https://doi.org/10.1186/s43055-024-01277-0

Egyptian Journal of Radiology and Nuclear Medicine

RESEARCH

Open Access

Image quality and patient satisfaction in cone-beam and multidetector computed tomography of the wrist: a randomized trial

Carolin S. Reidelbach[1†], Claudia Neubauer[1*†], Ann-Kristin H. Geissler[1,3], Florian Lampert[2,4], Horst Zajonc[2], Filip Simunovic[2], Fabian Bamberg[1], Elmar Kotter[1], Sebastian M. Goerke[2,5] and Jakob Neubauer[1]

Abstract

Background Musculoskeletal cone-beam computed tomography (CBCT) is an imaging technique for wrist assessment. In this study, we compared image quality and patient satisfaction between CBCT and multidetector computed tomography (MDCT) in traumatic wrist patients in a dose-matched setting.

Methods We prospectively enrolled traumatic patients who were scheduled for CT of the wrist. Patients were randomly assigned to CBCT or MDCT. Radiation dose was kept identical between both modalities. Subsequently, patients were asked to complete a questionnaire regarding the examination. Measurements of contrast-to-noise ratio (CNR) were performed. Three blinded readers independently rated image quality on Likert scales.

Results A total of 125 patients (mean age 35 years [standard deviation 16]; 91 men) were included. A total of 108 patients returned the questionnaire. With equivalent dose, CNRs were higher in CBCT compared to MDCT ($p < 0.001$) and the median ratings of image quality were better for CBCT compared to MDCT ($p \leq 0.04$). Patients only rated positioning in CBCT as more comfortable than in MDCT ($p < 0.001$), while there were no further differences regarding satisfaction with both modalities.

Conclusions At equivalent dose settings to MDCT, CBCT showed a high image quality for the depiction of bony structures, soft tissue and artifacts in wrist examinations of trauma patients. Overall, patients were equally satisfied with both methods. Altogether, CBCT might be a promising alternative for wrist imaging. However, further studies with more different devices are needed.

Keywords Contrast-to-noise ratio, Cone-beam computed tomography, Equivalent dose, Image quality, Multidetector computed tomography, Wrist imaging

†Carolin S. Reidelbach and Claudia Neubauer are Joined First Authors as these authors contributed equally to this work.

*Correspondence:
Claudia Neubauer
claudia.neubauer@uniklinik-freiburg.de
Full list of author information is available at the end of the article

Background

Computed tomographic examinations of the wrist and carpus are indicated for the clarification of both acute injuries and chronic pain [1, 2]. After compact cone-beam computed tomography (CBCT) scanners have become widely used for imaging of the facial skull [3], these scanners have also been increasingly established for musculoskeletal diagnostics of the extremities in the last 10 years [4–7]. Especially with diagnostically difficult traumatic injuries of the carpus, CBCT shows a good diagnostic performance [8].

CBCT devices differ from usual multidetector computed tomography (MDCT) scanners mainly in terms of their flat-panel detector, the smaller detector-focus distance and a simpler technical construction [9]. The flat-panel detector can generate a higher spatial resolution [10, 11]. Due to the lower dynamic range of the detector elements, CBCT is said to have a lower soft tissue contrast [12]. In addition, examinations typically take longer in CBCT than in MDCT. The simpler and therefore lighter design of CBCT scanners, however, allows a more natural tableside or seated positioning of the patient and in some cases even examinations under weight bearing, too [13, 14]. Their design allows CBCT scanners to be easier installed than MDCT scanners in numerous clinical settings. Based on the available literature, the current clinical standard for CT examinations of the wrist, however, is the multidetector CT.

The purpose of this study was to evaluate and compare patient's satisfaction as well as image quality between the dedicated musculoskeletal CBCT and the well-established MDCT for wrist examinations.

In addition, we wanted to investigate, if there were more artifacts (especially motion artifacts) in CBCT due to the longer examination time despite possibly more comfortable positioning.

We provided equal radiation doses in CBCT and MDCT examinations in this study. In this way, we ensured that differences in image quality could be attributed purely to differences in the two systems and not to a potentially higher radiation dose.

Based on our clinical experience, our hypothesis was, that patient's satisfaction is higher in CBCT compared to MDCT.

Regarding image quality, our hypothesis was, that artifacts might be less and image quality better in CBCT than in MDCT.

Methods

The ethics committee of our institution approved this prospective study (No. 245/13, approval 26/09/2013). Patient recruitment started on 03/03/2014; end of the study was 12/06/2015. Written informed consent was obtained from all patients participating in the study. This trial is registered at the German Clinical Trials Register (DRKS). There were no changes to methods after trial commencement.

Patients

We included all traumatic patients with a minimum age of 18 years scheduled for a computed tomography examination of the wrist in our institution over the above mentioned period. The patients were randomly assigned to either dedicated musculoskeletal CBCT or MDCT. Randomization envelopes were meticulously prepared, each containing a predetermined decision regarding either CBCT or MDCT, and subsequently sealed. Upon obtaining patient consent for study participation, an uninvolved colleague was summoned to unseal an envelope and disclose the randomized outcome, ensuring a blind and unbiased procedure for result reporting.

