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Improved Detection of Scaphoid Fractures with High-Resolution Peripheral Quantitative CT Compared with Conventional CT

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Background: Computed tomography (CT), magnetic resonance imaging, and bone scintigraphy are second-line imaging techniques that are frequently used for the evaluation of patients with a clinically suspected scaphoid fracture. However, as a result of varying diagnostic performance results, no true reference standard exists for scaphoid fracture diagnosis. We hypothesized that the use of high-resolution peripheral quantitative CT (HR-pQCT) in patients with a clinically suspected scaphoid fracture could improve scaphoid fracture detection compared with conventional CT in the clinical setting.

Methods: The present study included 91 consecutive patients (≥ 18 years of age) who presented to the emergency department with a clinically suspected scaphoid fracture between December 2017 and October 2018. All patients were clinically reassessed within 14 days after first presentation, followed by CT and HR-pQCT. If a scaphoid fracture was present, the fracture type was determined according to the Herbert classification system and correlation between CT and HR-pQCT was estimated with use of the Kendall W statistic or coefficient of concordance (W) (the closer to 1, the higher the correlation).

Results: The cohort included 45 men and 46 women with a median age of 52 years (interquartile range, 29 to 67 years). HR-pQCT revealed a scaphoid fracture in 24 patients (26%), whereas CT revealed a scaphoid fracture in 15 patients (16%). Patients with a scaphoid fracture were younger and more often male. The correlation between CT and HR-pQCT was high for scaphoid fracture type according to the Herbert classification system ($W = 0.793$; 95% confidence interval [CI], 0.57 to 0.91; $p < 0.001$) and very high for scaphoid fracture location ($W = 0.955$; 95% CI 0.90 to 0.98; $p < 0.001$).

Conclusions: In the present study, the number of patients diagnosed with a scaphoid fracture was 60% higher when using HR-pQCT as compared with CT. These findings imply that a substantial proportion of fractures—in this study, more than one-third—will be missed by the current application of CT scanning in patients with a clinically suspected scaphoid fracture.

Level of Evidence: Diagnostic Level II. See Instructions for Authors for a complete description of levels of evidence.

The scaphoid bone is the most commonly fractured carpal bone. Scaphoid fractures represent 2% to 6% of all fractures and occur mainly in young and active patients 15 to 40 years of age. In the Netherlands, scaphoid fractures account for 90% of all carpal fractures¹⁻⁴. The scaphoid bone articulates with 5 surrounding bones and therefore serves a key role in the function of the wrist⁵. Inadequate treatment of a scaphoid fracture can lead to malunion, nonunion, and early osteoarthritis^{1,6,7}. These complications are associated with pain,

decreased range of motion, reduced grip strength, and worse functional outcome. Consequently, early and accurate diagnosis is important. As up to 25% of scaphoid fractures remain radiographically occult with conventional imaging^{1,8-10}, patients with a suspected scaphoid fracture are generally managed with cast immobilization, and reassessment takes place after approximately 10 days, resulting in a diagnostic delay of up to 2 weeks. According to the existing literature, only 10% to 20% of clinically suspected fractures are true fractures^{4,8,11-14}. This implies

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that most patients are overtreated, with unnecessary socioeconomic effects, as result of cast immobilization.

Radiographic diagnosis of scaphoid fractures is difficult because of the unique shape, size, and orientation of this carpal bone. Various imaging techniques have been suggested for the improvement of diagnosis and the reduction of overtreatment. Computed tomography (CT), magnetic resonance imaging (MRI), and bone scintigraphy (BS) are most frequently used today, but all have limitations^{11-13,15-24}. None of the investigated diagnostic modalities is both sensitive and specific, and therefore no true reference standard exists. Despite advanced knowledge and imaging methods, diagnosing scaphoid fractures remains challenging, and the preferred imaging technique differs according to hospital. The technique used at the hospital involved in the present study is CT.

The development of high-resolution peripheral quantitative CT (HR-pQCT), a novel high-resolution and low-radiation-dose technique, allows for the assessment of cortical and trabecular bone microarchitecture at the distal parts of the radius and tibia^{25,26}. Recent research has shown that studying the fracture-healing process of stable distal radial fractures^{27,28} and scanning the scaphoid bone in patients with a clinically suspected scaphoid fracture are feasible with HR-pQCT²⁹. We hypothesized that the use of HR-pQCT for patients with a clinically suspected scaphoid fracture would improve scaphoid fracture detection when compared with conventional CT in the clinical setting.

