Gantry-Free High-Resolution Cone-Beam CT: Efficacy for Distal Radius and Scaphoid Fracture Detection and Characterization

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Objectives: Gantry-free cone-beam CT (CBCT) allows for comfortable patient positioning due to an open scanner architecture. Since CBCT without gantry is not yet established for clinical wrist trauma imaging, this study’s aim was to investigate its diagnostic value in the preoperative workup of patients with distal radius and scaphoid fractures.

Methods: Within a 12-month period, 113 patients with severe wrist trauma underwent both radiography and CBCT with the same gantry-free multi-use scanner before surgery. Two radiologists retrospectively analyzed all datasets for the morphology of distal radius (n = 95) and scaphoid fractures (n = 20). In all 115 wrists (two bilateral injuries), surgical reports served as the standard of reference.

Results: While accuracy for distal radius fractures was comparable among CBCT and radiographs, the former was superior with regard to scaphoid fractures (Reader 1: 100.0% vs. 75.0%; Reader 2: 100.0% vs. 65.0%). Accuracy for multi-fragmentary radius injuries (100.0% vs. 90.5%; 100.0% vs. 93.7%), and articular affliction (99.0% vs. 84.2%; 100.0% vs. 83.2%) was also higher in CBCT. Regarding scaphoid fractures, CBCT proved superior for diagnosis of proximal pole or waist involvement (100.0% vs. 70.0%; 100.0% vs. 65.0%) and comminuted patterns (100.0% vs. 70.0%; 100.0% vs. 75.0%). Median effective dose of CBCT was as low as 3.65 μSv compared with 0.16 μSv for standard radiography.

Conclusion: Gantry-free CBCT allows for excellent diagnostic accuracy in the assessment of distal radius and scaphoid fracture morphology. Even in patients with limited mobility, very low radiation dose is sufficient to maintain high image quality.

Key Words: Cone-beam computed tomography; Wrist; Trauma; Fracture; Radiography.

INTRODUCTION

For surgical decision making and operative planning of distal radius and scaphoid fractures, sufficient radiographic imaging is essential. According to the ACR Appropriateness Criteria, CT imaging without intravenous contrast is recommended for hand and wrist trauma in case of suspected fractures and equivocal or negative initial radiographs (1). Several studies have indicated that adjunct CT improves reliability and accuracy in detection of intraarticular and displaced fractures of the distal radius and scaphoid, frequently influencing treatment decisions for geometrically complex fractures in particular (2,3). In recent years, Bain and Hintringer have postulated the importance of preoperative assessment of so-called “key-fragments” in distal radius fractures. The authors emphasize the impact such knowledge has in employing modern treatment strategies and selecting the appropriate surgical approach (4,5). In order to ensure that radiation exposure remains "as low as reasonably achievable" (ALARA principle), multidetector CT (MDCT) scans of the wrist and hand are performed in superman position (prone position with the injured arm stretched out above head level), if possible (6). However, conventional gantry-based CT...
architecture and limited patient mobility, e.g., in case of concomitant injuries of the elbow or shoulder or external fixation, frequently enforce compromises such as positioning the upper extremity either on or adjacent to the patient’s trunk, penalizing image quality and increasing radiation exposure considerably (7,8).

Originating in the field of dental and maxillofacial imaging in the 1990s, cone-beam computed tomography (CBCT) combines energy-integrating flat-panel detector technology with pyramidal beam geometry to achieve superior spatial resolution and dose efficiency in limited scan volumes (9). Due to the development of specialized extremity scanners in recent years, CBCT has become increasingly recognized as a precise tool for cross-sectional examinations of the peripheral skeletal system (10–12). A further advantage of newer CBCT scanners lies in the high degrees of freedom regarding patient positioning options. The gantry-free twin robotic x-ray system utilized in this study allows for upper extremities to be examined in 90° abduction and full extension, as well as with incurvation of the elbow joint, if necessary. While recent literature has reported high accuracy in the detection of occult radiocarpal fractures (13), studies evaluating the performance of CBCT in severe trauma settings of the wrist with robust surgical reference standards are lacking.