We aimed to include at least 100 patients with complete data sets.

MDCT device and protocol

For CT examinations, we used a 320 detector row MDCT (AquilionOne, Toshiba, Otawara-shi, Japan).

Dose levels were evaluated with Monte Carlo simulations that were performed according to a study of Neubauer et al. [11]. By default, the MDCT had a higher dose than the CBCT. Therefore, for this study, the dose of MDCT was decreased to meet the dose of CBCT.

In MDCT, patients were positioned in the superman position (prone position with the arm overhead and fully extended with pronation in the elbow joint for the hand to lie flat on the examination table). In addition, the hand was fixed with a strip of tape running from the examination table over the hand to minimize movement. Scouts were omitted, as the correct positioning of the hand was possible with the help of lasers only which were centered on the radiocarpal joint. The investigated volume covered 12.8 cm in length.

MDCT was performed at 100 kV and 22 mAs in a single-shot mode with a 180 degree rotation without pitch due to detector size. Axial reconstructions with a medium hard kernel FC30 were performed for a field of view of 16 × 16 cm, a matrix of 512 × 512 pixel and a slice thickness and gap of 0.2 mm (compare Table 1).

CBCT device and protocol

We used a CBCT scanner for imaging of extremities (Verity, Planmed, Helsinki, Finland). Patients were seated in a chair and the CBCT gantry was positioned to allow comfortable hand positioning in the device. The lower arm was pronated, allowing the hand to lie flatly on the balm on the examination table. In addition, the hand

Table 1 Comparison of multidetector computed tomography (MDCT) and cone-beam computed tomography (CBCT) device and protocol

	MDCT	CBCT
Manufacturer	Toshiba, Otawara-shi, Japan	Planmed, Helsinki, Finland
Model	AquilionOne	Verity
Manufactured/installed	2011/2011	2011/2012
Quality control	Every 3 months	Every 3 months
Protocol		
Positioning	Superman position with tape-fixed hand	Seated in chair with tape-fixed hand
Tube voltage	100 pkV	90 pkV
Tube currant	22 mA	36 mA
Rotation	180°	210°
Gantry rotation time	0.5 s	18 s
Pitch	Not applicable due to wide detector range	Not applicable due to wide detector range
Radiation dose	7.1 mGy	7.1 mGy
Reconstruction		
Kernel (medium hard)	FC30	Hamming filter
Field of view	16 × 16 × 12.8 cm	16 × 16 × 12.8 cm
Matrix	512 × 512 pixel	801 × 801 pixel
Slice thickness and gap	0.2 mm	0.2 mm
Pixel size in axial plane	0.3 mm	0.2 mm

was fixed in this position with a strip of tape to minimize movement artifacts. Scouts were not performed in CBCT examinations for the same reason as in MDCT examinations. The examination was centered on the radiocarpal joint with the help of lasers and covered 12.8 cm in length. CBCT was performed at standard dose with 90 kV and 36 mAs with a 210 degree rotation without pitch. Reconstructions were performed using a Hamming filter for medium hard kernels and included axial reconstructions for a field of view of 16 × 16 cm, a matrix of 801 × 801 pixel and slice thickness and gap of 0.2 mm (compare Table 1).

Patient's questionnaire

A questionnaire was designed in cooperation with a certified psychologist. Following the examination, all patients were asked to conclude the questionnaire. In the questionnaire, patients evaluated on a 6-point Likert scale, whether they found the duration of the examination adequate, whether the positioning was comfortable, whether the examination position was pleasant for them despite other physical illnesses, whether they were able to keep their hands steady during the exam, whether they were in additional pain during the exam, whether they found the methods for radiation protection (lead apron etc.) convenient, whether they felt protected by the radiation protection methods, and whether they were getting intimidated by the scanner.

Image analysis

For evaluation axial thin-slice images with an initial window/level setting of 500/2000 were used, which could be freely adjusted by the readers and from which any 3D multiplanar reconstruction could be generated as required. A consensus reading of the entire imaging and clinical record by two board approved radiologists with 16 and 8 years of experience in musculoskeletal radiology was used as a reference for the presence of a fracture.

The DICOM files of all patients were anonymized and all relevant data regarding the CT device were removed from the DICOM header in our PACS (Impax 8, Agfa, Mortsel, Belgium), used for analysis of the examinations. With the help of software (iNtuition, TeraRecon, Foster City, CA, USA), CT tables were manually cut out from all images to blind the reader for the type of device.

The reading took place under constant light conditions at a standard workstation. Examinations were presented in a random order.

In consensus, a board approved radiologist with 8 years of experience in musculoskeletal radiology and a medical student performed region of interest (ROI) measurements of the cortical bone of the distal radius, the trabecular bone of the distal radius, and, if possible, in the muscle of the thenar and hypodermic fatty tissue of the distal forearm in all patients.

