radiologists using a scoring system such as the modified total Sharp score in radiography. The quantification of destructive lesions in RA is made based on this score.[16,17] Although misinterpretation of JSW in projected images resulting from the oblique incidence of X-rays may affect the score, the details of these errors are unknown in both modalities. We therefore conducted a clinical study to compare the scoring results between radiography and tomosynthesis. We hypothesized that by analyzing the results of phantom and clinical studies, we could determine the modality that can better suppress the perceptional or measured error of JSW caused by the oblique incidence of X-rays. This will help in realizing an accurate evaluation of the progression of RA and the determination of an appropriate treatment strategy.

The objective of this study was therefore to examine whether tomosynthesis, a recently developed modality, facilitates a more accurate evaluation of JSW than radiography, a traditional method, considering the oblique incidence of X-rays. In doing so, we hope to make clear the relationship between the quantitative error in a phantom study to that of scoring discrepancies in clinical images between radiography and tomosynthesis.

METHODS AND MATERIALS

Phantom study

Phantom and imaging setups

We prepared four phantoms, each simulating different sizes of joint space, 0.5, 1.0, 2.0 and 3.0 mm, and obtained phantom images in both radiography and tomosynthesis. The phantom was made with titanium medical apatite (TMA). TMA is a recently introduced material which can be processed more easily than hydroxyapatite. Its CT value (Hounsfield unit) is nearly equal to that of the cortical bone.[18] In this study, JSWs reproduced by the phantom were determined based on the data of JSW of metacarpophalangeal (MP) and proximal interphalangeal (PIP) joints in patients with RA suggested by Goligher et al[19] [mean (95% confidence interval) values of 1.64 (1.58 and 1.70) for males and 1.31 (1.25 and 1.38) for females]. The phantom was U-shaped, curved from a cube with one side 12 mm (Figure 1), although the actual anteroposterior diameter of the metacarpal or phalangeal bones at MP and PIP joints was not available in the literature.

The X-ray instrument and flat panel detector system used in this study were RADspeed (Shimadzu Corporation, Kyoto, Japan) and CALNEO C Wireless 1417S SQ (Fujifilm Corporation, Tokyo, Japan), respectively. The tomosynthesis instrument was a SONIALVISION Safire II (Shimadzu Corporation, Kyoto, Japan). Imaging parameters of radiography and tomosynthesis are shown in Tables 1 and 2, respectively.

Position of the phantom

Each of the 4 phantoms were placed and imaged using radiography and tomosynthesis in 16 different intersection positions of 4

Figure 1. The design drawing of the titanium medical apatite (TMA) phantom and design drawing of the U-shaped TMA phantom (joint space width of 3.0 mm). Arrows indicate shallow grooves created to serve as a marking for measurement on both sides of the phantom parallel to and at a distance of 3 mm from the surface of the phantom.

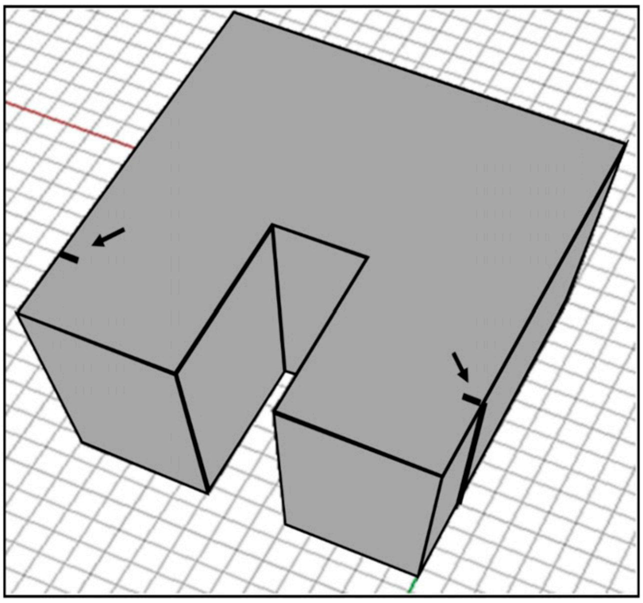


Table 1. Imaging parameters of radiography

Imaging parameters	
Tube voltage	50 kV
Tube current	100 mA
Exposure time	20 ms
SID	100 cm

SID, source-to-image distance.

rows and 4 columns in a square area with one side 11.4 cm. In the first position, the joint space coincided with the centre of the incident X-rays; in other positions, it was off the centre of incident X-rays, as shown in Figure 2. Here, the centre of the light field was regarded as the centre of the incident X-ray beam. To ensure reproducibility, the phantom positions were set by using a dedicated acrylic sheet (15.5 × 6.8 cm). The centre-to-centre distance of two neighbouring positions was 3.35 cm. The row and column direction in this study was defined as vertical and parallel to the direction of the long axis, respectively, of the examination bed. The direction of the long axis of the examination bed was parallel to that of the X-ray tube axis in radiography and sweep direction in tomosynthesis, as shown in Figure 2. We also defined JSW direction as the direction parallel to the joint width in the phantom. JSW direction in the phantom was set parallel and vertical to the X-ray tube axis in radiography and sweep direction in tomosynthesis (Figure 3).

Joint space width measurement and analyses

JSWs in each phantom position were measured by image analysis software, ImageJ (National Institutes of Health, Bethesda, MD). JSWs in each phantom position were determined on the basis of full width at half maximum of joint space signal in the profile curve depicted by ImageJ. The "select" line suggested by the white arrow in Figure 3 to provide the profile curve was carefully drawn to be parallel to the JSW direction.

