Comparison of scattered entrance skin dose burden in MSCT, CBCT, and X-ray for suspected scaphoid injury: Regional dose measurements in a phantom model

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INTRODUCTION

The scaphoid is the most frequently fractured carpal bone, often as a result of fall onto an outstretched hand.[1,2] As the scaphoid has only a single intraosseous vessel blood supply, fractures have a high risk of vascular disruption to the proximal pole and can result in avascular necrosis.[3] Around 30% of scaphoid fractures may not be demonstrated on initial radiographs.[4] The poor specificity of clinical examination combined with the high risk of complications of scaphoid fractures means many patients undergo repeat radiography and over-treatment for possible scaphoid injury despite initial negative radiographs.[5,6] In order to reduce the time to diagnosis and healthcare resource use, alternate management pathways for suspected scaphoid injury have considered the utility other imaging modalities.[7] Current guidance in the UK suggests the use of magnetic resonance imaging (MRI) as first line imaging for possible scaphoid fracture although this is not routinely achieved in practice.[8,9] Multi-slice CT (MSCT) has been proposed as an alternate cross-sectional modality to MRI due to its' wider availability and lower cost, as it has been demonstrated to have comparable diagnostic accuracy to MRI.[10]

Cone beam CT (CBCT) is an emerging modality which is gaining favour for extremity imaging, having initially been developed for dental applications. It has been trialled for the early diagnosis of scaphoid fracture and has been shown to carry a lower radiation burden than MSCT.[11,12]

The effective dose of MSCT exams of the extremities are lower than those of the head, chest, abdomen or pelvis, with the most predominant radio-sensitive structure within the wrist being red bone marrow.[13] Simulated effective dose calculations have established a typical conversion coefficient (or k factor) for calculating effective dose of MSCT exam of the ankle from Dose-Length-Product (DLP) as 0.0002 in adult patients, compared to 0.009 for chest and abdomen MSCT exams based on the same CTDI phantom.[14,15]

While all examinations using X-rays carry the risk of radiation induced pathology, extremity-focussed MSCT imaging causes less than 1% of imaging induced cancer.[16] However, increasing the use of early MSCT for possible scaphoid injury would increase radiation burden across the population in both direct dose to the wrist and scattered radiation to the body as the number of scans performed increases. It is therefore important to understand the burden of scattered radiation to patients as part of the adoption of imaging practice changes, although information on scattered doses from wrist CBCT is currently limited. We aimed to compare and quantify scattered dose burden across modalities.

METHODS AND MATERIALS

In order to define the acquisition parameters for all scattered dose measurements, a review of exposure parameters for examinations performed on each modality (radiography, MSCT and CBCT) was undertaken. This single-centre is based in Northern England and consists of three acute hospital sites. All patients > 18 years old referred by the emergency department (ED) between March and August 2019 inclusive for investigation of suspected scaphoid fracture were included. Where a cast or wrist support were present on the images, these were excluded.

All acquisition parameters, including field of view, were recorded from the DICOM header data and Radiology Information System. Variation in exposure values were noted for the Radiography and CBCT examinations, which were not present in the MSCT examinations, although there was variation in the scan ranges and resultant dose. The range of exposures for each procedure were reviewed, and three values based on the lowest, mean, and highest most commonly manually set values were used as a basis for low, average and high exposures respectively to account for variation in technique (Table 1).

All of the above data was recorded without any patient-identifiable data being extracted from clinical systems as part of routine clinical audit. As no participants were recruited for the study, nor any tissues, samples or patient information were to be included, Research Ethics Committee approval was not required or sought.

Two anthropomorphic phantoms (torso [Multipurpose Chest Phantom N1 "LUNGMAN", Kyoto Kagaku, Japan] and right wrist [Alderson Hand/Wrist Normal, Rothband, UK]) were positioned and imaged as a proxy patient undergoing examinations for possible scaphoid fracture. Scattered entrance surface dose (ESD) measurements were recorded in microgray (μGy), using a survey radiation dose-sensor [Raysafe XI Survey, Unfors Raysafe AB, Sweden] on the torso phantom at positions corresponding to the anatomical regions of the neck, chest, and abdomen. These anatomical regions were used as a proxy for the high and medium risk tissues of the thyroid, lungs/breasts, and stomach/colon. (See Figure 1).[17] Each ESD measurement was repeated three times at each sensor location and exposure.