A board approved radiologist with 6 years of experience in musculoskeletal radiology, a board approved radiologist with 7 years of experience in musculoskeletal radiology and 4 years of experience in wrist surgery as well as a board approved wrist surgeon with 8 years of experience in wrist surgery scored the image quality of all examinations regarding the depiction of cortical bone, trabecular bone, articular surfaces, soft tissue and fractures (if applicable) on a 5-point Likert scale with 1 being very good depiction, 2 being good depiction, 3 being fair depiction, 4 being bad depiction and 5 being very bad depiction. The readers also evaluated the images for the amount of artifacts and scored the amount of artifacts on a 3-point Likert scale with 1 being no artifacts, 2 being few artifacts without diagnostic impairment and 3 being severe artifacts with diagnostic impairment. The raters were provided with a lexicon of exemplary images for each category that was compiled by a board approved radiologist with 22 years of experience in musculoskeletal radiology and did not contain images from patients of the study.

Statistics

Inter-rater correlation was evaluated with Krippendorff's alpha [15]. Measurements and ratings were compared with Mann–Whitney U test and for binary categories with Fisher´s exact test. P values < 0.05 were considered to denote statistical significance and corrected with the Bonferroni method for all P values. Statistical analysis was performed with R (R version 4.0.2).

Results

Within the inclusion period, 155 patients were recruited. Thirty of these had to be excluded from the study due to incomplete imaging (n = 23 with 15 MDCT and 8 CBCT examinations) or missing imaging protocols (n = 7 with 4 MDCT and 3 CBCT examinations). Consequently, 125 patients were included in the study, 91 of them are male (Fig. 1). The mean age of patients was 35 years with a standard deviation of 16 years. Of these 125 patients, 68 patients received an MDCT examination and 57 patients

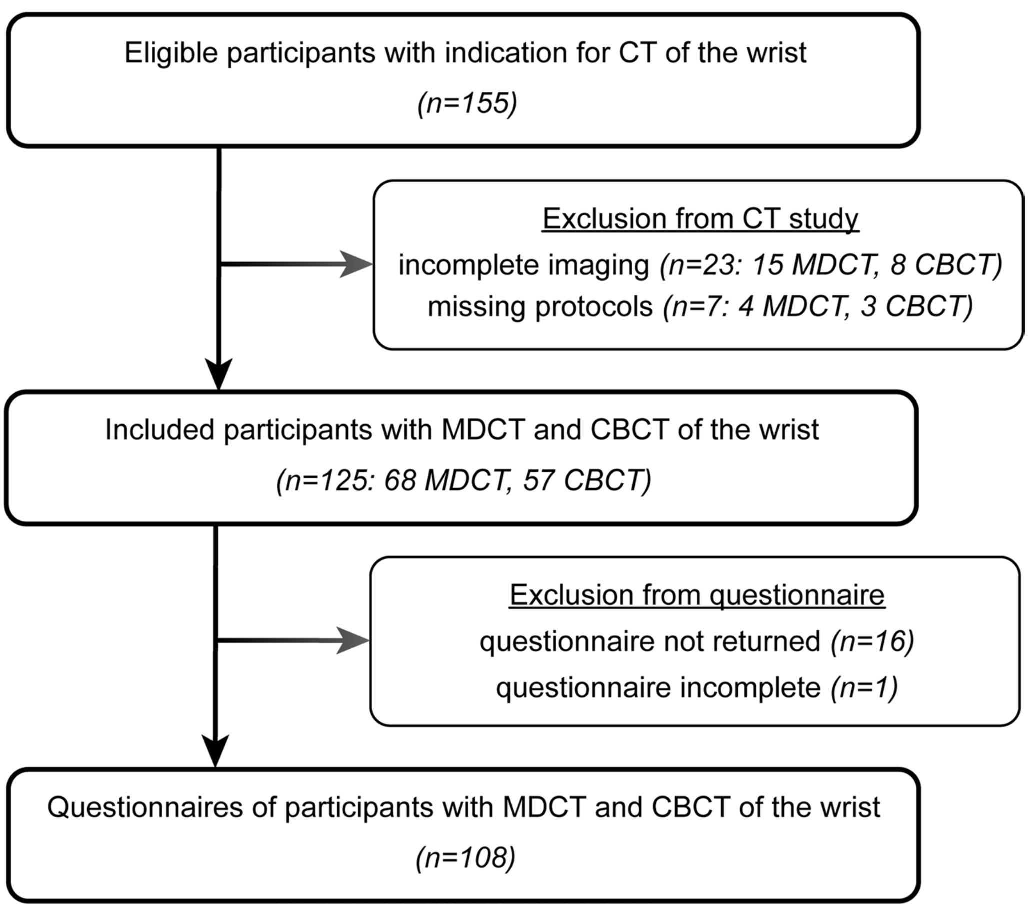

Fig. 1 Flow diagram of participants. The initial number of participants and those excluded for any reason are shown as well as the number of questionnaires of all in the study integrated participants, which were returned or excluded for the above-named reasons. *MDCT* multidetector computed tomography, *CBCT* cone-beam computed tomography

