European Journal of Radiology 89 (2017) 191–199

Contents lists available at ScienceDirect

European Journal of Radiology

journal homepage: www.elsevier.com/locate/ejrad

Ultra-high resolution C-Arm CT arthrography of the wrist: Radiation dose and image quality compared to conventional multidetector computed tomography

Thomas Werncke[a,*], Lena Sonnow[a], Bernhard C. Meyer[a], Matthias Lüpke[b], Jan Hinrichs[a], Frank K. Wacker[a], Christian von Falck[a]

[a] Institute of Diagnostic and Interventional Radiology, Hannover Medical School, Carl-Neuberg-Str. 1, 30625 Hannover, Germany
[b] University of Veterinary Medicine Hannover, Institute for General Radiology and Medical Physics, Bischofsholer Damm 15, 30173 Hannover, Germany

ARTICLE INFO

Article history:
Received 12 September 2016
Received in revised form 16 January 2017
Accepted 5 February 2017

Keywords:
Arthrography
C-Arm CT
Spiral computed tomography
Wrist
Thermoluminescent dosimetry

ABSTRACT

Objective: Objective of this phantom and cadaveric study was to compare the effective radiation dose (ED) and image quality (IQ) between C-arm computed tomography (CACT) using an ultra-high resolution 1×1 binning with a standard 16-slice CT (MDCT) arthrography of the wrist.
Methods: ED was determined with thermoluminescence dosimetry using an anthropomorphic phantom and different patient positions. Imaging was conducted in 10 human cadaveric wrists after tri-compartmental injection of diluted iodinated contrast material and a wire phantom. IQ of MDCT was compared with CACT reconstructed with a soft (CACT1) and sharp (CACT2) kernel. High and low contrast resolution was determined. Three radiologists assessed IQ of wrist structures and occurrence of image artifacts using a 5-point Likert scale.
Results: ED of MDCT was comparable to standard CACT (4.3 μSv/3.7 μSv). High contrast resolution was best for CACT2, decreased to CACT1 and MDCT. Low contrast resolution increased between CACT2 and MDCT ($P < 0.001$). IQ was best for CACT2 (1.3 ± 0.5), decreased to CACT1 (1.9 ± 0.6) and MDCT (3.5 ± 0.6). Non-compromising artifacts were only reported for CACT.
Conclusions: The results of this phantom and cadaveric study indicate that ultra-high resolution C-Arm CT arthrography of the wrist bears the potential to outperform MDCT arthrography in terms of image quality and workflow at the cost of mildly increasing image artifacts while radiation dose to the patient is comparably low for both, MDCT and C-Arm CT.

1. Introduction

Fall onto the outstretched hand is a common trauma mechanism and can lead to severe injuries of the wrist. While fractures of the distal radius and static scapholunate dissociation can be readily diagnosed on plain film radiographs, the identification of more complex wrist injuries usually requires further diagnostic work-up [1–3]. In particular, tears of the scapholunate ligament (SL-ligament), the lunotriquetral ligament (LT-ligament) and lesions of the triangular fibrocartilage complex (TFCC) are often associated with hyperextension trauma and need to be recognized in early stage to be treated correctly in order to prevent chronic wrist pain, long-term osteoarthritic changes and disability [1,4–6].

Due to its non-invasiveness and ability to detect soft-tissue injury, magnetic resonance imaging (MRI) is a valuable technique to evaluate intraarticular radiocarpal derangement [7]. However, the diagnostic accuracy of a native MRI can be considerably limited in subacute cases without traumatic joint effusion resulting in low distinction of intraarticular structures. In these cases a three-compartment MR arthrography with intra-articular gadolinium administration is regarded as the gold standard with a sensitivity of up to 100% for the detection of ligament and TFCC tears [7,8].

Another imaging modality is the multidetector computed tomography (MDCT) arthrography of the wrist after intra-articular injection of iodinated contrast material, which is considered as least as accurate as MR arthrography for detecting intrinsic ligament and TFCC tears [9–12].

An innovative recent application of physical x-rays in musculoskeletal imaging is the flat panel C-Arm computed tomography (CACT) which has the potential to outperform MDCT in CT arthrog-

* Corresponding author.
E-mail address: Werncke.Thomas@mh-hannover.de (T. Werncke).

http://dx.doi.org/10.1016/j.ejrad.2017.02.009

raphy based on its superior spatial resolution using a dedicated 1 × 1 binning [13]. However, CACT is prone to more artifacts, for example streak artifacts due to misalignment or cone beam artifacts which might impair the diagnostic image quality. Since the intraarticular injection of contrast material is normally conducted under fluoroscopic guidance in the angiographic unit the use of CACT in the same unit might considerably optimize the workflow and shorten procedure time by omitting the need for a patient transfer to the CT unit.

In recent studies, Guggenberger and et al. and Neubauer et al. indicated that CACT arthrography using a standard 2 × 2 binning might be as feasible as MDCT and offer at least similar image quality [12,14,15]. However, to date it is still unknown whether CACT using a dedicated 1 × 1 binning of the wrist has the potential to outperform MDCT in terms of image quality and radiation dose.

The objective of this prospective phantom and cadaveric study was first to compare radiation dose and image quality between MDCT and CACT arthrography of the wrist. Second, different patient positions were simulated to find an optimal position with a radiation exposure as low as possible for the patient.

2. Materials and methods

Institutional review board approval was not required for this prospective phantom and cadaveric study.

