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SCIENTIFIC ARTICLE

Digital tomosynthesis with metal artifact reduction for assessing cementless hip arthroplasty: a diagnostic cohort study of 48 patients

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Abstract
Objectives For postoperative imaging assessment of cementless hip arthroplasty, radiography and computed tomography (CT) were restricted by overlapping structures and metal artifacts, respectively. A new tomosynthesis with metal artifact reduction (TMAR) is introduced by using metal extraction and ordered subset-expectation maximization (OS-EM) reconstruction. This study investigated the effectiveness of TMAR in assessing fixation stability of cementless hip arthroplasty components.
Materials and methods We prospectively included 48 consecutive patients scheduled for revision hip arthroplasty in our hospital, with 41 femoral and 35 acetabular cementless components available for evaluation. All patients took the three examinations of radiography, CT, and TMAR preoperatively, with intraoperative mechanical tests, and absence or presence of osteointegration on retrieved prosthesis as reference standards. Three senior surgeons and four junior surgeons evaluated these images independently with uniform criteria.
Results For TMAR, 82 % diagnoses on the femoral side and 84 % diagnoses on the acetabular side were accurate. The corresponding values were 44 and 67 % for radiography, and 39 % and 74 % for CT. Senior surgeons had significantly higher accuracy than junior surgeons by radiography ($p < 0.05$), but not by TMAR or CT.
Conclusions By minimizing metal artifacts in the bone–implant interface and clearly depicting peri-implant trabecular structures, the TMAR technique improved the diagnostic accuracy of assessing fixation stability of cementless hip arthroplasty, and shortened the learning curve of less experienced surgeons.
Level of evidence Level II, diagnostic cohort study.

Keywords Cementless total hip arthroplasty · Fixation stability · Digital tomosynthesis · Diagnostic accuracy · Spot weld · Radiolucent line

Introduction

In recent years, cementless hip arthroplasty has become increasingly popular in clinical practice, and reliable biological fixation is essential to the success of cementless hip arthroplasty [1, 2]. To determine the fixation stability of hip arthroplasty components, imaging examinations like radiography and computed tomography (CT) have been widely used, but only with moderate accuracy with a considerable amount of radiation exposure [3–6].

Radiography features no metal artifacts and high-density resolution to discriminate different tissue types, but its application is limited because all structures overlap each other, leading to very low depth resolution to identify anatomical structures from layers at different depths [7, 8]. While CT has much higher depth resolution, the images are usually distorted due to heavy metal artifacts, especially at the bone–implant interface. Besides, CT is associated with high dose of radiation exposure with average effective dose that is around

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ten times higher than radiography and digital tomosynthesis [6, 9, 10].

Tomosynthesis is a technique that evolved from conventional tomography, which requires considerable radiation dose to obtain a single section of anatomy. By tomosynthesis, a series of images can be generated from images projected from different angles, obtained in a single sweep of radiography, using a radiation dose much lower than conventional tomography [8, 11]. A new tomosynthesis with metal artifact reduction (TMAR) is introduced by using metal extraction and ordered subset-expectation maximization (OS-EM) reconstruction [12]: projection images were first separated into metal and metal-free images, then these images were repeatedly approximated to reduce metal artifacts, and finally these two images were merged together [11]. TMAR can be advantageous over radiography because of its improvement in reducing overlapping structures [7, 13], and it can overcome the shortcomings of artifacts in CT while reducing radiation exposure dose.

In order to find out whether the improved image quality of TMAR could lead to higher diagnostic accuracy of assessing fixation stability of cementless hip arthroplasty, we conducted a diagnostic cohort research by comparing TMAR, radiography, and CT images of patients scheduled for revision hip arthroplasty surgeries. We asked three major questions: (1) For TMAR, radiography, and CT, what is the accuracy of assessing cementless hip arthroplasty fixation stability for each method? (2) Are there any differences in diagnostic accuracy by experienced senior doctors and less-experienced junior doctors, using the three imaging modalities? (3) How much is the mean effective radiation dose of the three imaging techniques for patients with hip arthroplasty?

Materials and methods

Patients

With the approval of the ethics committee in our hospital, we prospectively included 48 consecutive patients who were scheduled for hip arthroplasty revisions in our center between August 2013 and March 2014, and there were 41 cementless femoral stems and 35 cementless acetabular cups available for evaluation (Fig. 1). Indications to revision surgery were: recurrent dislocation, periprosthetic infection, severe wear of acetabular liner, malposition of implants, component loosening, leg-length discrepancy ≥ 3 cm, periprosthetic fracture, and persistent postoperative pain [14, 15]. The inclusion criteria were: age > 50 years, scheduled for hip arthroplasty revision surgery, cementless components utilized in the primary prostheses. We excluded cemented components, patients with hip resurfacing implants, age > 90 years, ASA score ≥ 4, and those who refused to participate in the study. Informed consent was obtained from all patients. Nineteen (39.6 %) patients were female. Median age of patients was 63 years (51 – 78 years). The mean time from initial surgery to imaging examination was 3.4 years (SD 3.2; range, 0.8 – 11.2 years). The implants were different models from nine different manufacturers. As standard of care for patients indicated for revision hip arthroplasty at our institution, all patients took radiography, TMAR, and CT examinations within 2 weeks before surgery.