Table 2 Patient characteristics

Patient characteristics	Value
Number of patients enrolled	125 (68 MDCT, 57 CBCT)
Mean age	35 years
Age standard deviation	16 years
Male gender (%)	91 (73%)
Patients with fracture (%)	51 (41%)
Metacarpal bone fracture	1 (1 in CBCT)
Metacarpal and carpal bone fracture	2 (2 in MDCT)
Carpal bone fracture	47 (26 in MDCT, 21 in CBCT)
Distal radius fracture	1 (1 in MDCT)

MDCT multidetector computed tomography, *CBCT* cone-beam computed tomography

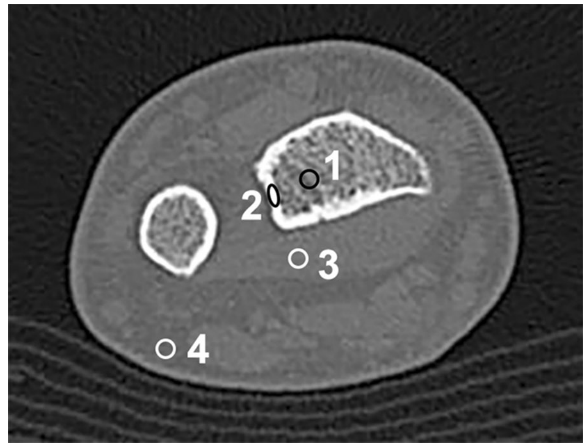

Fig. 2 ROI measurements. ROI measurements were performed using small ROIs in the trabecular bone (1), the cortical bone (2), muscle (3) and subcutaneous fat (4), here exemplified by means of a cone-beam CT slice

a CBCT examination. A fracture was diagnosed in 51 patients (Table 2).

A total of 108 patients returned the questionnaire, composed of 55 patients with MDCT examinations and 53 patients with CBCT examinations. Sixteen patients did not hand in the questionnaire and one patient handed in the questionnaire without completing it. The median rating for the comfort of positioning was 2 for MDCT and 1 for CBCT ($p<0.001$). For the ratings on all other questions including duration of the examination, contentment with positioning, steadiness of hands, presence of additional pain, convenience and protection with methods of radiation protection, intimidation by the device, there was no difference between the two modalities ($p>0.1$).

ROI measurements of the cortical bone and muscle were possible in all patients, ROI measurements of the trabecular bone in 123 patients and measurements of the subcutaneous fat in 92 patients (Fig. 2). This was the case because several patients had so little subcutaneous fat that meaningful placement of a ROI was not possible. The mean contrast-to-noise ratio (CNR) between cortex/muscle was 17.8 for MDCT and 35.4 for CBCT ($p<0.001$). The mean CNR between cancellous bone and muscle was 1.2 for the MDCT and 2.9 for the CBCT ($p<0.001$). The mean CNR between fat/muscle was 2.4 for MDCT and 3.6 for CBCT ($p<0.001$).

Inter-rater correlation was 0.5, 0.5, 0.5, −0.3, 0.4, 0.05 for the depiction of cortical bone, trabecular bone, articular surfaces, soft tissue, fractures and artifacts. On a 5-point Likert scale, the median rating for the depiction of cortical bone was 2 for MDCT and 1 for CBCT ($p<0.001$). The median rating for the depiction of trabecular bone was 3 for MDCT and 1 for CBCT ($p<0.001$). The median rating for the depiction of articular surfaces was 2 for MDCT and 1 for CBCT ($p<0.001$). In the 51 patients with a fracture, the median rating for the depiction of fractures was 2 for MDCT and 1 for CBCT ($p<0.001$). The median rating for the depiction of soft tissue was 3 for MDCT and 2 for CBCT ($p=0.04$). On a 3-point Likert scale, the median (mean) rating for artifacts was 2 (1.96) for MDCT and 2 (1.84) for CBCT ($p=0.04$). Imaging examples can be found in Figs. 3 and 4.

Discussion

In this study, we showed that with equivalent dose settings, CBCT had good ratings for the depiction of bony structures, soft tissue and artifacts in examinations of the wrist. CNR values were higher for CBCT compared to MDCT. While positioning in the CBCT was perceived to be more comfortable than in the MDCT, all other rated criteria of patient's satisfaction were equal. These criteria included no difference in the ability to keep the hands steady during the examination, the sensation of additional pain, convenience with radiation protection measurements and the feeling of being protected by those measurements, as well as intimidation by the scanner.