Therefore, the presented investigation aims to establish CBCT as a viable alternative to MDCT for cross-sectional imaging in the preoperative workup of patients with suchlike injuries.

MATERIALS AND METHODS

Permission for conducting this monocentric study was granted by the local ethics committee, which waived the need for additional written informed consent due to the retrospective design. The Standards for Reporting of Diagnostic Accuracy (STARD) guidelines were adhered to (14).

Participants

Patients were enrolled during a 12-month period between January and December 2021, referring a total of 259 individuals (261 scans including two bilateral examinations) to this study. Anyone who had been subjected to imaging of the hand and wrist for acute trauma by means of CBCT in high-resolution scan mode with a gantry-free, twin robotic x-ray system (Multitom Rax, Siemens Healthineers, Erlangen, Germany) was eligible. Further inclusion criteria involved prior radiographs on the same multi-use x-ray system in two planes of the same region for the same indication. Twenty-five patients (25 scans) with examinations focused on regions distal of the carpus were excluded (16 finger, 9 metacarpal scans). All remaining 234 patients (236 scans) with radiographs and CBCT focused on depiction of the wrist and carpus were reviewed within the study. Afterwards, lack of ensuing surgical procedure of the distal radius or scaphoid and thus lack of robust reference standard mandated exclusion of 121 more participants (121 scans), resulting in a final study cohort of 113 patients (115 scans). A flow-chart illustrating the study design with a summary of inclusions and exclusions is presented in Figure 1.

Imaging

All digital radiographs and CBCT examinations were made with the same multi-use x-ray system by trained radiographers. Instead of a conventional, gantry-based CT architecture, the twin robotic scanner employs two telescopic arms connected to ceiling rails. The 3D scan mode (version VF11, Siemens Healthineers) relies on synchronized arm trajectories with asymmetrical source-to-image distance of 115 cm and a sweep angle of 200 degrees around the isocenter. Additionally, the high-resolution CBCT mode applies un-binned readout of the energy-integrating flat-panel detector. 3D scans require 14 seconds for the acquisition of 318 projection images, which are then post-processed with specialized software (syngo.via View&GO, Siemens Healthineers). Radiographs were made in anterior-posterior and lateral view with median tube voltage and current-time product set to 49.9 / 54.9 kV and 2.0 / 2.5 mAs, respectively. CBCT examinations were performed in the so-called “tableside position” with the afflicted arm in 90° lateral abduction and the wrist in a comfortable pronation position. Acquisition parameters for CBCT studies were set to a tube voltage of 80.3 kV and a median tube-current-time product of 197.2 mAs. Dose-area products of radiographs and CBCT were recorded from the standardized patient reports that are generated with every scan. Effective radiation dose was calculated by means of established conversion factors (15,16). Acquisition parameters and associated dose values are presented in Table 1.

Raw image data were reconstructed in ultra-high-resolution settings with a scanner-specific bone kernel and a field of view of 100 mm. Reformatted images were presented in axial, coronal and sagittal orientation, selected slice thickness was 1 mm with an increment of 0.5 mm. Supplemental 3D virtual renderings for visualization of fracture geometry were prepared on the basis of an intermediate convolution kernel.

Fracture Analysis

The reference standard for all included wrists consisted of surgical reports. Radiography and CBCT data sets were reviewed separately, individually and in randomized fashion by two radiologists with nine and 5 years of training in musculoskeletal imaging, who were blinded to clinical presentation and surgical findings. Readers were explicitly tasked with finding fractures of the distal radius and scaphoid bone. For radius injuries, the presence of articular surface involvement was assessed dichotomously, whereas involvement of the proximal pole and/or scaphoid waist was evaluated in similar fashion in scaphoid fractures. In addition, the presence of multi-fragmentary fracture patterns was determined by the two readers. Finally, subjective ratings of diagnostic confidence were collected by means of an equidistant five-point
scale (1 = total lack of confidence; 5 = superb confidence). Image reading was conducted with standard radiological workstations and PACS software (Merlin, Phönix-PACS, Freiburg, Germany).