Radiography examination

The radiography examination was conducted with a digital radiography equipment (KODAK DIRECTVIEW DR7500, Kodak, Carestream Health), and included posterior-anterior and lateral views of the hip (75 kV, 25 mAs, active image area, 43 × 43 cm, image matrix size, 3000 × 3000, pixel pitch, 143 μm) with focus-detector distance at 100 cm, according to the standard protocol of our hospital. The dose area product (DAP) of radiography was measured by using a DAP meter (DoseGuard 100, RTI Electronics, Mölndal, Sweden), and the effective dose (ED) was calibrated by using RTI WinODS 2.0 software.

Computed tomography examination

The hip CT was obtained by using a 64-section equipment (Aquilion 64, Toshiba, Tokyo, Japan). The patient was positioned supine with the hip joint extended, neutral in abduction/adduction and rotation. Axial sections of 1.0 mm thick were obtained from 3.0 cm above the superior rim of acetabular cup to 4.0 cm distal to the stem tip, according to the standard protocol in our hospital (120 kV, 250 mA, 153 mAs, rotation time 0.5 s, field of view dimension 37.9 cm, spiral slice thickness 5.0 mm, matrix size 512 × 512). Axial images of 1.0 mm thick were reconstructed with the algorithm of filtered back projection (FBP). Sagittal and coronal images of the same thickness were calculated through multiplanar reconstruction. The evaluation of CT scans was performed on the 1-mm-thick images. Effective doses for CT were calculated using the DLP and k coefficients (0.015) from the European Guidelines [16].

Digital tomosynthesis examination

The frontal and lateral view TMAR examinations were conducted with commercially available equipment (Sonialvision Safire II, Shimazhu, Kyoto, Japan). The images were scanned with patients in supine and lateral decubitus position (80 – 90 kV, 300 – 350 mA), respectively. The radiography tube performed a continuous arc-shaped movement from -40° to +40° in the standard anterior-posterior plane with the flat panel detector moving in counter direction. Seventy-four low-dose projection images were collected within 5 s. For both the AP and lateral views, 61 images (matrix size 1024 × 1024) were reconstructed at 2-mm pitch with the metal

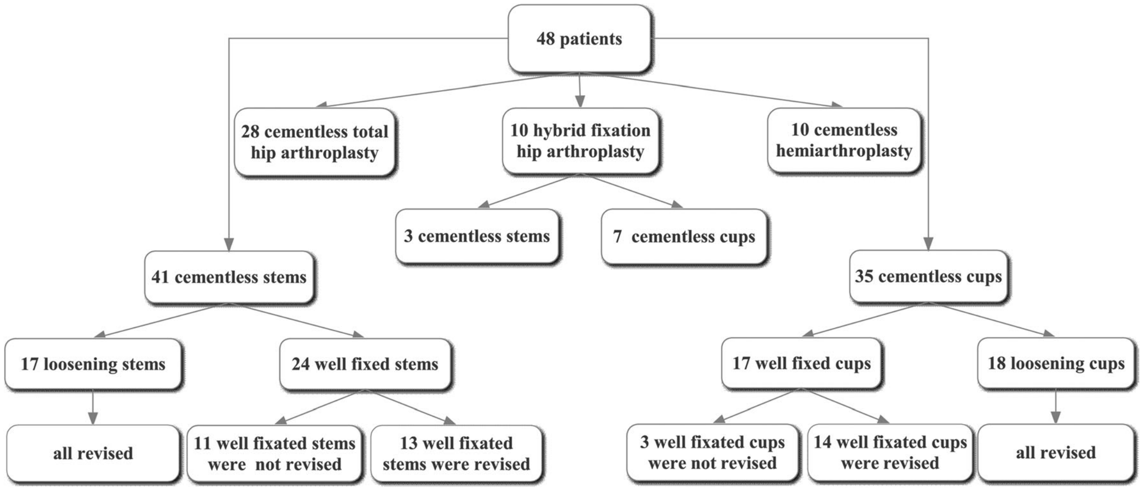

Fig. 1 Schematic flowchart of cases included in this study

extraction and ordered subset-expectation maximization (OS-EM) algorithm. The evaluation of TMAR was performed on these 2-mm-thick images. The DAP and ED for TMAR were measured with the same DAP meter and software as used for radiography.

Image assessment

The diagnostic criteria for the three imaging techniques were as follows [2, 17–19]:

1) Loosening: prosthesis encircled by complete circumferential radiolucent lines (RLL);
2) Not loosening (definite osteointegration fixation): implants with evidences of spot welds (sites of osteointegration);
3) Possible loosening (not sure): implants with partial but not circumferential RLL and no signs of spot welds can be observed.

Traditionally, an RLL could not be reckoned as diagnostic for loosening unless more than 2 mm in width [17, 18]. However, it was reported that as much as 16.3 % components without frank signs of loosening on radiography and CT were found to be loosening [4]. With recent progress in imaging techniques, continuous RLL much narrower than 2 mm could be clearly observed, which traditionally necessitated contrast arthrography to be confirmed [20]. Thus, we classified RLL into two groups: the narrower group (≤1.0 mm wide), and the wider group (>1.0 mm wide).

All images were prospectively collected and analyzed after surgery for this investigation. Seven orthopedic surgeons, blinded to each other's judgment of imaging interpretation, evaluated these images independently and were divided into the senior group (three surgeons with 6 – 13 years' clinical experience) and the junior group (four surgeons with 2 – 4 years' clinical experience). Surgeons were blinded to all the clinical and surgical findings of patients and results of the CT, TMAR, and radiography images while interpreting each. Preliminary training and standardization of the diagnostic criteria were performed for all surgeons. Radiographies were evaluated first, followed by CT 4 weeks later, and after another 4 weeks' interval the images of TMAR were assessed. The prostheses were divided into 14 zones on the anterior-posterior and lateral views of femoral stems, and into three zones on the anterior-posterior view of acetabular cups (Fig. 2) [2, 21, 22]. At evaluation of every image, the diagnosis and observed evidences, including spot welds, segmental or contained bone defects, regional and complete RLL (narrower or wider group), were recorded by each rater (Appendix. 1). Two months after each reading, the most experienced surgeon performed a second assessment of the three imaging methods to examine intraobserver reliability.