Materials and Methods

The present study was approved by the medical ethics committee (NL 62476.068.17) and was conducted according to the principles of the Declaration of Helsinki and in accordance with the Medical Research Involving Human Subjects Act (WMO).

Study Population

For the present study, all patients with a clinically suspected scaphoid fracture presenting to the emergency department within 1 week after trauma were screened for eligibility. Pregnant women and patients with a previous ipsilateral scaphoid fracture were excluded. Between December 2017 and October 2018, a total of 91 patients ≥ 18 years of age were enrolled in our study (Fig. 1). In the emergency department, conventional radiographs were made in 4 views: posteroanterior, true lateral, semipronated oblique, and posteroanterior with the wrist in ulnar deviation. Independent of the diagnosis on these initial radiographs, cast immobilization was applied until the definite diagnosis was obtained. All patients, regardless of the findings on the initial radiographs, received written information on the study from their treating physician in the emergency department and were, after granting permission, contacted by telephone within the next 4 days by the investigator to answer any remaining questions that they had regarding the study. CT and HR-pQCT were scheduled immediately following reassessment in the outpatient clinic. According to current clinical practice, this reassessment was performed within 7 to 14 days after

trauma. Informed consent was obtained during this visit and was followed by physical examination, questionnaires, CT, and HR-pQCT. Medical history, smoking status, alcohol use, medication use, hand dominance, and trauma mechanism were registered.

CT Scanning

CT of the affected forearm was performed with use of the SOMATOM Definition AS (Siemens). This scanner contains an 80-kW generator and Ultra-Fast Ceramics detector with a rotation time of 1 second (tube voltage, 120 kV; tube current range, 35 μ A; pitch, 0.6; 128 slices; slice thickness, 1.0 mm; slice increment, 0.5 mm). The effective radiation dose of 1 CT scan of the hand and wrist is 46 μ Sv. All scans were conducted with the wrist in a fiberglass cast. According to the local protocol, all scans were reconstructed in the transverse, coronal, and sagittal planes of the wrist. In cases in which no fracture was detected on the 3 conventional reconstructed planes, reconstruction in the plane of the scaphoid was obtained. CT images were uploaded into IMPAX Client software (AGFA).

HR-pQCT Scanning

Second-generation HR-pQCT (XtremeCT II; Scanco Medical AG) was used to scan the affected forearm. All scans were conducted with the wrist in a fiberglass cast with a detachable fiberglass cast around the thumb, which was only applied during the HR-pQCT procedure for added stability of the thumb. The forearm was placed into an anatomically shaped holder to obtain a standardized position. On the basis of a scout view, the region of interest was determined, and a reference line was placed on the rim at the joint surface of the distal part of the radius. The standard scan protocol of the distal part of the radius, with an isotropic voxel size of 0.061 mm, was adapted to 3 consecutive stacks of 10.2 mm, resulting in a scanned region of 30.6 mm to cover the entire scaphoid bone. The effective radiation dose of HR-pQCT scanning of the scaphoid is 15 μ Sv. The maximum dose to which patients were exposed was 30 μ Sv when repetition of the scan was necessary because of motion artifacts (grade-4 to 5)³⁰⁻³³, which were graded according to the manufacturer's protocol and the method of Pialat et al.³². In the present study, all scans were considered to be of acceptable quality for fracture assessment, including 3 scans that had grade-4 quality in only 1 of the 3 stacks. Scans were exported in Digital Imaging and Communications in Medicine (DICOM) format. Source images were reconstructed into transverse, coronal, and sagittal planes. All HR-pQCT images and reconstructions were anonymized and uploaded to the local workstation.

Scan Evaluation

All CT scans were evaluated by a radiologist (within 48 hours) and a dedicated hand and wrist orthopaedic trauma surgeon (within 1 week); both were blinded to the other's assessment of the patients as well as to their clinical data. They were asked to state the type of fracture (i.e., scaphoid, distal radial, carpal) on the basis of their expert opinion and to classify the scaphoid

Fig. 1

Flowchart illustrating inclusion and exclusion of patients with a clinically suspected scaphoid fracture at the emergency department (ED).

fracture, if present, according to the Herbert classification system (Fig. 2)³⁴. Additional assessment by a third investigator was used for scans with a discrepant judgment by the 2 observers (n = 4). The subsequent decision regarding diagnosis was based on majority assessment.