The better ratings for the depiction of the different evaluated structures indicate a higher image quality of the CBCT compared to the MDCT for wrist examinations. Since the investigations were performed at equivalent dose settings, an influence of different radiation doses can be excluded. We rather think that the difference may be contributed to the CBCTs properties tailored to extremity examinations, such as the small detector-focus distance and the high spatial resolution of the flat-panel detector. This is particularly interesting as single previous studies have partly described a better image quality of MDCT [16]. Most likely, this is due to the technical

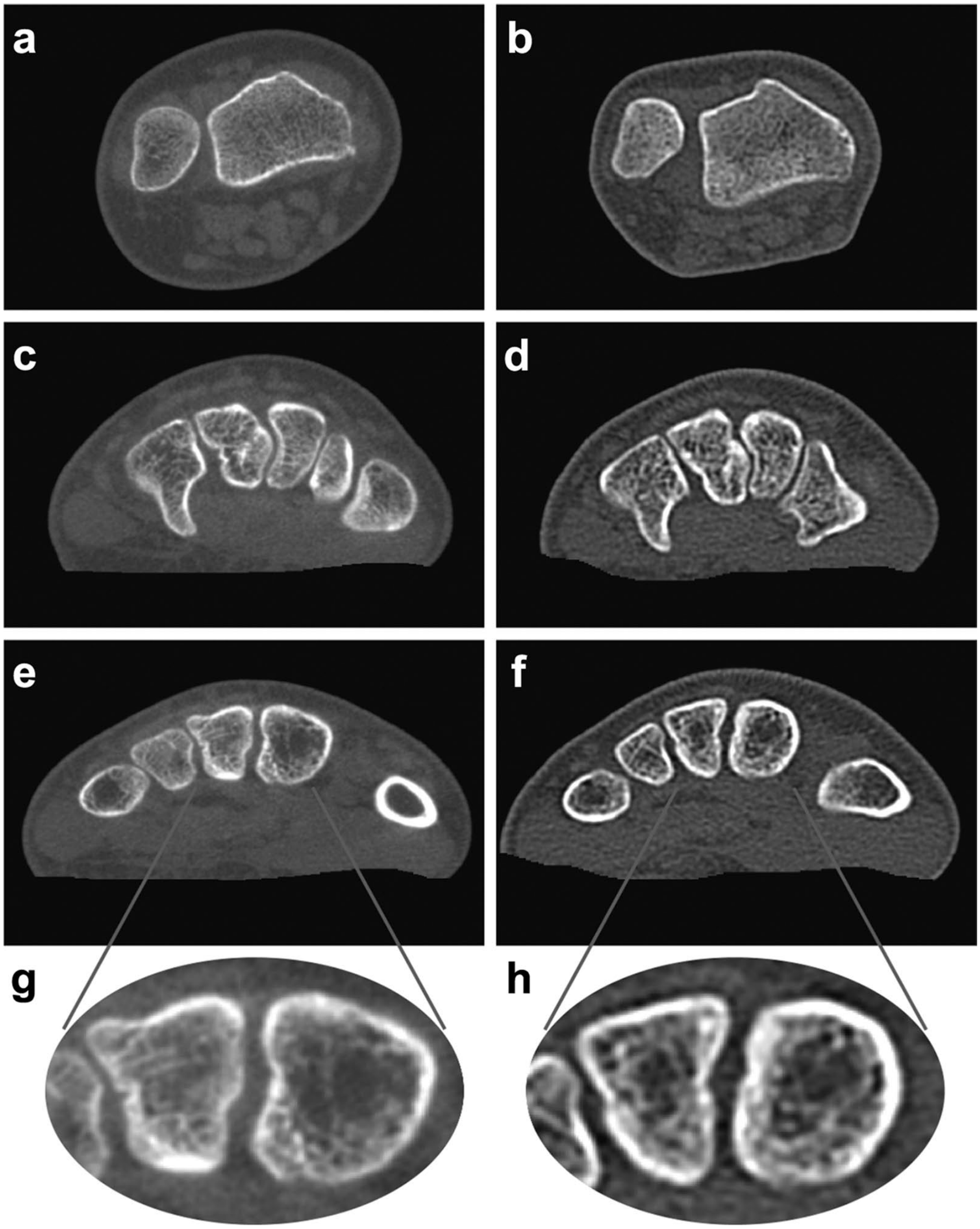

Fig. 3 Bone imaging in cone-beam CT and multidetector CT. The figure shows axial CT reconstructions at the level of the distal forearm (**a**, **b**), carpus (**c**, **d**) and metacarpus (**e**, **f**). The reconstructions are from two different patients, one examined by cone-beam CT (**a**, **c**, **e**), the other by multidetector CT (**b**, **d**, **f**). Magnification views of the metacarpal bones are attached to better appreciate the differences in the representation of the bone structure (**g**, **h**). *CT* computed tomography

advancement of the reconstruction algorithms of CBCT over the past years and other dose settings.