Reference standard

The reference standard for judging fixation stability included two major clinical criteria:

1) Intraoperative mechanical tests: during surgeries, all cups and stems were tested manually by forceful pulling out and twisting maneuvers to induce micro-movements. Any micro-motion or extrusion of blood from the implant–bone interface was considered as evidence of loosening, and vice versa [23, 24].
2) Postoperative retrieval findings: for implants revised, the results of intraoperative mechanical tests were further confirmed by the presence or absence of osteointegration on retrieved components. If sites of bone in-growth/on-growth existed, it was confirmed as sound evidence for

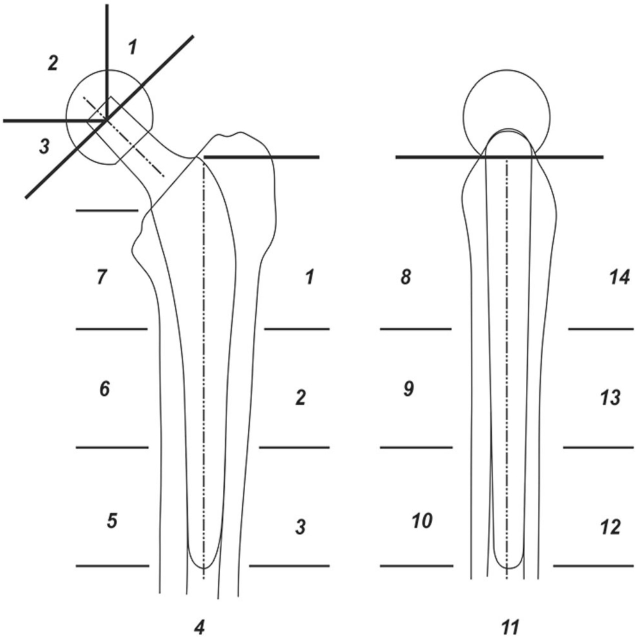

Fig. 2 Schematic division of the femoral side into 14 zones and the acetabular side into three zones for recording evidence of diagnoses based on Gruen and John Charnley's methods [21, 22]

biological fixation, and vice versa [2, 25]. In this study, no cases were found to have conflictive intraoperative mechanical tests and postoperative retrieval findings.

All loosening components were revised, and the decisions to remove or keep well-fixated components were made by senior surgeons, depending on the overall health conditions of patients and the requirements of debridement and joint reconstruction. In total, 17 out of the 41 cementless stems were loosening, and 18 out of the 35 cementless cups were loosening (Fig. 1).

Statistical analysis

With the clinical standards as reference, a three-category outcome was determined for each diagnosis by combining the correct diagnoses of "loosening" and "not loosening" into the "accurate" group, false diagnoses of "loosening" and "non-loosening" into the "wrong" group, and the diagnoses of "possible loosening" into "not sure" group. Diagnostic accuracy was defined as the rate of "accurate" group for each imaging examination.

Chi-square tests were used to examine the enumeration data, and Chi-square decomposition tests were used for multiple comparisons. Interobserver and intraobserver agreement for each imaging modality was assessed by the means of intraclass correlation coefficient. All statistical analysis was done using SPSS software (version 15.0; IBM, Armonk, NY, USA), and p values of <0.05 were significant for a single comparison, while p values of <0.017 were significant for multiple comparisons among the three imaging modalities.

Results

The diagnostic accuracy by TMAR was 82.6 % for femoral stem and 84.5 % for acetabular cup, which were significantly higher ($p < 0.017$) than the corresponding values of radiography (44.6 and 67.3 %) and CT (39.6 and 74.6 %) (Fig. 3).

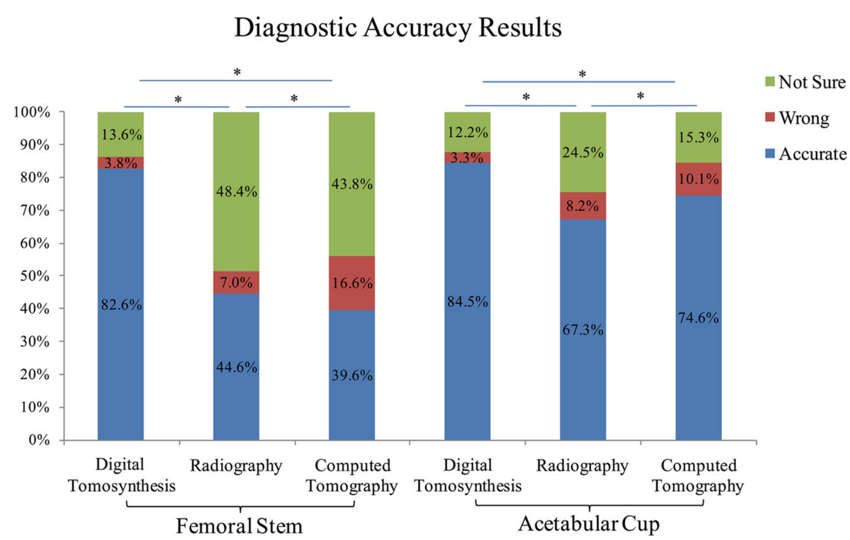

Fig. 3 Diagnostic accuracy results of the three imaging modalities. Results on the femoral side and the acetabular side are listed separately. * $p < 0.017$ is considered significant