All HR-pQCT scans were evaluated by a musculoskeletal radiologist. In a previous study, the interobserver agreement for 4 observers (2 musculoskeletal radiologists and 2 orthopaedic trauma surgeons) was shown to be almost perfect regarding scaphoid fracture diagnosis with HR-pQCT in patients with a clinically suspected scaphoid fracture³⁵. The observers evaluated each HR-pQCT scan independently and were asked to determine the presence of a scaphoid fracture or other fracture (i.e., distal radial, carpal, metacarpal) on the basis of their expert opinion and to classify the scaphoid fracture, if present, according to the Herbert classification system (Fig. 2)³⁴. The observers were aware of the fact that all patients were clinically suspected of having a scaphoid fracture on the basis of physical examination in the emergency department. All observers were blinded to the diagnosis on

conventional radiographs and CT and were not aware of the others' assessments. The observers did not have access to any clinical data on the patients.

Statistical Analysis

Statistical analysis was performed with use of SPSS Statistics (version 24; IBM). The distribution of the data was tested with Q-Q (quantile-quantile) plots and Kolmogorov-Smirnov analysis. Normally distributed data are presented as the mean and the standard deviation (SD). Age was non-normally distributed and therefore is presented as the median with the interquartile range (IQR). Chi-square and independent-sample t tests were used to analyze differences between patients with a fracture (scaphoid or other) and without a fracture. Crosstab calculation with McNemar testing was conducted to compare the proportions of scaphoid fractures diagnosed on CT and HR-pQCT. The correlation between scaphoid fracture classification and location with CT and HR-pQCT was estimated with use of the Kendall W statistic or coefficient of concordance (W); the closer to 1, the higher the correlation. Diagnostics performance characteristics were calculated with use of the MedCalc diagnostic test evaluation calculator and are presented as percentages with 95% confidence intervals (CIs). The level of significance was set at 0.05.

Results

Patient Characteristics

All patients were reassessed at the outpatient clinic within 14 days after presentation at the emergency department (median, 10 days; IQR, 6 to 14 days). The cohort consisted of

Fig. 2

Illustrations depicting the Herbert scaphoid fracture classification system (1984).

TABLE I Distribution of Scaphoid Fracture Incidence by Sex and Age Group for CT and HR-pQCT Diagnosis

	Scaphoid Fracture (no. [%] of patients)				
	18-29 Years	30-49 Years	50-69 Years	70+ Years	Total
CT (n = 15)					
Men	5 (33.3%)	3 (20.0%)	1 (6.7%)	1 (6.7%)	10 (66.7%)
Women	1 (6.7%)	2 (13.3%)	1 (6.7%)	1 (6.7%)	5 (33.3%)
HR-pQCT (n = 24)					
Men	7 (29.2%)	5 (20.8%)	2 (8.3%)	1 (4.2%)	15 (62.5%)
Women	3 (12.5%)	3 (12.5%)	2 (8.3%)	1 (4.2%)	9 (37.5%)

45 men and 46 women with a median age of 52 years (IQR, 29 to 67 years). Men were significantly younger compared with women (37 versus 62 years; $p < 0.001$). On CT, 15 patients with a median age of 41 years (IQR, 22 to 53 years) were diagnosed with a scaphoid fracture. On HR-pQCT, 24 patients with a median age of 44 years (IQR, 35 to 65 years) were diagnosed with a scaphoid fracture. The number and proportion of scaphoid fractures on CT and HR-pQCT according to sex and age are shown in Table I.

Fracture Diagnosis

In the entire cohort, 1 nondisplaced triquetral fracture was diagnosed on HR-pQCT but not on CT and 6 distal radial fractures were not diagnosed on HR-pQCT because of the restricted scanned region; those fractures were not registered as missed diagnoses.

Nine scaphoid fractures (37.5%) that were diagnosed with HR-pQCT were not diagnosed with CT, resulting in a significant difference in the proportion of patients with a scaphoid fracture on CT and HR-pQCT ($p = 0.004$) (Fig. 3). Figures 4 and 5 demonstrate the CT and HR-pQCT images for 2 patients with a scaphoid fracture that was detected on HR-pQCT but not on CT.