Although higher spatial resolution usually leads to higher image noise, we were able to show higher CNR values for different tissue contrasts in CBCT. Since the reconstruction of CBCT data is currently not iterative according to the manufacturer, an effective filter mechanism in image post-processing must be assumed. From a subjective point of view, however, the images do not look very smoothed, which is probably due to a balance between filtering and high spatial resolution. Similar results were observed for CBCT examinations of the midface [17].

Fig. 4 Scaphoid fracture in cone-beam CT and multidetector CT. The figure shows coronal (**a**, **c**) and sagittal (**b**, **d**) CT reconstructions of two different patients with scaphoid fractures. One was examined in cone-beam CT (upper row, **a** and **b**), the other in multidetector CT (lower row, c and d). *CT* computed tomography

Interestingly, the CBCT examinations were evaluated as less artifact laden. CBCT is otherwise known for the occurrence of certain artifacts such as extinction artifacts, beam hardening artifacts, partial volume artifacts, exponential edge-gradient effect, aliasing artifacts, ring artifacts and motion artifacts, some of which are rarely encountered in MDCT due to technical reasons and countermeasures [18–22]. As all wrists were examined with MDCT and CBCT directly after trauma, there were no foreign materials such as orthopedic reconstruction materials present. More artifacts would have been expected in post-surgical examinations in CBCT.

Especially due to a longer examination time, CBCT is generally more susceptible to motion artifacts [23]. In our clinic, patients in CBCT are fixed to the examination table with adhesive tape. This procedure is obviously effective and recommendable, since our data did not show movement artifacts that would have significantly restricted the evaluability and would have been expected without fixation.

Since bony structures in CT show an endogenously high contrast, especially the spatial resolution is of great importance for the perceived imaging quality. It is known from multiple studies that CBCT has a higher spatial resolution compared to MDCT [10, 11]. In this respect, our results are consistent with the previous literature. The fact that we could also find higher CNR values for the imaging of bony structures and soft tissue is somewhat surprising, since at equivalent dose, a lower soft tissue contrast of CBCT must be assumed due to a lower dynamic range of the detector elements [24]. However, one study on a dentomaxillary CBCT came to similar results [17]. Subjectively, the imaging of soft tissue was described as better in CBCT in several studies. As mentioned above, these results can best be explained by subsequent image filtering.

Due to simpler technical constructions, in CBCT patients can be positioned on a chair. In addition, the height and angulation of the gantry of the CBCT scanner can be adjusted to the patient. In MDCT, however, the examination is performed in a lying position with the arm elevated above the head. In our view, these points explain well the difference in the evaluation of positioning found in this study. Aside from that, positioning in the CBCT has been described as comfortable in several other papers [9, 13, 25], so our results in this respect are in line with the literature.

Dedicated musculoskeletal CBCT might therefore be an alternative to MDCT in CT diagnostics of the wrist, especially if MDCT scanners are not available. For some specific indications, such as the diagnosis of radiocarpal fractures including suspected scaphoid fractures, dedicated musculoskeletal CBCT already showed high sensitivity and specificity for fracture diagnosis and follow-up and therefore appears to be a promising procedure [8, 26, 27]. In single studies, CBCT shows promising results not only in the assessment of traumatic changes such as fractures, but also osteoarthritis-related subchondral bone changes and fracture healing [28].

The main limitation of this study is that it was conducted in an unpaired manner. However, the double examination of a patient in both MDCT and CBCT was not supported by our institutional review board because of ethical concerns and would have significantly complicated recruitment in our rather radiation-sensitized patient population. By randomization, we tried to ensure a homogeneous distribution of patients in both study arms. In addition, our collective has a male dominance. We included patients with a clinical indication for CT scan of the wrist, as CT examinations are commonly used in patients with suspected carpal fractures in our institution. A male predominance has been described in this patient group [29]. Thus, our collective seems to be representative. Regarding image reconstruction, in MDCT an iterative reconstruction technique was used, in CBCT, however, only filtered back projection was available; therefore, both devices use different methods.

Another limitation is the single-center design and the comparison of only one CBCT device to one MDCT device. Furthermore, we used a dose-matched approach for both methods, to exclude influences of dose-related image quality improvement. So far, MDCT uses higher dose settings for standard wrist imaging. Therefore, more studies with a variety of devices, dose settings and image reconstruction methods would be necessary to confirm, expand and guide our present results.

The patient satisfaction survey could not be blinded, and therefore, it could be inherently biased, as patients may consider new technologies simply better. However, there is nothing that can be done to mitigate this potential bias.

Conclusions

When compared in a dose-matched setting to multidetector computed tomography, cone-beam computed tomography showed high image quality for the depiction of bony structures, soft tissue and artifacts in wrist examinations of trauma patients.

Altogether, patients were equally satisfied with both methods when performing wrist examinations.

Abbreviations

CBCT	Cone-beam computed tomography
CNR	Contrast-to-noise ratio
CT	Computed tomography
MDCT	Multidetector computed tomography
ROI	Region of interest

Acknowledgements
Not applicable.