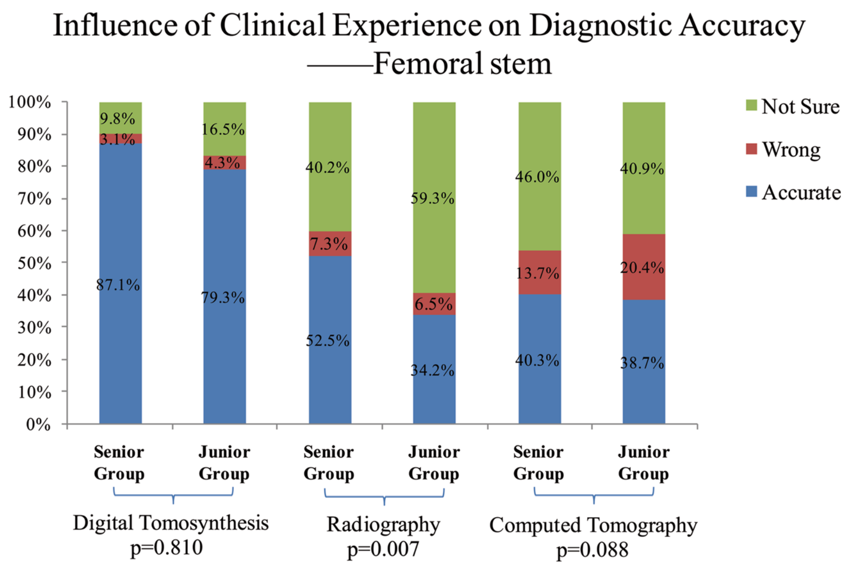

Fig. 4 Influence of clinical experiences on diagnostic accuracy of the femoral side. * $p < 0.05$ is considered significant

For radiography, the diagnostic accuracy in the group of senior surgeons was significantly higher than that of the junior group ($p < 0.05$), but no significant differences were found between the two groups for TMAR and CT (Fig. 4 and 5).

TMAR detected significantly more spot welds and complete RLL less than 1.0 mm wide than radiography and CT (Table. 1).

For radiography, TMAR, and CT images, the intraobserver agreement was 0.942, 0.973, and 0.948 for femoral stems, and 0.804, 0.971, and 0.953 for acetabular cups, respectively; the interobserver agreement was 0.849, 0.962, and 0.631 for femoral stems, and 0.836, 0.956, and 0.923 for acetabular cups.

The dose parameters for each scan are recorded in the Materials and methods section. The mean volume CT dose index ($CTDI_{vol}$) was 14.8 mGy, and the mean dose length product (DLP) was 508.5 mGy.cm. The mean effective dose of radiation was 0.93 mSv for radiography, 1.22 mSv for TMAR, and 7.63 mSv for CT.

Discussion

This study showed that the diagnostic accuracy of assessing fixation stability of cementless hip arthroplasty by TMAR was much higher than by radiography and CT for both the femoral

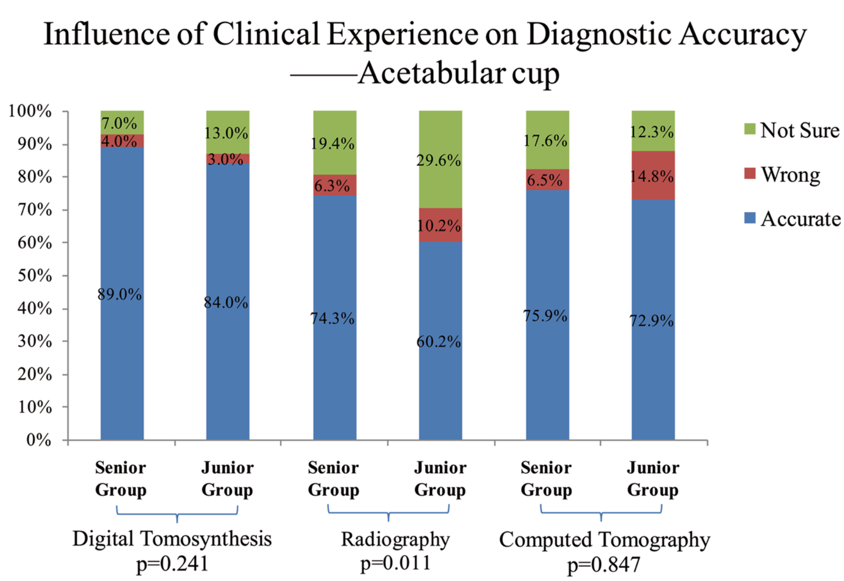

Fig. 5 Influence of clinical experience on diagnostic accuracy of the acetabular side. * $p < 0.05$ is considered significant