Table 2. Imaging parameters of tomosynthesis

Imaging parameters	
Tube voltage	47 kV
Tube current–exposure time product	2.50 mAs
Added filter	0.2 mm Cu + 0.9 mm Al
SID	110 cm
Frame rate	15 fps
Resolution	1028 × 1028
Exposure time	5.0 s
Number of projections	74
Sweep angle	40°
Reconstruction filter	Thickness++(Metal2)
Reconstruction pitch	2.0 mm

fps, frames per second; SID, source-to-image distance.
Thickness ++ (Metal 2) is one of the reconstruction filters installed in a tomosynthesis instrument made by SHIMADZU, Kyoto, Japan. By using this particular filter, reconstruction images with high signal-to-noise ratio can be obtained.

After JSWs were measured for 4 phantoms in 16 positions and 2 directions (parallel and vertical to the X-ray tube axis in radiography and sweep direction in tomosynthesis) using radiography and tomosynthesis, the errors in the measurement of JSW were calculated. In this study, the measured value of JSW in radiography at the centre of the incident X-ray beam (position 1 in Figure 2) was used as the gold standard of JSW because radiography has a high level of accuracy and precision in measurements of JSW in the centre of the incident X-ray beam.[20]

$$\begin{aligned}\text{Error} = {} & (\text{measured value using radiography or tomosynthesis} \\ & \text{at various positions and directions}) \\ & - (\text{measured value using radiography} \\ & \text{at the centre of the X-ray beam})\end{aligned}$$

We then determined the positional effect, to generate the error caused by the oblique incidence of the X-rays. Is the magnitude of error altered when it is located at a distance from the centre of the incident X-ray beam? Is it affected by JSW direction against the row or column? We also evaluated the tendency of the error caused by the oblique incidence of the X-rays. Is the measured value overestimated or underestimated when it is located at a distance from the centre of the incident X-ray beam? Is the magnitude of the error related to the degree of the oblique incidence of the X-rays? Is it affected by the JSW size?

Clinical study

Patients

This study, which met the requirements of our institutional review board for a retrospective observational study, included 20 consecutive patients (6 males and 14 females; median age, 65 years; age range, 32–88 years), who were assessed and imaged between July 2012 and October 2012. At the time of entry, all patients fulfilled the American College of Rheumatology's 1987 or 2010 diagnostic criteria for RA. The median symptom duration of the patients was 23 months (range, 2–576 months). Tomosynthesis of the hands was performed an average (standard deviation) of 14.0 (17.7) days after hand radiography. Each patient received a disease-modifying antirheumatic drug such as methotrexate, according to disease activity for the treatment of RA.

Assessment of score in clinical images

Radiographs and tomosynthesis images of 320 finger joints (MP joint and PIP joint of the second–fifth fingers in both hands) of 20 patients with RA were randomly ordered and scored using the Sharp–van der Heijde scoring method[17] by two rheumatologists (Hk and Ys) with more than 20 (Hk) and 7 (Ys) years' experience in the radiographic assessment of arthritis. The readers were blinded to clinical information and independently scored the images. Rheumatologists Hk and Ys routinely use radiographs and tomosynthesis images to evaluate patients with RA at the Department of Rheumatology, NTT Sapporo Medical Center, Sapporo, Japan. The principles of the Sharp–van der Heijde scoring method for

Figure 2. The phantom setting position: the row and column direction with 16 phantom positions. The direction of the long axis of the examination bed was parallel to that of the X-ray tube axis in radiography and sweep direction in tomosynthesis. Phantom positions are shown as numbers in circles (a). Phantoms were placed in 16 square pits in the acrylic pedestal. In the first position (number 1 in circle), the joint space coincided with the centre of the incident X-rays; in other positions, it was off the centre of incident X-rays. The angles at which the X-ray beam hit the phantoms are shown for the fourth and ninth position (circled numbers 4 and 9) as examples. The bird's eye views of 16 phantom positions are also shown when the joint space width (JSW) direction is parallel (b) and vertical (c) to the X-ray tube axis or sweep direction in tomosynthesis. Each phantom was placed in the 16 positions with 2 directions. The incident angle of X-ray beam in each position is shown in (d).