Author contributions
JN and SMG had the concept. EK and FB were responsible for the devices. AHG, CSR, FL, FS, HZ, JN and SMG were responsible for patient recruitment. CSR and JN accompanied the investigations. AHG, CSR, FL, JN and SMG evaluated the data. JN and AHG performed the statistics. CSR, JN and CN organized the data and wrote the manuscript. All authors approved the final manuscript.

Funding
No funding was received for conducting this study.

Availability of data and materials
Data are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The ethics committee of our institution approved this prospective study (No. 245/13, approval 26/09/2013).

Consent for publication
Written informed consent was obtained from all patients participating in the study.

Competing interests
The authors have no competing interests to declare that are relevant to the content of this article.

Author details
[1]Department of Diagnostic and Interventional Radiology, Faculty of Medicine, Medical Center – University of Freiburg, University of Freiburg, Freiburg im Breisgau, Germany. [2]Department of Hand and Plastic Surgery, Faculty of Medicine, Medical Center – University of Freiburg, University of Freiburg, Freiburg im Breisgau, Germany. [3]Clinic for Hematology, Oncology, Immunology and Palliative Care, ViDia Christliche Kliniken Karlsruhe, Karlsruhe, Germany. [4]Center for Hand and Plastic Surgery, Orthopedic Clinic Markgröningen gGmbH, Markgröningen, Germany. [5]Radiology Team Orthenau, Lahr, Germany.