Table 1 Incidence of radiographic evidence detected for diagnosis

Variable	Radiography	CT	TMAR	*p* value
Femoral side				
Spot weld	537	378	624	0.000
Complete RLL ≤ 1.0 mm wide	27	15	57	0.000
Complete RLL > 1.0 mm wide	37	54	53	0.281
Regional RLL ≤ 1.0 mm wide	135	117	124	0.507
Regional RLL > 1.0 mm wide	226	186	174	0.019
Segmental bone defect	28	22	24	0.683
Contained bone defect	48	36	42	0.421
Acetabular side				
Spot weld	154	133	182	0.007
Complete RLL ≤ 1.0 mm wide	29	32	56	0.001
Complete RLL > 1.0 mm wide	67	63	70	0.715
Regional RLL ≤ 1.0 mm wide	22	12	20	0.187
Regional RLL > 1.0 mm wide	46	38	35	0.422
Segmental bone defect	4	3	4	0.913
Contained bone defect	20	9	14	0.116

RLL radiolucent line, *CT* computed tomography, *TMAR* tomosynthesis with metal artifact reduction. $p < 0.05$ is considered significant

and acetabular sides (Fig. 3), and the performance of less-experienced orthopedic surgeons were significantly improved by TMAR in comparison of radiography and CT. This could be explained by the strength of tomosynthesis in delineating structures in the bone–implant interface: significantly more spot welds and complete enveloping RLL less than 1 mm wide could be observed with tomosynthesis than with radiography and CT (Table 1).

TMAR was more accurate than single-time radiography for assessing cementless hip arthroplasty due to reduction of overlapping anatomical structures, and this is consistent with previous reports [8, 26, 27]. Göthlin et al. reported that tomosynthesis was superior to radiography with sharper delineation of demineralization and osteolysis [8]. However, they also stated that tomosynthesis did not change diagnosis from radiography, limiting its clinical utility. This might be because cemented and uncemented cases were mixed together in their research material, which actually had very different signs and diagnostic criteria of loosening in imaging apart from demineralization and osteolysis [21, 28, 29], and no clinical results were included for assessing the effectiveness of radiography.

The strength of TMAR in metal artifact reduction entitled its advantages over CT [30]. Traditionally, metal artifacts, including beam hardening, noise-induced streaking, and partial volume effect, severely crippled the strength of CT to display evidences of fixation stability like spot welds and RLL, which lay in the bone–metal interface and suffered most from artifacts [13, 31] (Fig. 6, 7, 8, 9, and 10). Recently, computed tomography with metal artifact reduction (CTMAR) is getting increasingly more attention. Nevertheless, most of the current studies were focused on images of pelvic or periprosthetic soft tissues, and very little

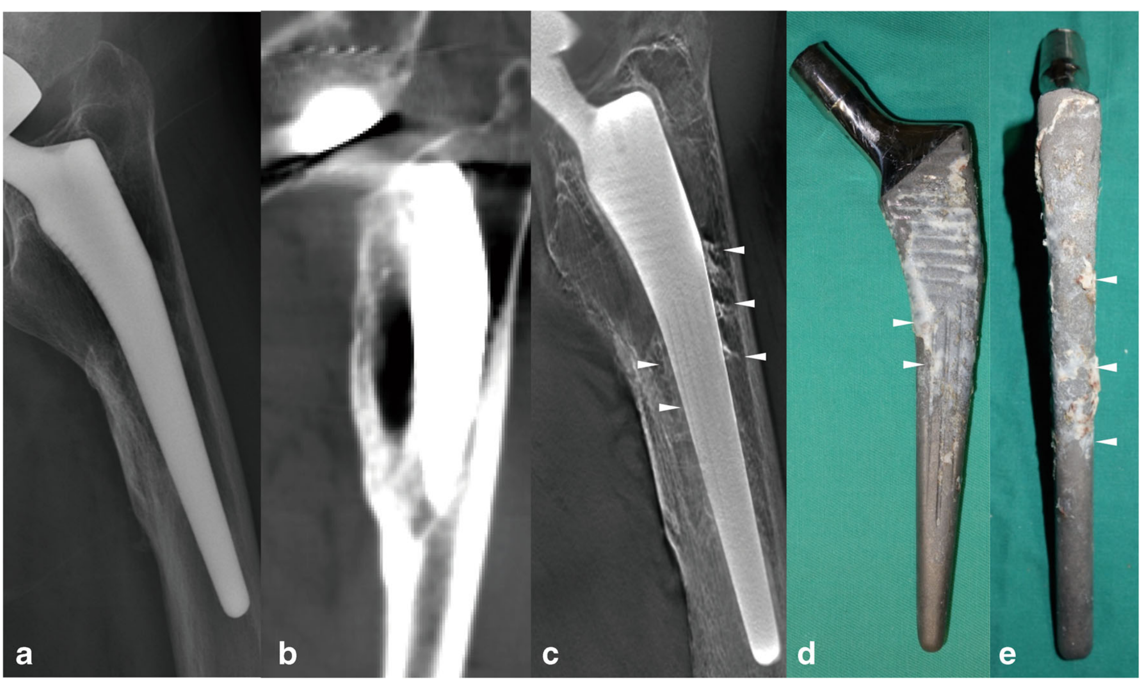

Fig. 6 **a** AP radiography from a 58-year-old man with periprosthetic fracture 4 years after hip replacement showed subsidence of the femoral stem. **b** The coronal section of CT was blurred by metal artifacts. **c** Digital tomosynthesis showed sites of spot welds (*triangles*), corresponding to residue bony structures (*triangles*) found on (**d** and **e**) the retrieved femoral stem