Statistics

Data analysis was aided by dedicated software (SPSS Statistics 28, IBM, Armonk, NY). Parametric data are stated as means ± standard deviation, whereas non-parametric variables are provided as absolute and relative frequencies with median and interquartile ranges. Classification functions for radiography and CBCT were calculated separately for the distal radius and scaphoid bone. The McNemar test was employed for evaluating differences in diagnostic test accuracy whenever statistically possible (17), otherwise absolute values and percentages are reported. Wilcoxon signed rank tests served for comparing paired ordinal-scaled variables. An alpha level of 0.05 was considered representative of statistical significance.

RESULTS

Study Cohort

After applying the stated exclusion criteria, the final study cohort consisted of 113 individuals (61 women; 52.6 ± 19.2 years) receiving 115 scans. One patient with both-sided, simultaneous fractures of the distal radius and one patient with both-sided, simultaneous scaphoid fractures were included. The left upper extremity was afflicted in 63 patients (54.8 %). The distal radius was fractured in 95 wrists (82.6% of all patients), of which 87 (91.6%) displayed an intraarticular fracture involvement and 91 (95.8%) exhibited a multifragmentary pattern. Of the 20 scaphoid fractures (17.4% of

**TABLE 1. Scan Settings**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Dorsovolar / Lateral Radiographs</th>
<th>High-Resolution Cone-Beam CT Scan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube potential [kV]</td>
<td>49.90 / 54.90</td>
<td>80.30</td>
</tr>
<tr>
<td>Current-time product [mAs]</td>
<td>2.03 / 2.24</td>
<td>197.16</td>
</tr>
<tr>
<td>Median DAP (IQR) [dGy·cm²]</td>
<td>0.16 (0.14 – 0.19)</td>
<td>11.77 (11.71 – 13.89)</td>
</tr>
<tr>
<td>Median estimated ED (IQR) [µSv]</td>
<td>0.16 (0.14 – 0.19)</td>
<td>3.65 (3.42 – 4.29)</td>
</tr>
</tbody>
</table>

Note: DAP, dose-area-product; ED, effective dose; IQR, interquartile range
all patients), 6 (30.0%) showed a comminuted pattern while 19 (95.0%) afflicted either the proximal pole or scaphoid waist.

Radiation Dose

For standard anterior–posterior and lateral radiographs, the combined median dose-area product was 0.16 (interquartile range 0.14 – 0.19 dGy*cm²), whereas the median dose-area product of CBCT examinations was 11.77 dGy*cm² (11.71 – 13.89 dGy*cm²). This amounted to an estimated effective dose of 0.16 μSv (0.14 – 0.19 μSv) and 3.65 μSv (3.42 – 4.29 μSv), respectively.

Diagnostic Accuracy

While diagnostic accuracy for fractures of the radius was identical among CBCT and radiography (R1: 100.0% vs. 100.0%; R2: 100.0% vs. 100.0%), detection of multi-fragmentary fracture patterns (R1: 100.0% vs. 90.5%; R2: 100.0% vs. 93.7%), and articular involvement (R1: 99.0% vs. 84.2%; R2: 100.0% vs. 83.2%) was higher for CBCT. Figure 2 displays a patient case with joint surface affliction difficult to rule out in conventional radiographs, whereas Figure 3 provides an example of a falsely suspected articular injury that was ruled out in CBCT. With regards to scaphoid fractures, accuracy of CBCT superseded radiography considerably (R1: 100.0% vs. 75.0%; R2: 100.0% vs. 65.0%). The “greater arc injury” visualized in Figure 4 includes a radiographically occult scaphoid waist fracture concomitant to the displaced injury of the distal forearm. Superior results were also observed for assessment of multi-fragmentary fracture geometry (R1: 100.0% vs. 70.0%; R2: 100.0% vs. 75.0%) and involvement of the proximal pole and scaphoid waist (R1: 100.0% vs. 70.0%; R2: 100.0% vs. 65.0%). Suchlike injuries may entail a delayed fracture healing, as is exemplified in Figure 5. Detailed classification functions of diagnostic accuracy in severe radius and scaphoid fractures are summarized in Table 2.