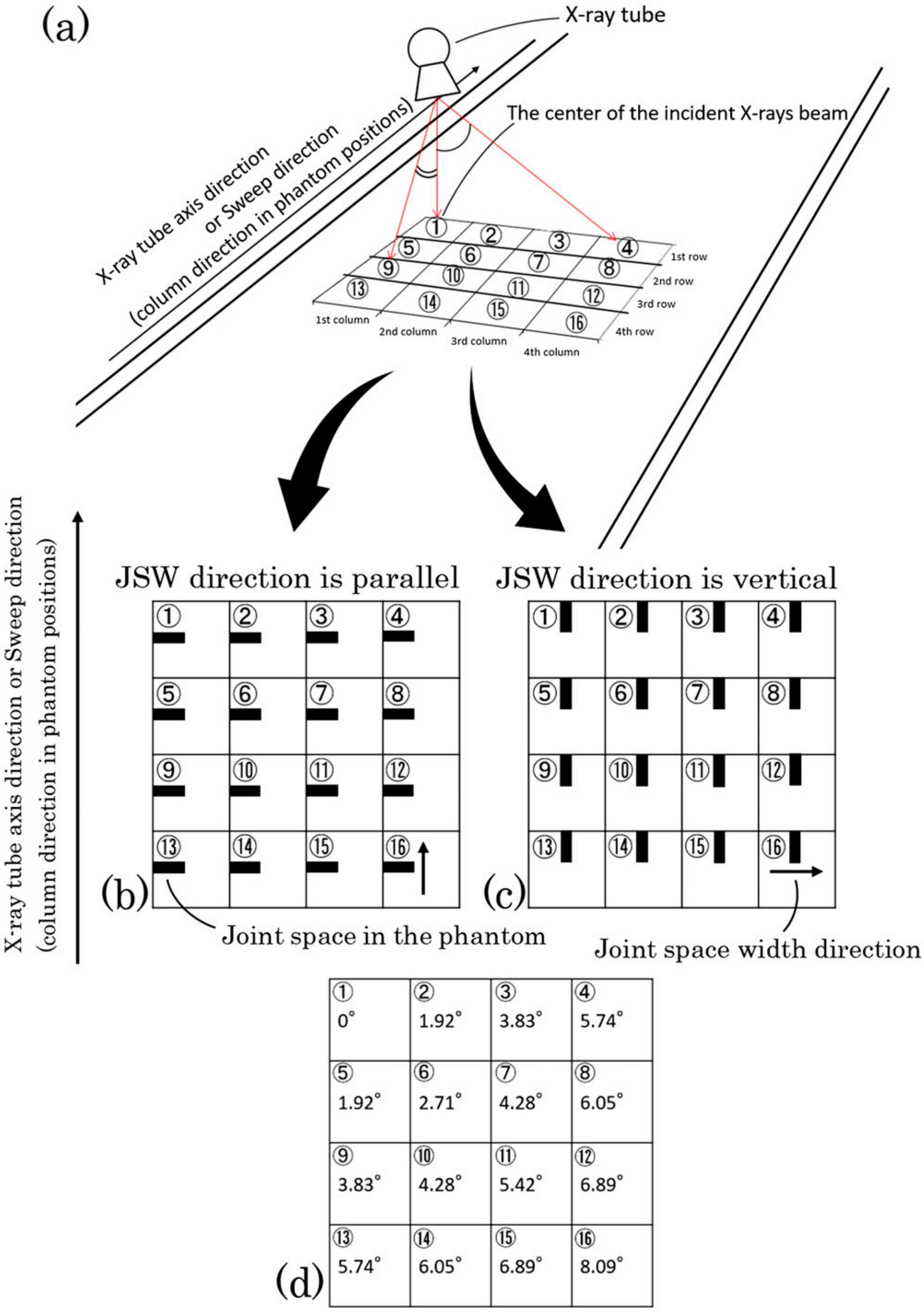
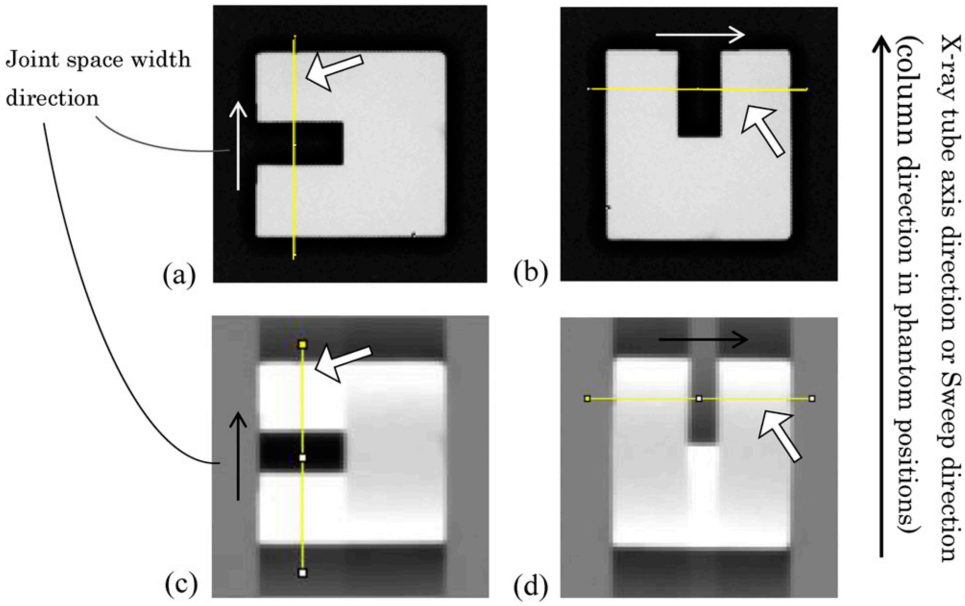


Figure 3. Joint space width (JSW) directions in the phantom in relation to the direction of the column: (a) JSW direction; parallel to the column in radiograph, (b) JSW direction; vertical to the column in radiograph, (c) JSW direction; parallel to the column in the tomosynthesis image and (d) JSW direction; vertical to the column in the tomosynthesis image. We defined the JSW direction as the direction parallel to the joint width in the phantom. JSW direction in the phantom was set parallel and vertical to the row and column. Examples of JSW direction are demonstrated with parallel (a, c) and vertical (b, d) to the column. Arrows indicate the line for joint space measurement.



the assessment of wrist and hand radiographs and tomosynthesis images were applied, with a JSN score ranging from 0 to 4. Individual joint space was given a score of 1 when focal or doubtful, a score of 2 or 3 when JSW >50% or <50% original joint space, respectively, and a score of 4 when ankylosis or complete luxation was observed. We evaluated the difference