Received: 23 February 2024 Accepted: 15 May 2024
Published online: 22 May 2024

References

1. Rubin DA, Roberts CC et al (2018) ACR Appropriateness Criteria® chronic wrist pain. J Am Coll Radiol 15:S39–S55. https://doi.org/10.1016/j.jacr.2018.03.021
2. Torabi M, Lenchik L et al (2019) ACR Appropriateness Criteria® acute hand and wrist trauma. J Am Coll Radiol 16:S7–S17. https://doi.org/10.1016/j.jacr.2019.02.029
3. De Vos W, Casselman J, Swennen GRJ (2009) Cone-beam computerized tomography (CBCT) imaging of the oral and maxillofacial region: a systematic review of the literature. Int J Oral Maxillofac Surg 38:609–625. https://doi.org/10.1016/j.ijom.2009.02.028
4. Huang AJ, Chang CY, Thomas BJ, MacMahon PJ, Palmer WE (2015) Using cone-beam CT as a low-dose 3D imaging technique for the extremities: initial experience in 50 subjects. Skeletal Radiol 44:797–809. https://doi.org/10.1007/s00256-015-2105-9
5. Goerke SM, Neubauer J, Zajonc H, Thiele JR, Kotter E, Langer M et al (2015) Digitale Volumentomografie (DVT) des knöchernen Handskeletts: Erste Erfahrungen und Anwendungsmöglichkeiten [Application possibilities and initial experience with digital volume tomography in hand and wrist imaging]. Handchir Mikrochir Plast Chir 47:24–31. https://doi.org/10.1055/s-0034-1398546
6. Neubauer J, Benndorf M, Reidelbach C, Krauß T, Lampert F, Zajonc H et al (2016) Comparison of diagnostic accuracy of radiation dose-equivalent radiography, multidetector computed tomography and cone beam computed tomography for fractures of adult cadaveric wrists. PLoS ONE 11:e0164859. https://doi.org/10.1371/journal.pone.0164859
7. Carrino JA, Al Muhit A, Zbijewski W, Thawait GK, Stayman JW, Packard N et al (2014) Dedicated cone-beam CT system for extremity imaging. Radiology 270:816–824. https://doi.org/10.1148/radiol.13130225
8. Yang TW, Lin YY, Hsu SC, Chu KC, Hsiao CW, Hsu CW et al (2021) Diagnostic performance of cone-beam computed tomography for scaphoid fractures: a systematic review and diagnostic meta-analysis. Sci Rep 11:2587. https://doi.org/10.1038/s41598-021-82351-9
9. Scarfe WC, Farman AG (2008) What is cone-beam CT and how does it work? Dent Clin North Am 52:707–730. https://doi.org/10.1016/j.cden.2008.05.005
10. Lechuga L, Weidlich GA (2016) Cone beam CT vs. fan beam CT: a comparison of image quality and dose delivered between two differing CT imaging modalities. Cureus 8:e778. https://doi.org/10.7759/cureus.778
11. Neubauer J, Voigt JM, Lang H, Scheuer C, Goerke SM, Langer M et al (2014) Comparing the image quality of a mobile flat-panel computed tomography and a multidetector computed tomography: a phantom study. Invest Radiol 49:491–497. https://doi.org/10.1097/RLI.0000000000000042
12. Demehri S, Muhit A, Zbijewski W, Stayman JW, Yorkston J, Packard N et al (2015) Assessment of image quality in soft tissue and bone visualization tasks for a dedicated extremity cone-beam CT system. Eur Radiol 25:1742–1751. https://doi.org/10.1007/s00330-014-3546-6
13. Tuominen EKJ, Kankare J, Koskinen SK, Mattila KT (2013) Weight-bearing CT imaging of the lower extremity. Am J Roentgenol 200:146–148. https://doi.org/10.2214/AJR.12.8481
14. Zbijewski W, De Jean P, Prakash P, Ding Y, Stayman JW, Packard N et al (2011) A dedicated cone-beam CT system for musculoskeletal extremities imaging: design, optimization, and initial performance characterization. Med Phys 38:4700–4713. https://doi.org/10.1118/1.3611039
15. Krippendorff K (1984) Content analysis: an introduction to its methodology. J Am Stat Assoc 79:239–240
16. Lang H, Neubauer J, Fritz B, Spira EM, Strube J, Langer M et al (2016) A retrospective, semi-quantitative image quality analysis of cone beam computed tomography (CBCT) and MSCT in the diagnosis of distal radius fractures. Eur Radiol 26:4551–4561. https://doi.org/10.1007/s00330-016-4321-7
17. Veldhoen S, Schöllchen M, Hanken H, Precht C, Henes FO, Schön G et al (2017) Performance of cone-beam computed tomography and multidetector computed tomography in diagnostic imaging of the midface: a comparative study on phantom and cadaver head scans. Eur Radiol 27:790–800. https://doi.org/10.1007/s00330-016-4387-2
18. Schulze R, Heil U, Gross D, Bruellmann DD, Dranischnikow E, Schwanecke U et al (2011) Artefacts in CBCT: a review. Dentomaxillofac Radiol 40:265–273. https://doi.org/10.1259/dmfr/30642039
19. Orth RC, Wallace MJ, Kuo MD (2008) C-arm cone-beam CT: general principles and technical considerations for use in interventional radiology. J Vasc Interv Radiol 19:814–820. https://doi.org/10.1016/j.jvir.2008.02.002
20. Watanabe H, Honda E, Tetsumura A, Kurabayashi T (2011) A comparative study for spatial resolution and subjective image characteristics of a multi-slice CT and a cone-beam CT for dental use. Eur J Radiol 77:397–402. https://doi.org/10.1016/j.ejrad.2009.09.023
21. Pauwels R, Stamatakis H, Bosmans H, Bogaerts R, Jacobs R, Horner K et al (2013) SEDENTEXCT Project Consortium. Quantification of metal artifacts on cone beam computed tomography images. Clin Oral Implants Res 24(Suppl A100):94–99. https://doi.org/10.1111/j.1600-0501.2011.02382.x
22. Finkenstaedt T, Morsbach F, Calcagni M, Vich M, Pfirrmann CW, Alkadhi H et al (2014) Metallic artifacts from internal scaphoid fracture fixation screws: comparison between C-arm flat-panel, cone-beam, and multidetector computed tomography. Invest Radiol 49:532–539. https://doi.org/10.1097/RLI.0000000000000052
23. Posadzy M, Desimpel J, Vanhoenacker F (2018) Cone beam CT of the musculoskeletal system: clinical applications. Insights Imaging 9:35–45. https://doi.org/10.1007/s13244-017-0582-1
24. Gupta R, Grasruck M, Suess C, Bartling SH, Schmidt B, Stierstorfer K et al (2006) Ultra-high resolution flat-panel volume CT: fundamental principles, design architecture, and system characterization. Eur Radiol 16:1191–1205. https://doi.org/10.1007/s00330-006-0156-y
25. De Cock J, Mermuys K, Goubau J, Van Petegem S, Houthoofd B, Casselman JW (2012) Cone-beam computed tomography: a new low dose, high resolution imaging technique of the wrist, presentation of three cases with technique. Skeletal Radiol 41:93–96. https://doi.org/10.1007/s00256-011-1198-z
26. Fitzpatrick E, Sharma V, Rojoa D, Raheman F, Singh H (2022) The use of cone-beam computed tomography (CBCT) in radiocarpal fractures: a diagnostic test accuracy meta-analysis. Skeletal Radiol 51:923–934. https://doi.org/10.1007/s00256-021-03883-9
27. Pallaver A, Honigmann P (2019) The role of cone-beam computed tomography (CBCT) scan for detection and follow-up of traumatic wrist pathologies. J Hand Surg Am 44:1081–1087. https://doi.org/10.1016/j.jhsa.2019.07.014
28. Ibad HA, de Cesar NC, Shakoor D, Sisniega A, Liu SZ, Siewerdsen JH et al (2023) Computed tomography: state-of-the-art advancements in musculoskeletal imaging. Invest Radiol 58:99–110. https://doi.org/10.1097/RLI.0000000000000908
29. Duckworth AD, Jenkins PJ, Aitken SA, Clement ND, Court-Brown CM, McQueen MM (2012) Scaphoid fracture epidemiology. J Trauma Acute Care Surg 72:E41–E45. https://doi.org/10.1097/ta.0b013e31822458e8

Publisher's Note