Two of the 9 patients in whom a scaphoid fracture was diagnosed on HR-pQCT only did not want to receive treatment

as they experienced no discomfort as a result of the fracture and refused follow-up. The other 7 patients were managed with cast immobilization for at least 6 weeks, as were the patients in whom a scaphoid fracture was diagnosed on both CT and HR-pQCT. One of those 7 patients had a concurrent fracture of the hamate that was diagnosed on both CT and HR-pQCT.

There was no significant difference between men and women in terms of median age or between patients with and without a scaphoid fracture (on either CT or HR-pQCT) in terms of trauma mechanism (low-energy, high-energy, or sports/bicycle accidents).

Scaphoid Fracture Classification

The highest proportions of fracture types according to the Herbert classification system were type A1 on CT (40%) and type A2 on HR-pQCT (29%) (Figs. 6-A and 6-B). The most common location was distal on CT (53%) and the scaphoid waist on HR-pQCT (46%) (Figs. 7-A and 7-B). The correlation between CT and HR-pQCT was high for scaphoid fracture type ($W = 0.793$; 95% CI, 0.57 to 0.91; $p < 0.001$) and very high for scaphoid fracture location ($W = 0.955$; 95% CI, 0.90 to 0.98; $p < 0.001$). There was no significant difference between type-A and B fractures (as diagnosed on both CT and HR-pQCT) in terms of sex, age, or trauma mechanism (low-energy, high-energy, and sports/bicycle accidents).

Fig. 3

Pie charts showing the rates of scaphoid fracture on CT (**Fig. 3-A**) and HR-pQCT (**Fig. 3-B**) ($p = 0.004$).

Fig. 4

Figs. 4-A through 4-F A 25-year-old woman with a type-B3 scaphoid fracture that was diagnosed on HR-pQCT scans. **Figs. 4-A, 4-B, and 4-C** Transverse (**Fig. 4-A**), coronal (**Fig. 4-B**), and sagittal (**Fig. 4-C**) CT slices that were negative for scaphoid fracture. **Figs. 4-D, 4-E, and 4-F** Transverse (**Fig. 4-D**), coronal (**Fig. 4-E**), and sagittal (**Fig. 4-F**) HR-pQCT scans that were positive for scaphoid fracture (arrows).

Discussion

To our knowledge, the present study is the first clinical study comparing CT and HR-pQCT for the diagnosis of scaph-

oid fractures. Many studies examining the use of CT, MRI, and BS for the diagnosis of such fractures have demonstrated a wide variation in diagnostic performance^{11,18,21,22,36}. This variation

Fig. 5

Figs. 5-A through 5-F A 38-year-old woman with a type-A2 scaphoid fracture that was diagnosed on HR-pQCT scans. **Figs. 5-A, 5-B, and 5-C** Transverse (**Fig. 5-A**), coronal (**Fig. 5-B**), and sagittal (**Fig. 5-C**) CT slices that were negative for scaphoid fracture. **Figs. 5-D, 5-E, and 5-F** Transverse (**Fig. 5-D**), coronal (**Fig. 5-E**), and sagittal (**Fig. 5-F**) HR-pQCT scans that were positive for scaphoid fracture (arrows).

Fig. 6

Pie chart showing the Herbert scaphoid fracture classification on CT (**Fig. 6-A**) and HR-pQCT (**Fig. 6-B**) ($W = 0.793$).

might be a result of the low incidence of scaphoid fractures and the use of different scanning protocols. MRI is an appropriate imaging technique to exclude a scaphoid fracture (specificity, 94% to 100%)^{17,20,22,37,38}. However, MRI is time-consuming, has restricted availability in many hospitals, and is relatively expensive¹⁶. In contrast, CT is readily available and less expensive. A limitation of CT in diagnosing scaphoid fractures is its relatively low sensitivity compared with MRI and BS and the exposure of patients to radiation^{11,18,21,36}. BS has high sensitivity but low specificity^{17,21,22,37,38} and is invasive, is time-consuming, and leads to a delay in diagnosis of 3 to 5 days. Most studies have used an unreliable method—namely, repeated radiographs after 6 weeks^{22,39-42}—as the reference standard^{11,16-18}. The lack of a universal reference standard makes it difficult to compare the results of previous studies and contributes to the described variation.