Table 3. Positional effect of phantom to generate errors

Imaging modality		Radiography	Tomosynthesis
Parallel JSW direction			
ANOVA		0.000	0.000
Multiple comparison	1 *vs* 2 row	0.736	0.933
	1 *vs* 3 row[a]	0.007	0.043
	1 *vs* 4 row[a]	0.000	0.000
	2 *vs* 3 row	0.103	0.163
	2 *vs* 4 row[a]	0.000	0.000
	3 *vs* 4 row[a]	0.034	0.033
Vertical JSW direction			
ANOVA		0.000	0.000
Multiple comparison	1 *vs* 2 column	0.823	0.823
	1 *vs* 3 column[a]	0.013	0.013
	1 *vs* 4 column[a]	0.000	0.000
	2 *vs* 3 column	0.115	0.115
	2 *vs* 4 column[a]	0.000	0.000
	3 *vs* 4 column[a]	0.019	0.019

ANOVA, analysis of variance; JSW, joint space width.
The values in the table are *p*-values.
Parallel JSW direction, JSW direction was set parallel to column; vertical JSW direction, JSW direction was set vertical to column.
[a]Statistically significant.

of the scores caused by the difference of modality in each joint.

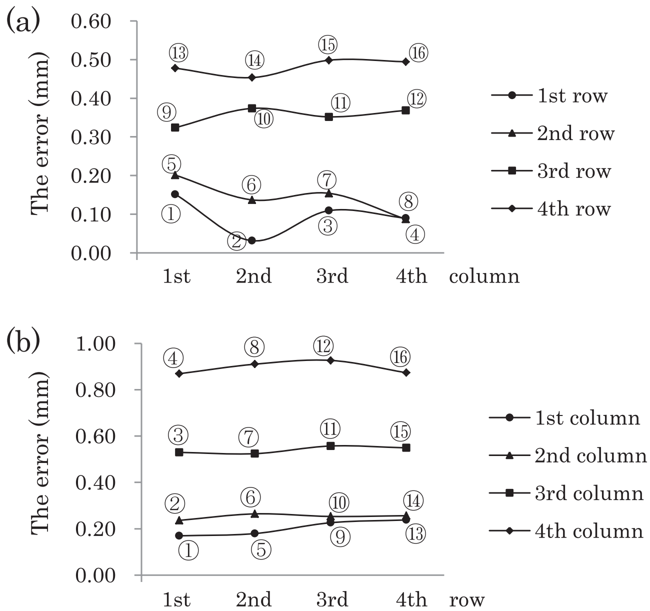
Statistical analysis

All statistical analyses were performed with statistical analysis software, Predictive Analytics Software (PASW) 10 Statistics 22 (IBM Corp., New York, NY; formerly SPSS Inc., Chicago, IL). Analysis of variance with *post hoc* Tukey's method and the two-group *t*-test were performed in the assessment of the positional effect, to generate the significant error and the assessment of the tendency of the error, respectively. $p < 0.05$ was considered to indicate a statistically significant difference in all statistical analyses. The Wilcoxon signed-ranks test was also performed in the assessment of the score in clinical images, for which only one reader (Rheumatologist A) was taken into account. In addition, the intraclass correlation coefficient (ICC) with a two-way mixed model was used to test for agreement between Sharp–van der Heijde scores of the two readers. ICC above 0.75 was considered excellent agreement; when it was in the range of 0.40–0.75, it was considered fair to good, and an ICC below 0.40 was considered poor.[21]

RESULTS

Measured JSWs in images of 4 phantoms in 16 positions and 2 directions (parallel and vertical to the row and column) were as follows: in radiography, the mean ± standard deviation was 0.79 ± 0.35 with JSW of 0.5 mm, 0.91 ± 0.11 with JSW of 1.0 mm, 1.8 ± 0.17 with JSW of 2.0 mm and 2.9 ± 0.16 with JSW of 3.0 mm. In tomosynthesis, the mean ± standard deviation was 0.86 ± 0.24 with JSW of 0.5 mm, 1.0 ± 0.12 with JSW of 1.0 mm, 1.9 ± 0.074 with JSW of 2.0 mm and 2.9 ± 0.085 with JSW of 3.0 mm.

Figure 4. Measured errors in each phantom position [example of tomosynthesis with joint space width (JSW) at 0.5 mm]. The measured errors in the different phantom positions; JSW direction is parallel (a) and vertical (b) to the X-ray tube axis or sweep direction. This figure is an example in this assessment. The error was prominent when the target joint was away from the centre of the incident X-ray beam along the JSW direction. This error tendency in each JSW measurement was almost identical in radiography and tomosynthesis. The labelled numbers (circled numbers) and definition of the row and column direction are shown in Figure 2. Errors are in millimetre.