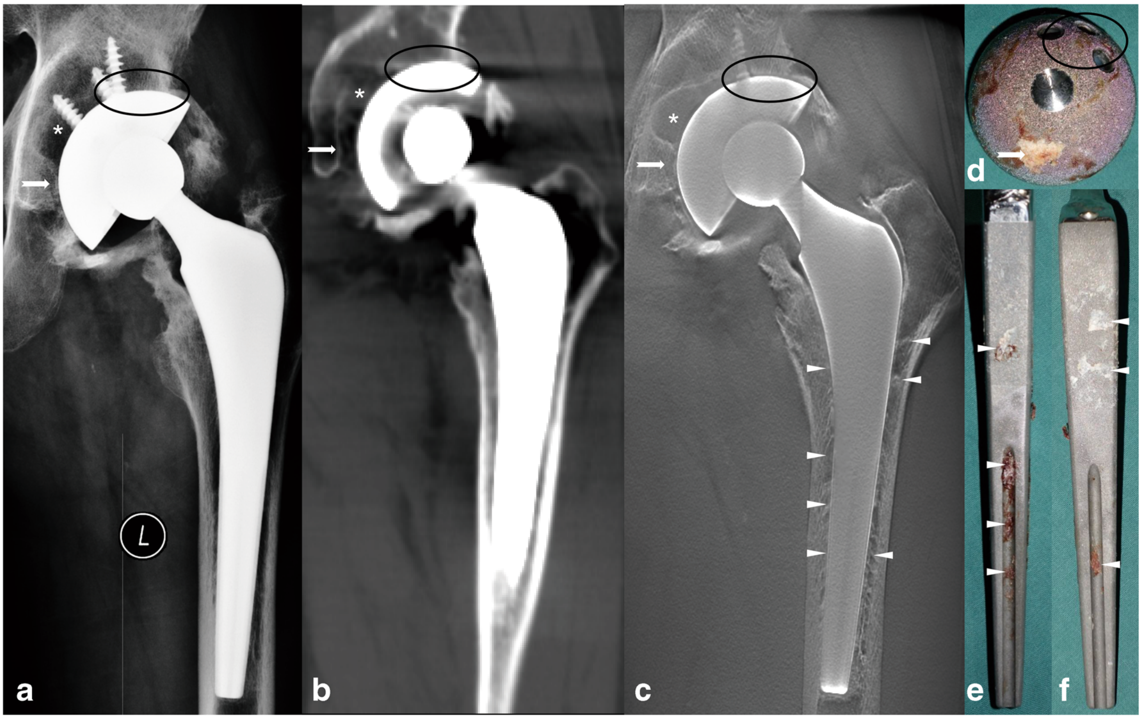

Fig. 7 **a** AP radiography of a 56-year-old women 14 years after primary surgery showed possible subsidence of the femoral stem, as well as osteolysis (*asterisk*) and osteointegration (*arrow*) on the acetabular side. **b** On CT coronal section, spot weld is false negative at the inferior medial part (*arrow*) but false positive (*circle*) at the superior lateral part of the cup. **c** Digital tomosynthesis showed spot welds on both the femoral stem (*triangles*) and acetabular cup (*arrow*) as well as radiolucent line < 1 mm (*circle*), consistent with residue bony structures found on (**d**) the retrieved prosthesis

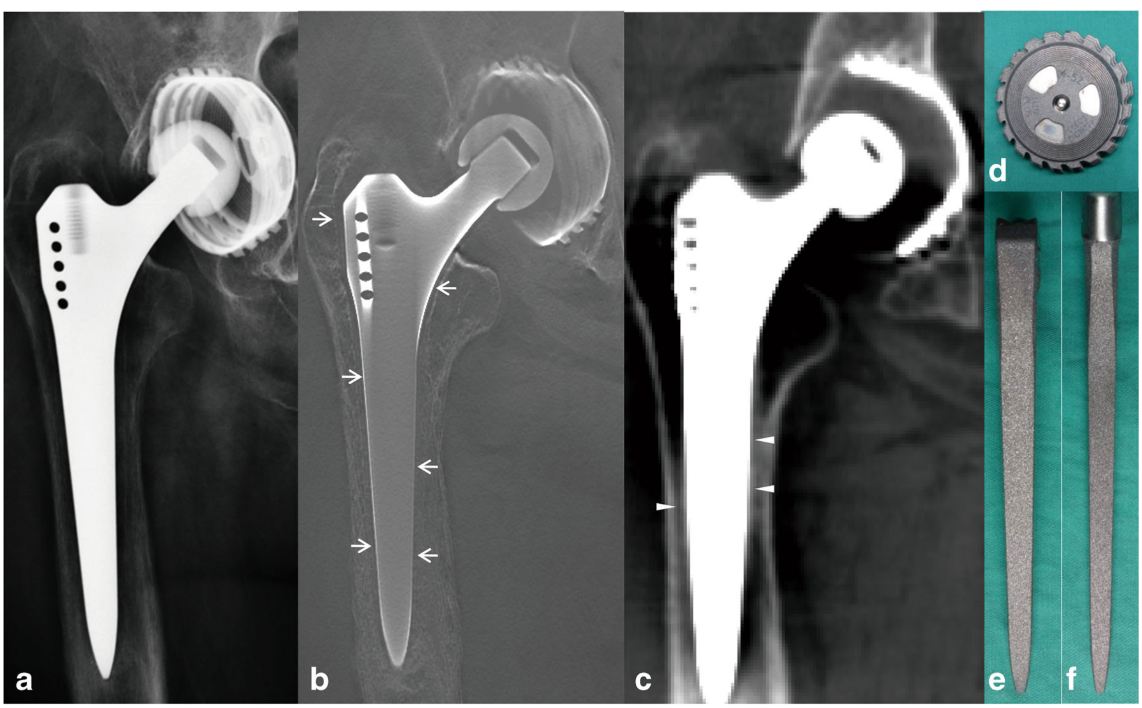

Fig. 8 **a** AP radiography of a 72-year-old man 2 years after total hip arthroplasty showed loosening of the acetabular cup and no sound evidence for loosening of the femoral stem. **b** Digital tomosynthesis depicted complete fine radiolucent line < 1 mm (*arrows*) enveloping the prosthesis. **c** Coronal section of CT showed possible “osteointegration” (*triangles*), but intraoperative micromovements were positive and d. the retrieved acetabular cup and E-F. femoral stem showed no evidences of osteointegration