Figure 2. After being involved in a bicycle accident, a 52-year-old man was admitted to the emergency department for increasing left wrist pain and swelling. (a/b) Initial radiographs in lateral and dorsovolar orientation showed a distal radius fracture with slight metaphyseal impaction and concomitant fracture of the ulnar styloid process, corresponding to a AO-OTA 2RA2.3 injury. (c/d) Ultra-high-resolution CBCT revealed fracture involvement of both the distal radioulnar and radiocarpal joints (arrows), hence upgrading the injury to AO-OTA type 2RC1.3. (e/f) One day after the accident, internal fixation was performed after open reduction. Intraoperative fluoroscopy in lateral and volodorsal projection depicted correct placement of the inserted volar locking plate. Clinical and imaging follow-up at 1 and 3 months revealed satisfactory fracture healing.
Subjective Diagnostic Confidence

With assessment on the basis of CBCT scans, diagnostic confidence of both readers was considerably higher compared with analysis of radiographs (R1/R2: \( p < 0.001 \)). Ratings scores of “high confidence” or more (rating scores of four or five) were attributed to all 115 CBCT scans (R1 and R2) and 86 (74.8%; R1) and 90 (78.3%; R2) radiographs. While no ratings of poor confidence or worse (ratings one and two) were assigned to CBCT scans, radiography received suchlike ratings in 11 (9.6%; R1) and 10 (8.7%; R2) wrists. Confidence ratings are summarized in Table 3.

DISCUSSION

In this retrospective study of 113 individuals with 115 surgically confirmed and treated fractures of the distal radius and scaphoid bone, gantry-free cone-beam CT was established as a highly reliable diagnostic tool for preoperative workup in severe wrist trauma. With almost perfect diagnostic accuracy and reader confidence for fracture presence, intraarticular surface involvement, and multi-fragmentary geometry, the results suggest that this method constitutes a full-fledged alternative to gantry-based multidetector CT. Supported by the twin robotic arms’ superior patient positioning options and consecutive distance of the hand to the radiation sensitive body trunk, achieved median effective dose was as low as 3.65 \( \mu \)Sv.

While CBCT has been shown to outperform radiography in the detection of occult small bone and joint fractures, suchlike studies are usually impaired by an inconsistent reference standard like clinical follow-up, adjunct MRI and consensus reading (18–20). However, particularly in the presence of severe trauma, the true extent and complexity of injuries may be masked in diagnostic imaging (21,22). As patients in our institution do not receive simultaneous CBCT and MDCT examinations of the same anatomical region, this study offers neither a direct comparison of both techniques, nor a statement concerning superior diagnostic capabilities of either. Notwithstanding, by relying solely on surgical confirmation of the reported findings, the methodology of the current investigation ensures that CBCT performance assessment is held to the highest possible reference standard (Fig 6). The reported superior accuracy of cross-sectional imaging compared with two-dimensional radiographs for detailed characterization of distal radius fracture...
morphology is in line with the findings of Harness et al. (23). In contrast, regarding the scaphoid bone, the fracture detection rate itself benefits from CBCT imaging, which supports the recent results of Daniels et al. (24). While not in the specific focus of the current investigation, fractures of other carpal bones may also be detectable with superior accuracy in CBCT studies, since over-projection constitutes a major limitation for the diagnostic assessability of 2D wrist imaging.

While the ACR Appropriateness Criteria for acute hand and wrist trauma mandate an effective dose of less than 100 μSv (1), the median radiation exposure for gantry-free CBCT in this study amounted to less than 4% of that limit. In contrast, current low-dose MDCT imaging studies of the wrist report effective doses of 89 μSv (25) and even compared with a recent meta-analysis focused specifically on CBCT imaging of peripheral joints, the radiation dose in this study is approximately half as high (26). It must be noted, though, that the dose effect in wrist examinations is smaller than in scans of the radiation-sensitive body trunk due to a small tissue weighting factor.