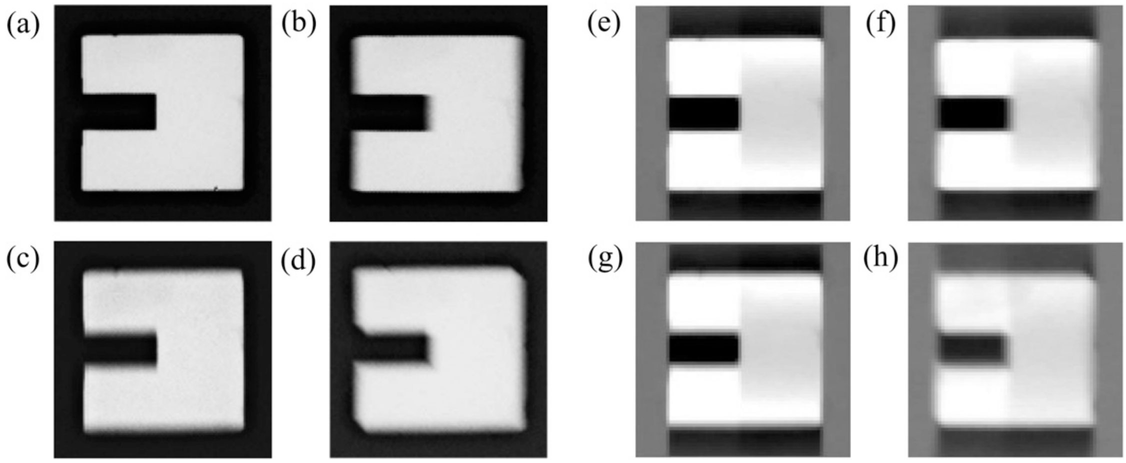
In the assessment of the positional effect to generate errors of JSW measurement, the error was significantly greater when the target joint was away from the centre of the incident X-ray beam along the JSW direction in both modalities (Table 3 and Figure 4). In either JSW directions or modalities, first *vs* third and first or second or third *vs* fourth row/column pairs showed significant difference in errors. No significant difference occurred in the errors at four positions in the same row and column, when row/column and JSW direction were located vertically. Therefore, it was concluded that the error was caused by blurring of the edge of the phantom, when the incident X-rays pass through the joint space parallel to the JSW direction. Also, the positional effect to generate the significant error was common in radiography and tomosynthesis. Phantom images at the four corner positions obtained in this study are shown in Figure 5.

In the assessment of the tendency of the error, the errors caused by the oblique incidence of X-rays were an overestimation in JSW 0.5 mm and an underestimation in JSW 2.0 and 3.0 mm. In JSW 1.0 mm, the error caused by the oblique incidence of X-rays tended to shift from an underestimation to an overestimation (Figures 6 and 7). This may be caused by the following reasons judging from the tendency of the error of JSW 0.5, 2.0 and 3.0 mm: when the JSW is narrow, the edge of the joint space and the part of true joint space in the projected image overlap by the oblique incidence of X-rays, which leads to an overestimation. When the JSW was broad, they were shifted but did not overlap by the oblique incidence of X-rays, which led to an underestimation. We believe that JSW 1.0 mm is the boundary between overestimation and underestimation. These tendencies were observed in both modalities.

In terms of the degree of the error caused by the oblique incidence of X-rays, radiography was greater than tomosynthesis in many settings in our phantom results. This was because the effect of the joint space edge shift, which may be a major factor of these errors, was suppressed in tomosynthesis. When the images were acquired, three-dimensional structures were projected onto a two-dimensional image in radiography, whereas an arbitrary section of a three-dimensional image avoiding the overlap of structure was possible to be displayed in tomosynthesis. The errors in tomosynthesis were also lower than in radiography at any distance from the centre of the incident X-ray beam, which was observed only when JSW was 0.5 mm and the JSW direction was parallel to the column (Figure 6a).

In the assessment of score in clinical images, the correlation between the two readers was fair to good in both modalities (ICC was 0.71 in radiography and 0.57 in tomosynthesis). A

Figure 5. Radiographs and tomosynthesis images of four different phantom positions: (a–d), radiographs; (e–h), tomosynthesis images. (a, e) Images at the centre of the incident X-rays (position 1 of Figure 2). (b, f) Images at a position away from the centre of the incident X-rays by 10.05 cm in the row direction (position 4 of Figure 2). (c, g) Images at a position away from the centre of the incident X-rays by 10.05 cm in the column direction (position 13 of Figure 2). (d, h) Images at position away from the centre of incident X-rays by 10.05 cm in row and column direction (position 16 of Figure 2).



significant difference was observed in some joints where the oblique incidence of X-rays was expected in the JSW direction (seven out of eight MP and PIP joints of the fourth and fifth finger *vs* three out of eight MP and PIP joints in the second and third finger). And, the scores for the relevant joints of tomosynthesis were significantly higher than those of radiography (Figure 8). Examples of RA fingers with oblique incidence of X-rays in radiography and tomosynthesis are shown in Figure 9.

DISCUSSION

RA is a chronic inflammatory disease leading to progressive structural damage of joints. Patients with progressive RA exhibit significant functional impairment, with a consequent reduction

Figure 6. The tendency of the error caused by the oblique incidence of X-rays: joint space width (JSW) direction is parallel to the column direction; (a) JSW 0.5 mm (b) JSW 1.0 mm (c) JSW 2.0 mm and (d) JSW 3.0 mm. The white and black markers indicate the error tendency of radiography and tomosynthesis, respectively. We marked an asterisk (*) when there was a statistically significant difference in error between radiography and tomosynthesis. Errors are in millimetres.