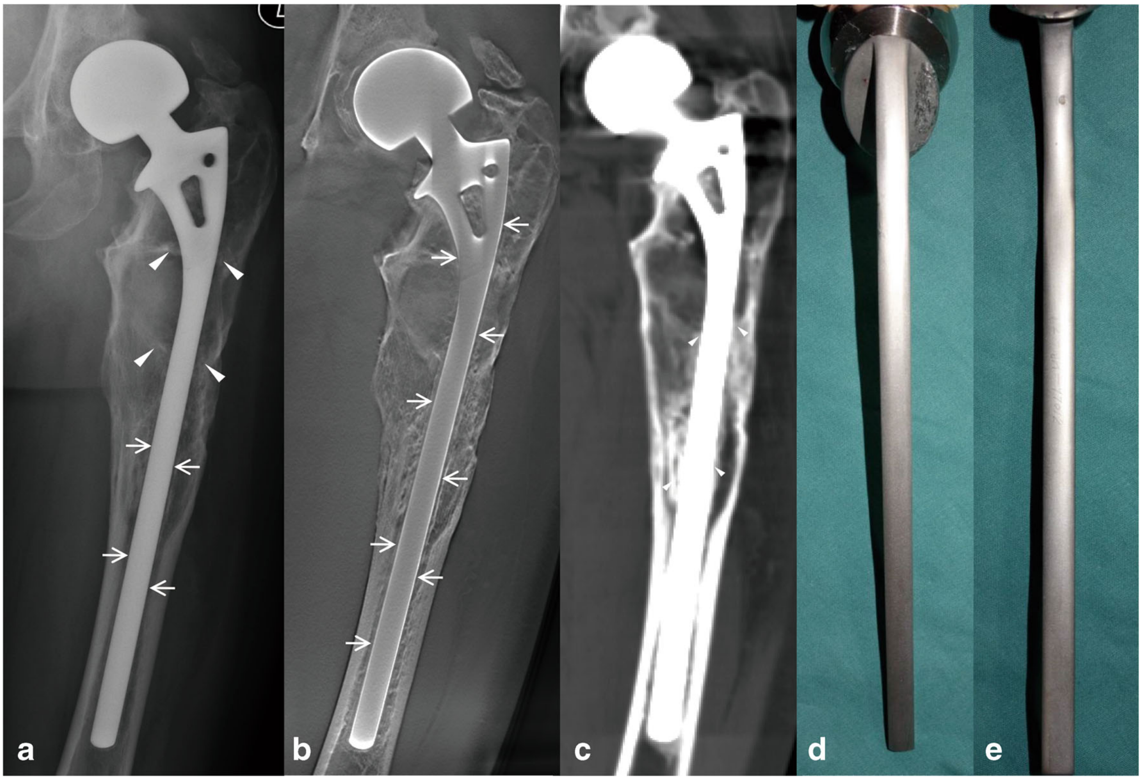

Fig. 9 **a** AP radiography of a 55-year-old woman 8 years after hemiarthroplasty showed regional radiolucent lines (*arrows*) and possible signs of "osteointegration" (*triangles*). **b** Digital tomosynthesis showed complete radiolucent lines enveloping the prosthesis (*arrows*). **c** Coronal section of CT showed "osteointegration" (*triangles*), but intraoperative mechanical tests were positive (**d**, **e**) retrieved femoral stem showed no evidence of biological fixation