2.1. Radiation dose measurements

Effective radiation dose was assessed for CACT and MDCT of the wrist using thermoluminscence (TLD) dosimetry. To enable a better comparison between the MDCT and CACT measurements, the acquisition length of the MDCT measurement was adjusted to the acquisition length of CACT of 10 cm.

TLD measurements were conducted according to Lüpke et al. and Werncke et al. [16,17] with 100 TLDs 100H (1 × 1 × 6 mm, LiF:MgCuP, Thermo Fisher Scientific, Waltham, USA) placed in an anthropomorphic whole body phantom (adult male phantom with arms, model 701 and model 701-10, CIRSinc, Norfolk, USA). Prior measurement, TLD were annealed in an annealing oven TLDO (PTW Freiburg, Germany) and calibrated in air kerma using a 90Sr/90Y-Irradiator 2210 with a calibration traceable back to a secondary standard (Material Testing Institute Dortmund, Germany). The energy-dependent calibration factor between air kerma and the absorbed dose in water for the X-ray spectra used was determined using an ionization chamber (TM30010, PTW Pychlau, Germany) with a calibration traceable back to a secondary standard (PTB Braunschweig, Germany).

An automatic thermoluminescence dosimetry reader 5500 (Thermo Fisher Scientific, Waltham, OH, USA) was used for the readout of the irradiated TLDs.

90 TLDs were placed along the right arm, on the trunk, and in the anthropomorphic phantom. The distribution of the TLDs and their assignment to the different organs is based on fused CT-datasets and given in detail in Table 1. The TLD-sampling was conducted in a conservative manner, to allow for an overestimation of the radiation dose rather than an underestimation. The coordinate system used for the TLD assignment is given in Fig. 1. The radiation dose of the breast for the female patient was conservatively estimated from this male phantom using TLDs on the skin and in the anterior bore holes in the breast region.

For the skin, musculature and bone marrow the distribution of these organs was taken into account as not all body regions were assessed. The skin distribution was approximated with "Wallace rule of nines" [18]. The bone marrow distribution was estimated using the distribution of the ICRP reference phantom given by Zankl et al. [19], and for the musculature we used the muscle distribution estimated with MR in Japanese volunteers as given by Abe et al. [20].

The remaining ten TLD were used for calibration and background subtraction. Though the main body of the phantom is in the field of scattered radiation only, 30 CACT and MDCT acquisitions were conducted to ensure a sufficient radiation dose to the TLDs. The TLDs nearby the direct irradiated field were removed after 4 acquisitions to avoid an excessive irradiation of these TLDs. The difference between the energy-dependent calibration factor between the different experimental settings was approximated with 1. The dose values and uncertainties were calculated according to ICRP 103 [21] and the ISO guideline 11929 [22].

2.2. Patient positions

For determination of radiation dose of MDCT, the phantom was placed in the standard prone position with the left arm above the head ("superman" position) (Fig. 2a and e).

To optimize the radiation exposure of the patient in CACT, the superman and a sitting patient position with and without lead aprons were tested. For the "superman" position, the radiation dose was determined without (Pos 1), and with an additional apron shielding using a lead-wrap (1.0 mm lead equivalent, Model RP689, Mavig, Munich, Germany) around the thorax and abdomen, and a x-ray lead acrylic shield (0.5 mm lead equivalent, Mavig, Munich, Germany) between head and detector (Pos. 2, Fig. 2b). The radiation dose in the sitting position with the left arm placed on the examination table was determined without shielding (Pos. 3, Fig. 2c), and using a x-ray lead acrylic shield (0.5 mm lead equivalent, Model OT 50001, Mavig, Munich, Germany), a thoracic lead shielding (0.25/0.5 mm lead equivalent, Model RA631, Mavig, Munich, Germany) and a thyroid shield (0.5 mm lead equivalent, Model RA615, Mavig, Munich, Germany) (Pos 4, Fig. 2d). The TLD's were positioned in and on the anthropomorphic phantom under the respective shielding for each experimental setting.

2.3. Arthrography of human cadaveric wrists

Ten upper extremity specimens from six embalmed cadavers were provided by the university's Institute for Functional and Applied Anatomy. Direct tri-compartimental arthrography of the wrist was conducted in these specimens under fluoroscopic guidance using a monoplane, ceiling–mounted angiographic system (Artis Zee Q®, Siemens, Forchheim, Germany). Diluted iodinated contrast material with a final iodine concentration of 150 mg/ml (Iomeprol 300 mg/ml, Imeron 300, Bracco, Konstanz, Germany; 1:1 dilution with NaCl 0.9%, B.Braun, Melsungen, Germany) was injected via a 25G needle in the distal radioulnar joint (DRUJ, 1.5 ml), the midcarpal joint (MC, 4.0 ml), and the radiocarpal joint (RC, 2.5 ml) as shown in Fig. 3.

As the assessment of high contrast resolution in the specimens is not clearly possible, an additional wire phantom with a 0.4 mm tungsten wire placed in a water-filled tube with a diameter of 4 cm was imaged in order to calculate the oversampled modulation transfer function (MTF) [17,23].

2.4. Image acquisition

Immediately after injection, C-Arm CT of the wrist was acquired using a C-Arm CT preset (20 s DynaCT micro, Dyna CT®, Siemens, Forchheim, Germany) combining a 20 s rotation run from −100° to 100° without additional filtering with a small focus of 0.4 mm, a 22 cm acquisition field of view (FOV) and 1 × 1 detector binning (Table 2). CACT images were reconstructed using a soft (CACT1)