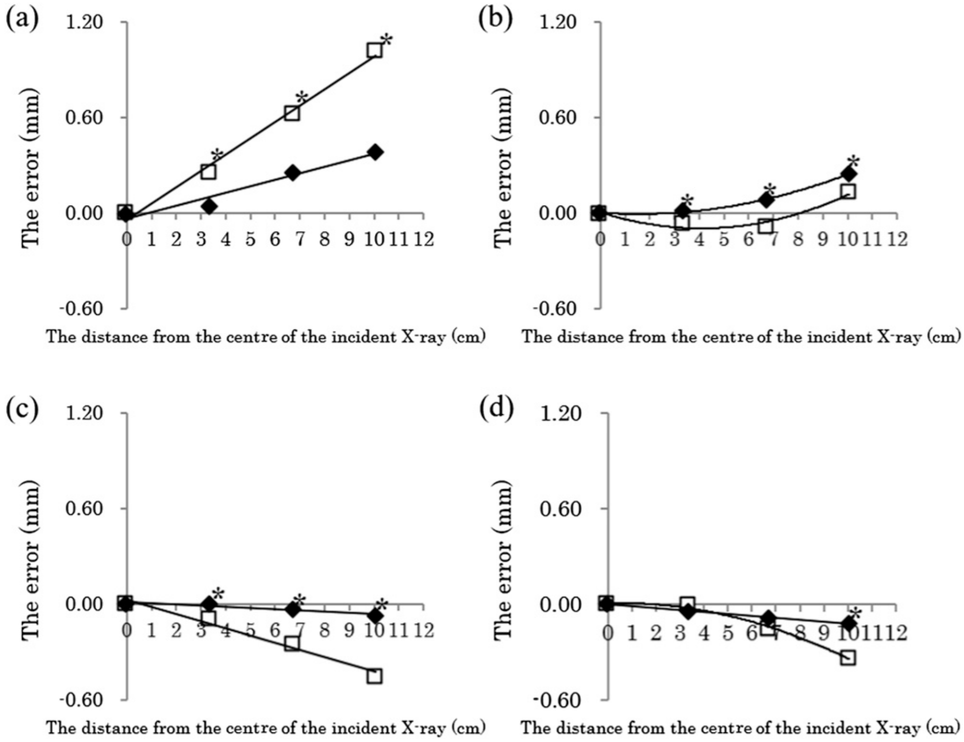
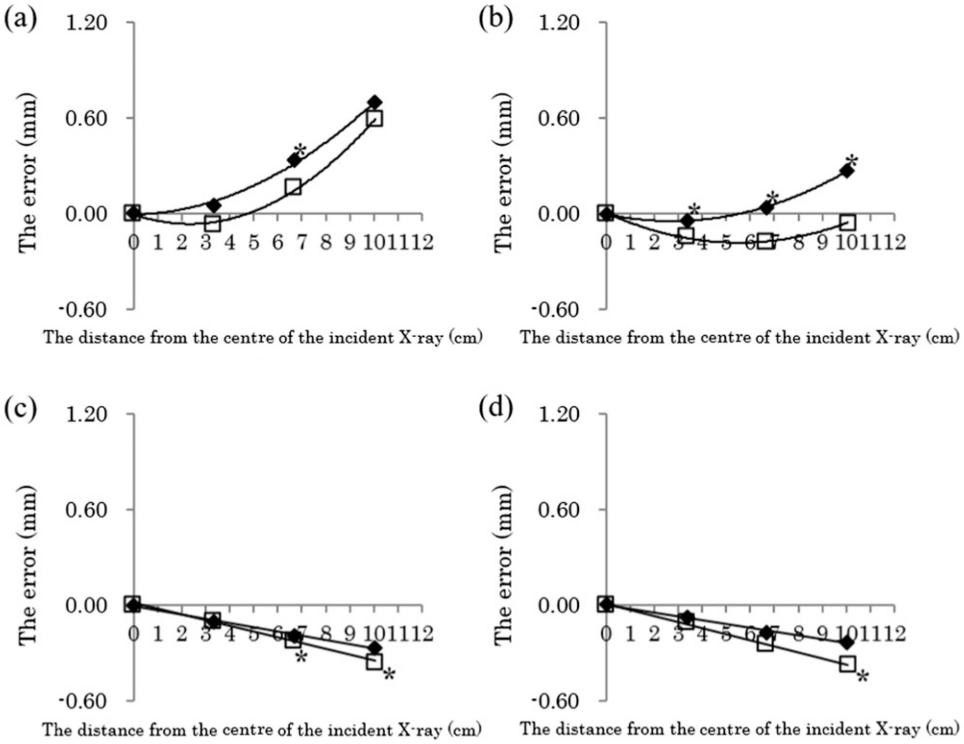


Figure 7. The tendency of the error caused by the oblique incidence of X-rays: joint space width (JSW) direction is vertical to the column direction; (a) JSW 0.5 mm (b) JSW 1.0 mm (c) JSW 2.0 mm and (d) JSW 3.0 mm. The white and black markers indicate the error tendency of radiography and tomosynthesis, respectively. We marked an asterisk (*) when there was a statistically significant difference in error between radiography and tomosynthesis. Errors are in millimetres.



in quality of life.[1,22–24] Cartilage thinning caused by RA is revealed as JSN in radiographic images.[3,4] The degree of JSN is an indirect index that suggests the degree of cartilage thinning or the progression of RA. Therefore, the accurate detection of JSW is linked to the determination of appropriate treatment strategy in each patient and the improvement of therapy

Figure 8. Results of scoring in the clinical image. The average of the scores of radiography and tomosynthesis are shown as white and black bars, respectively; (a) proximal interphalangeal joints in the left hand, (b) metacarpophalangeal joints in the left hand, (c) proximal interphalangeal joints in the right hand and (d) metacarpophalangeal joints in the right hand.