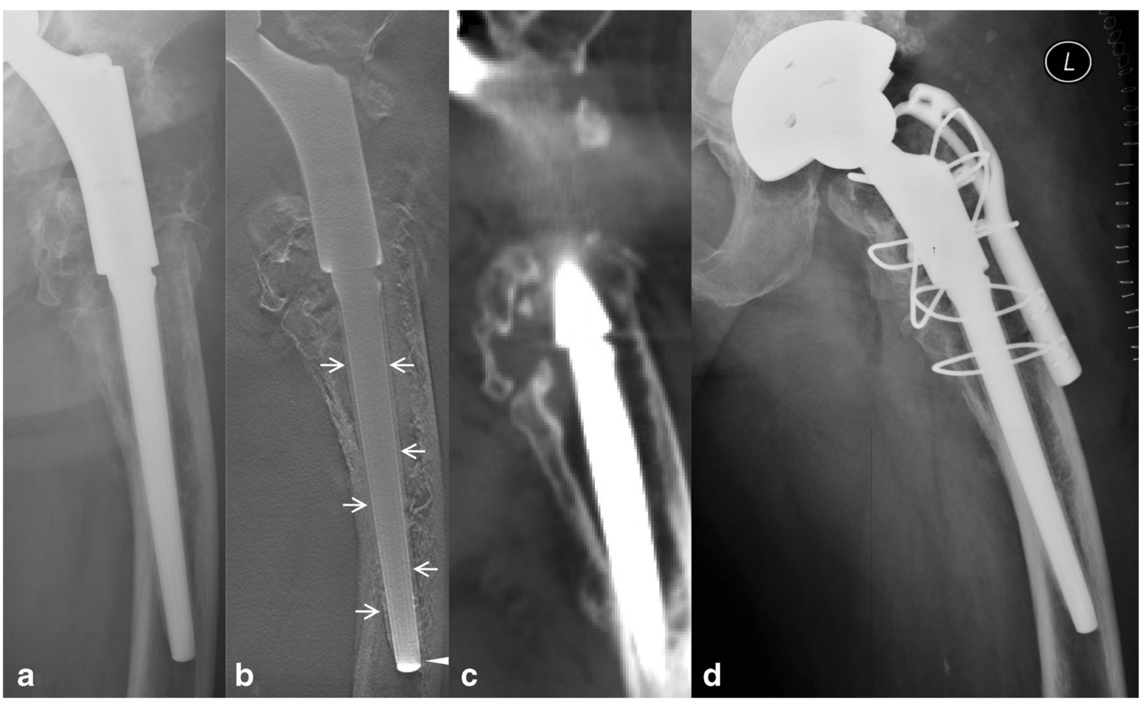

Fig. 10 **a** Preoperative AP radiography from a 64-year-old man 2 years after his first revision arthroplasty. **b** The shadows of stem wings on tomosynthesis misleadingly mimicked complete radiolucent lines surrounding the stem (*arrows*) and spot welds at distal tip might be missed (*white triangle*). **c** The coronal section of CT showed extensive contained bone defects and seemingly loosening of the distal stem which was found very stable and unrevised during surgery, as shown by **d**. Postoperative radiography

knowledge has been known about the effects of MAR on the implant–bone interface [32]. Recently, single-photon emission computed tomography/computed tomography (SPECT/CT) arthrography was introduced to evaluate the bone–implant interface of hip arthroplasty components, showing promising diagnostic accuracy compared to radiography [33]. However, this invasive method is concerned with risks of infection, anaphylactic reaction, and increased radiation exposure to patients [5].

Currently, even TMAR cannot completely avoid artifacts. For equipment from various manufacturers, the optimal parameters of scanning (sweep angle, sweep direction, projection density, and total dose) and reconstruction (pitch, reconstruction filter, iterations, and thickening) are different, and should always be tuned to minimize acquisition- and reconstruction-related artifacts [11]. RLL and spot welds should not be confirmed before artifacts can be ruled out: in our practice, the image quality of TMAR was not accepted until no recognizable artifacts existed surrounding stem neck areas, where artifacts can be easily identified without coexisting trabecular background. Metallic artifacts in TMAR manifested as continuous smooth lines surrounding implants [11]. In comparison, RLL was heterogeneous in density and width, and directly connected with trabecular structures (Figs. 8 and 9). Additionally, ghosting artifacts of longitudinal anti-rotation wings on femoral stems should be carefully differentiated from continuous RLL (Fig. 10).

We found that on both the femoral and acetabular sides, diagnostic accuracy of less-experienced orthopedic surgeons was significantly improved by TMAR than by radiography and CT (Figs. 4 and 5). This indicated that improvements in image quality shortened the learning curve of less-experienced surgeons, who traditionally needed long-term training to identify evidence of osteointegration and loosening in radiography and CT images.

The effective dose of a single tomosynthesis examination, including all sweep images, was nearly twice that of radiographs of the hip, and some 1/7 of computed tomography [9]. In our center, the cost of tomosynthesis is 1/4 of a CT scan. Although tomosynthesis provides lower depth and contrast resolution than CT, its advantages in artifact reduction, radiation exposure, examination swiftness, and cost-effectiveness make tomosynthesis a promising alternative for evaluating patients with cementless hip prostheses.

There were several limitations of our study. First, long-term serial radiographies were not included, leading to underestimated accuracy of radiography. However, it is of great clinical and economical significance if diagnoses can be made early with a single time imaging examination, and our outcome for a single TMAR scanning was comparable with previously reported accuracy data for serial radiographies (77 – 87 %) [3]. Second, CTMAR and similar tomosynthesis techniques by other vendors has also been previously reported as effective in reducing metal artifacts [8, 26, 32], but these techniques were not available in our hospital to be included in this study. Thus, further research comparing the effectiveness of various types of TMAR and CTMAR techniques is required. Third, the sample size was small and consisted of various types of cementless components, increasing the risk of selection bias and limiting the comparability between each cases. However, this cohort was consecutively included to minimize biased selection, and a sample of various designs actually reflects the clinical situation of revision hip arthroplasty faced by surgeons. Besides, a control group of asymptomatic patients was required to evaluate the abilities of the three imaging modalities in assessing well-fixed hip prostheses. Nevertheless, clinically it is easy to exclude loosening based on physical examination combined with conventional radiography for asymptomatic patients, and ethically it is inappropriate to do CT and TMAR scans for every asymptomatic patient, as the risks of radiation exposure and costs would be significantly increased.

This study showed that, compared to radiography and CT, the TMAR technique greatly improved the accuracy of assessing fixation stability of cementless hip arthroplasty components while limiting radiation exposure, and shortened the learning curve of less-experienced surgeons. TMAR is an effective and promising alternative for postoperative evaluation of cementless hip arthroplasty.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

Funding The authors state that this work has not received any funding. Institutional Review Board approval was obtained.

Informed consent Written informed consent was obtained from all subjects (patients) in this study.

Animal study The study is not on animals. No study subjects or cohorts have been previously reported.

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