The specific gantry-free CBCT architecture allows for an asymmetric acquisition geometry that offsets the restricting influence of the focal spot regarding image resolution. This, combined with an un-binned detector matrix readout results in a pixel size of 149 μm (9). In addition, dose penalties due to suboptimal positioning of the injured extremity adjacent to the trunk are eliminated completely by making use of the table-side synchronized trajectory for both robotic arms. While the effect of patient movement in CBCT imaging is far from overcome, due to longer acquisition times (14 seconds in this study), improved motion compensation algorithms and comfortable positioning are important factors in decreasing the extent of motion artifacts as much as possible. With the dose and positioning advantages over gantry-based MDCT, as well as the potential to perform CBCT scans immediately after radiography without repositioning or additional patient transfer, we argue that the clinical value of the twin robotic x-ray system also lies in the scanner’s “one-stop-shop” potential, allowing to customize each examination precisely to the needs of the individual trauma patient. If necessary, additional fluoroscopy can be performed.
for dynamic wrist examinations and arthrography directly in the same setting.

Limitations

Some limitations must be addressed for this study. First, no direct comparison with MDCT was available, since patients do not receive two forms of CT imaging at our department for radiation protection and ethical considerations. Second, relying solely on surgical reference standards incurred an inclusion bias focusing on severe injuries. In order to address this drawback and avoid reader bias, both radiologists reviewed all 236 examinations prior to final exclusion of cases without surgical confirmation (Fig 1). Lastly, due to the reported positive selection bias regarding fractures warranting surgery, no uninjured wrists were included in the analysis.

TABLE 2. Diagnostic Accuracy Numbers Given First Indicate Relative Frequencies, 95% Confidence Intervals Are Provided in Brackets, and Absolute Numbers of Items Are Displayed in Parentheses

<table>
<thead>
<tr>
<th></th>
<th>Cone-beam CT</th>
<th>Radiography</th>
<th>Cone-beam CT</th>
<th>Radiography</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius Fracture</td>
<td>100.00 (95/95)</td>
<td>100.00 (95/95)</td>
<td>100.00 (95/95)</td>
<td>100.00 (95/95)</td>
</tr>
<tr>
<td>Articular affliction</td>
<td>98.95 [94.27 – 99.97] (94/95)</td>
<td>84.21 [75.30 – 90.88] (80/95)</td>
<td>100.00 (95/95)</td>
<td>83.16 [74.10 – 90.05] (79/95)</td>
</tr>
<tr>
<td>Multi-fragmentary</td>
<td>100.00 (95/95)</td>
<td>90.53 [82.78 – 95.58] (86/95)</td>
<td>100.00 (95/95)</td>
<td>93.68 [86.76 – 97.65] (89/95)</td>
</tr>
<tr>
<td>Scaphoid Fracture</td>
<td>100.00 (20/20)</td>
<td>75.00 [50.90 – 91.34] (15/20)</td>
<td>100.00 (20/20)</td>
<td>65.00 [40.78 – 84-61] (13/20)</td>
</tr>
<tr>
<td>Waist or proximal pole</td>
<td>100.00 (20/20)</td>
<td>70.00 [45.72 – 88.11] (14/20)</td>
<td>100.00 (20/20)</td>
<td>65.00 [40.78 – 84-61] (13/20)</td>
</tr>
<tr>
<td>Multi-fragmentary</td>
<td>100.00 (20/20)</td>
<td>70.00 [45.72 – 88.11] (14/20)</td>
<td>100.00 (20/20)</td>
<td>75.00 [50.90 – 91.34] (15/20)</td>
</tr>
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</table>
Conclusions

Gantry-free cone-beam CT imaging allows for superior diagnostic accuracy and reader confidence compared with conventional radiography in distal radius and scaphoid fractures. The inherent high degree of freedom regarding wrist positioning facilitates low-dose imaging, even in the presence of limited patient mobility. Furthermore, a “one-stop-shop” approach without repositioning can be realized through the unique architecture of the two-armed robotic scanner, resulting in ubiquitous accessibility of cross-sectional imaging for surgical planning.

DISCLAIMER

Multitom Rax VF11 with 3D function is not available in all countries. Its future availability cannot be guaranteed.

REFERENCES