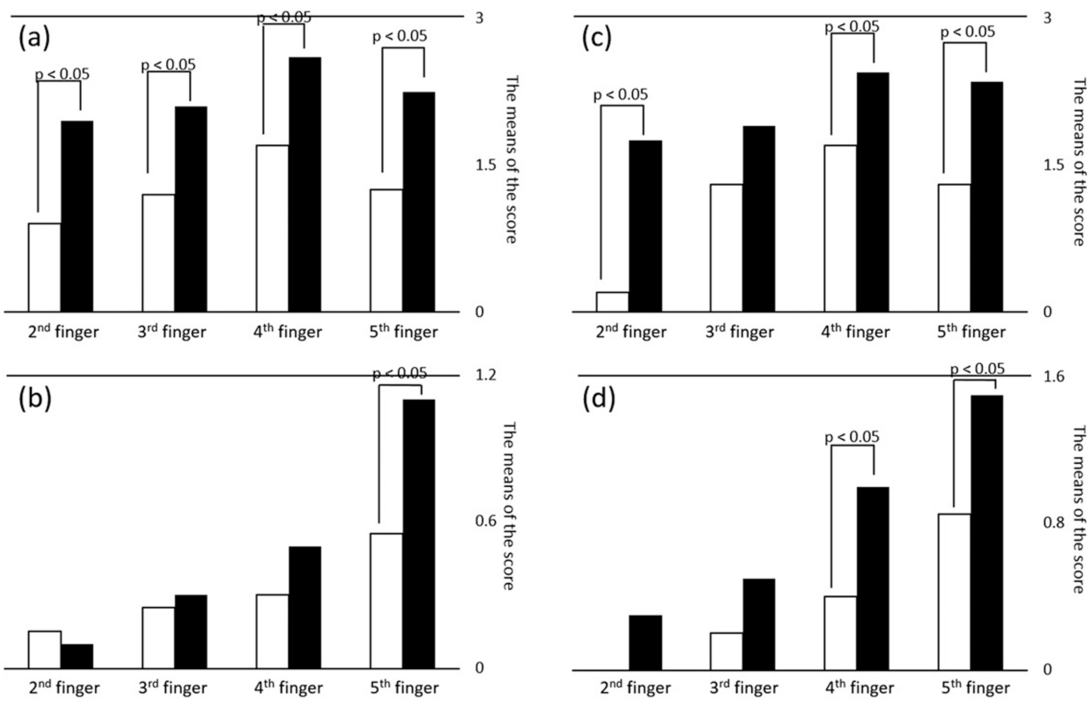
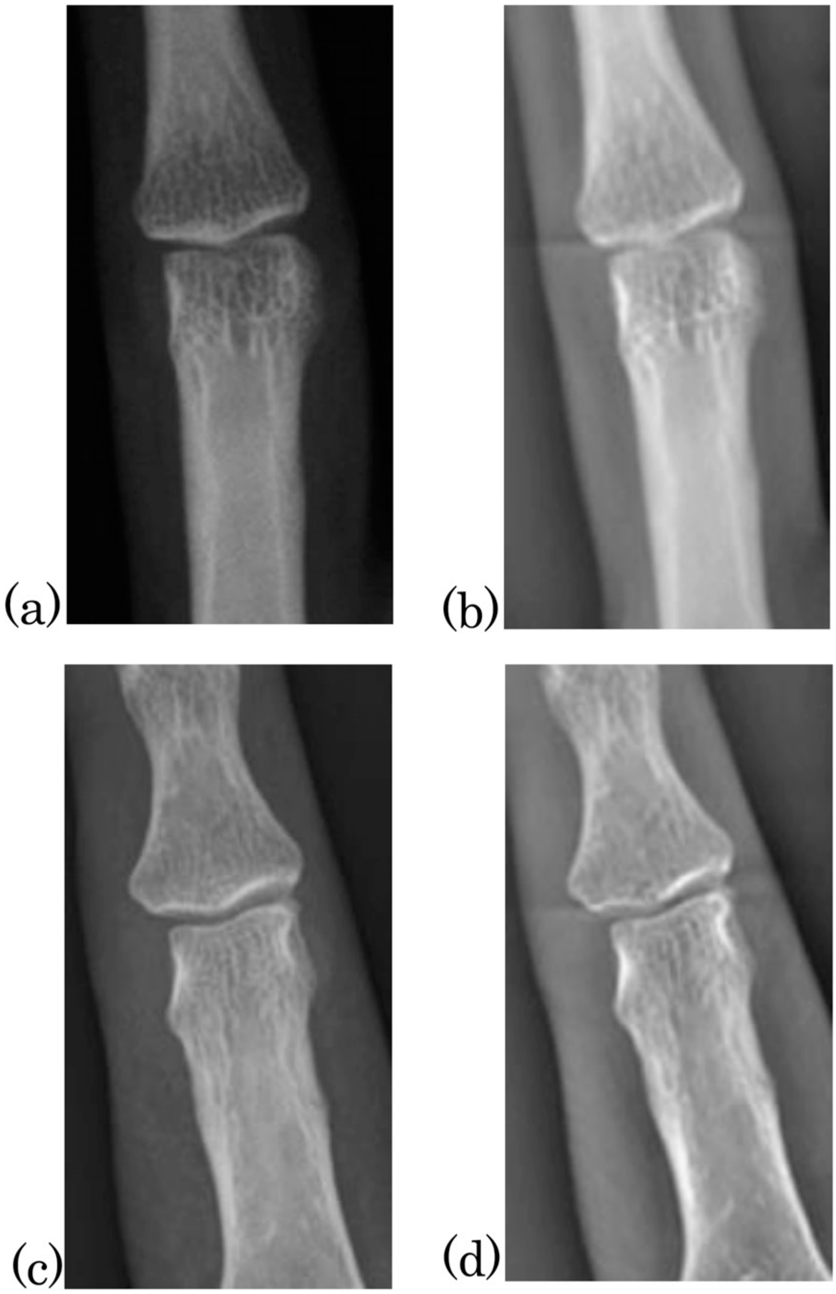


Figure 9. Example of clinical images of radiography and tomosynthesis graded by a rheumatologist. There is discrepancy in the Sharp–van der Heijde scores between images (a) and (b). There is no difference in the Sharp–van der Heijde scores between images (c) and (d). Radiograph (a) and tomosynthesis image (b) of the proximal interphalangeal joint of the middle finger in a female in her 30s with rheumatoid arthritis (RA) of 10-month duration (Score 7 on the 2010 ACR/EULAR criteria for diagnosing RA). Radiograph (a) and tomosynthesis images (b) were scored as Grades 0 and 3, respectively, in the Sharp–van der Heijde scoring method for the assessment of joint space narrowing. Radiograph (c) and tomosynthesis images (d) of the proximal interphalangeal joint of the index finger in a female in her 60s with RA of 32-month duration (Score 7 on the 2010 ACR/EULAR criteria for diagnosing RA). Both Sharp–van der Heijde scores of radiograph (c) and tomosynthesis images (d) were scored as Grade 0.



evaluation quality, which are important in minimizing the loss of quality of life in patients with RA.