Current clinical imaging techniques, as described above, lack the ability to assess bone microarchitecture and thereby separately assess cortical and trabecular bone. A noninvasive method that recently became available for the assessment of bone microarchitecture at the distal parts of the radius and tibia is HR-pQCT⁴³. Validation and reproducibility studies of HR-

pQCT have been performed extensively for the distal part of the radius⁴⁴⁻⁴⁷, and, in the last decade, widespread experience has been gathered in the use of this technique for clinical research^{48,49}. It is conceivable that distinctions between vascular structures, motion artifacts, and fractures are more apparent with this method because of its higher resolution, which may help to improve scaphoid fracture diagnosis. In the present study, the HR-pQCT scan had to be repeated because of poor quality for only 5 patients, resulting in a mean radiation dose of 16 μ Sv per patient. This lower dose of HR-QCT as compared with the dose of a CT scan of the hand/wrist (16 compared with 46 μ Sv) can be explained by the fact that the length of the scanned region with HR-pQCT covers only 30.6 mm at the level of the scaphoid bone, whereas CT covers the scaphoid bone, the distal part of the radius, and all carpal bones. Accordingly, the effective radiation dose of HR-pQCT is very low compared with CT but can be interpreted as equal if the length of the scanned region is taken into account.

In previous studies, we found that HR-pQCT is a feasible and reliable technique for scaphoid fracture diagnosis²⁹, with “almost perfect” interobserver agreement (Fleiss kappa, 0.91) according to the guidelines by Landis and Koch³⁵. In the present

Fig. 7

Pie chart showing the scaphoid fracture location assessment on CT (**Fig. 7-A**) and HR-pQCT (**Fig. 7-B**) ($W = 0.955$).

study, the number of patients diagnosed with a scaphoid fracture was 60% higher when using HR-pQCT as compared with CT.

In agreement with previous studies^{8,50,51}, our data showed male predominance and relatively young age in patients with scaphoid fractures. We found no difference in mechanism of injury between patients with a scaphoid fracture, with another type of fracture, and without a fracture in the present study. Regarding scaphoid fracture location, previous studies of adults have demonstrated that scaphoid waist fractures are the most common, inconsistently followed by proximal^{4,33,52} and distal⁵³⁻⁵⁵ fractures. In the present study, the most common fractures were type-A1 (tubercle) fractures based on CT and type-A2 fractures based on HR-pQCT (Figs. 6-A and 6-B). This finding implies that HR-pQCT detects more clinically relevant fractures. As a result of the relatively small numbers, no hard conclusions can be drawn on this topic yet.

The present study is limited by the lack of a true reference standard; one of the important challenges in diagnosing scaphoid fractures is the development of such a standard. In the present study, we compared a novel technique (HR-pQCT) with an existing technique (CT) for scaphoid fracture detection and found that HR-pQCT detects scaphoid fractures that CT does not. These findings are promising but need to be replicated in other studies, and further research should address the clinical consequences of scaphoid fractures that are missed on CT and investigate the cost-effectiveness of HR-pQCT. Although the implementation of HR-pQCT is achievable in daily practice as the scanning time for the scaphoid is only 6 minutes, HR-pQCT is currently used for research purposes and substantial processing time is required. In our facility, the costs of an HR-pQCT scan are roughly 3 times higher than the costs of a regular CT scan. On the basis of current developments related to high-resolution scanners, standard protocols for scanning the scaphoid will be developed and image processing and analysis time will most likely be reduced in the near future. The availability of HR-pQCT scanners worldwide remains a limitation. Another limitation of our study is the lack of assessment of intraobserver variability as the observers only assessed the scans once. The present study is strengthened by the relatively large cohort of patients with a clinically suspected scaphoid fracture. Moreover, all included patients underwent both CT and HR-pQCT on the same day.

In conclusion, scaphoid fracture detection is superior with HR-pQCT in comparison with CT. The number of patients with a diagnosed scaphoid fracture was 60% higher when using

HR-pQCT as compared with CT. HR-pQCT could be a promising new application for the detection of scaphoid fractures. ■

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