Radiography is a conventional method for the evaluation of JSN in patients with RA because it has advantages such as a short examination time, low radiation exposure and low cost.[8] Tomosynthesis can detect overlapping structures clearly because it is a tomographic technique. Radiation exposure in tomosynthesis is relatively low; it resulted in a reduction of dose by a factor of 28 compared with CT in a wrist assessment, according to Noël et al[11] For these reasons, tomosynthesis is expected to be applied to the detection of early RA bone lesions with low risk of radiation exposure,[9–12] although the accuracy of measurement for JSN with tomosynthesis has not yet been validated. We therefore conducted this study to elucidate

the potential of tomosynthesis for the quantification of JSW with oblique incidence of X-rays.

In the comparison regarding which of the two modalities (tomosynthesis or radiography) can more accurately measure JSW, we first conducted a phantom analysis evaluating the effect of oblique incidence of X-rays. We found that the measured JSW in tomosynthesis was generally closer to the true width than that in radiography. JSW was overestimated when JSW was narrower (0.5 mm) and underestimated when JSW was broader (2.0 and 3.0 mm). This phenomenon was common to both modalities, which may be attributed to the blurring of the phantom edges due to overlapping of the shadows of the phantom edge and joint space, especially in the case when JSW was narrower and/or the effect of oblique incidence of X-rays was prominent.

We then recruited two experienced rheumatologists and asked them to score the JSW in both modalities (tomosynthesis and radiography) of the same finger joints of the same patients taken on relatively close examination dates. We found that the scores of tomosynthesis were significantly higher than those of radiography (*i.e.* JSW was regarded as narrower in tomosynthesis than in radiography) in some joints. This may be partially explained by the reader's habit of selecting the slice of the narrowest JSW out of multiple slices in tomosynthesis, to evaluate rigorously the degree of JSN, namely the observer did not evaluate the same portion of the joint on tomosynthesis and radiography. However, we need to further explain why a statistically significant difference was observed in the joints where the effect of oblique incidence of X-rays was expected. Furthermore, as JSW was more overestimated in radiography than in tomosynthesis only when JSW was narrow (0.5 mm) and parallel to the direction of the X-ray tube axis in radiography and sweep direction in tomosynthesis (Figure 6), we may assume that this particular phantom setting was reproduced in the actual finger joints.

To the best of our knowledge, this is the first study that investigated the effect of oblique incidence of X-rays on JSW quantification from both phantom and clinical images using radiography and tomosynthesis. It cannot be simply determined which modality can measure JSW more accurately in the clinical setting because the gold standard of evaluation has not been established. However, we demonstrated that tomosynthesis can detect JSW more accurately under the condition of oblique incidence of X-rays, by measuring the tendency of the error in both modalities in a phantom study and relating these results to a clinical image study. In addition, this study was achieved by creating a phantom made of TMA, which had an unprecedented characteristic and shape. We can reproduce the narrow joint having width of 1.0 mm or less because TMA can be processed in detail. The reproduction of a narrow joint having a width of 1.0 mm or less was very difficult previously. We believe that the results obtained in this phantom study are similar to the results obtained in clinical finger tests because the CT value of TMA is almost the same as that of the cortical bone of the human finger. Reproducibility was also demonstrated despite repeated exposure, by reproducing a constant JSW in the TMA phantom used in this study.

Our study has several limitations. First, in this study, the shape and size of the joint phantom are different from that of human finger joints. In truth, according to Goligher et al,[19] the average JSW of the second, third, fourth and fifth finger MP joints in patients with RA is 1.93, 1.69, 1.64 and 1.61 mm, respectively. JSWs of PIP joints may also be different from our phantom setting. However, the tendency of the error, according to the oblique incidence of X-rays, should have the universal feature: a narrow joint tends to be overestimated and a broad joint tends to be underestimated. We believe our phantom study results can be extrapolated to actual cases.

Second, all the radiography and tomosynthesis images analyzed in this study were not obtained on the same day. Although there was a delay of an average of 14 days in the acquisition of tomosynthesis images, this delay should not affect the results of this study because JSW changes caused by RA usually take years.[25]

Finally, although the conclusion in this study was drawn from the results of both phantom and clinical studies, their evaluation methods of JSW were different: quantitative image analysis using software was performed for the phantom study, while a human scoring method was performed for the clinical study. Nevertheless, we believe that these evaluation methods are pertinent because JSW evaluation using image analysis software is not the standard; visual evaluation of JSW is performed by rheumatologists or radiologists clinically.[16,17]

CONCLUSION

A significant error occurred when the target joint was away from the centre of the incident X-ray beam in the JSW direction for both radiography and tomosynthesis, but to a lesser extent for tomosynthesis. We observed the tendency that JSW in radiography was overestimated more than that in tomosynthesis in narrow joints with oblique incidence of X-rays; therefore, we conclude that tomosynthesis can facilitate accurate evaluation of JSW in RA finger joints, even with oblique incidence of X-rays.

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