Modalities

MSCT

MSCT exposures were made on a 128 slice CT scanner (Siemens SOMATOM Definition Edge, Siemens, Erlangen). The wrist phantom was placed in the head support and positioned in the isocentre of the gantry using laser localisers consistent with clinical practice. The torso phantom was placed prone and distal to the wrist phantom on the scan table as standard positioning at the same arm-distance as the radiography and CBCT exams based on a single volunteer (see Figure 2). The department protocol single AP topogram image with over-couch tube was performed on standard exposure settings with the exposure manually terminated by the radiographer once the anatomical range had been covered (mean scan length 36.7 cm, range 34 to 40 cm). [18]

The MSCT wrist volume data was then acquired using the exposure settings derived from the automatic tube current modulation with no variation in scan length and the standard protocol quality reference mAs of 80. At each exposure the DLP in milligray per centimetre (mGy*cm) and CT Dose Index for the volume (CTDIvol) in milligray (mGy) was recorded from the console. As in standard practice the MSCT system used modulates the exposure (tube current) over the Z-axis based off the topogram images, the tube potential (KVp) and scan range were manually set and the resultant exposure factors used. No variation in exposure factors for patient size was made for the topogram or volume images. In total nine topogram exposures and nine CT volume exposures were recorded based on three repeats for each measurement of scattered radiation dose to anatomical area.

CBCT

CBCT exams were performed on a dedicated extremity CBCT scanner (Carestream OnSight 3D Extremity, Carestream, New York). The wrist phantom was positioned within the scanner bore on the arm-board support with the wrist joint on the centre fiducial line and a support strap applied. The CBCT scanner used features removable lead-rubber shields that cover the gantry aperture around the body part being imaged, and these were used for all exposures. The body phantom was positioned in the patient chair to the left of the scanner gantry as a patient undergoing a right wrist exam.[19]

The standard scout images of PA and Lateral were performed at default exposure values. At each exposure the Dose-Area-Product (DAP) was recorded from the console in decigray per centimetre squared (dGy*cm^2). No variation in exposure factors for patient size was made for the scout images. The recommended volume exposure from the automatic exposure device (AED) based on the scout images was 2.1 mA. The CBCT volume scan was performed on the wrist phantom at each exposure setting, with the DLP in mGy*cm and CTDIvol in mGy recorded from the imaging console. In total 18 scout exposures and 27 CBCT exposures were recorded based on three PA and three lateral scout measurements and nine CBCT measurements per sensor position. All cross-sectional specific exam factors are listed in table 2.

Radiography

The standard four view scaphoid radiograph series consisting of Dorsi-palmar (DP), Oblique, Lateral, and DP with 30° of cranial angulation (Zitters) projections were performed on the wrist phantom.[20,21] For each projection the phantom was positioned and beam directed as described in the department standard positioning text on a DR detector (Carestream DRX-Evolution plus, Carestream, New York) with positioning aids where required outside the primary beam.

For each projection the x-ray tube was positioned at a source image distance of 110 cm and collimated to the field of view established in the review of acquisition parameters. The torso phantom was positioned to the left of the wrist phantom at the same arm-distance as the MSCT and CBCT exams based on the same single volunteer (see Figure 3). No lead shielding was applied to either phantom, in line with current guidance.[22] In order to highlight any unintentional variations in exposure settings, the DAP per exposure was recorded in dGy*cm2. In total 108 radiography exposures were recorded based on 36 measurements per sensor position.

Quality assurance

All modalities used were checked daily for variations in detector sensitivity as part of routine QA for clinical practice.

One CBCT scan measurement was discarded and the measurement repeated due to a scanner error resulting in early termination of exposure and an incomplete image volume. No other examinations were repeated.

Analysis

All exposure factors and doses were recorded and analysed in R studio (R studio Team, Boston, USA). Normality was assessed via shapiro-wilk test and analysis was performed via unpaired student t-test for cross-modality comparisons and paired student t-test for within-modality comparisons.[23,24]

RESULTS

Anatomical Region dose analysis per modality

For CBCT and MSCT the lowest, mean and highest ESD measurements per anatomical region and exposure setting (low, medium or high) were recorded.

For radiography, the lowest, mean and highest ESD measurements by anatomical region and exposure setting (low, medium or high) were combined from each of the four views to give a total examination ESD. (Table 3).

ESD was significantly higher for CBCT than the four view radiography series at the level of the neck (1.616 vs .031 mGy) (95% CI [1.45, 1.72], p<.0001), chest (2.759 vs .035 mGy) (95% CI [2.427, 3.019], p<.0001), and abdomen (1.279 vs .0214 mGy) (95% CI [1.119, 1.397], p<.0001).

ESD was significantly higher for MSCT than the CBCT at the level of the neck (21.343 vs 1.616 mGy) (95% CI [16.25, 16.52], p<.0001), chest (14.08 vs 2.759 mGy) (95% CI [4.957, 5.548], p<.0001), and abdomen (6.302 vs 1.279 mGy) (95% CI [1.518, 1.796], p<.0001). (Figure 4).

Wrist dose per modality

For volume acquisitions the mean CBCT wrist DLP was 47.247 mGy*cm, compared to 79.4 mGy*cm for MSCT. However the CBCT scan has a fixed scan length of 23.6 cm, compared to the 15.7 cm scan length used for MSCT. Based on the mean CTDIvol for each modality, if the MSCT scans were acquired with the same length as the CBCT, the average dose would be closer to 119 mGy*cm. Alternatively, if the CBCT scan length was reduced to that used in the MSCT acquisition, the mean CBCT DLP would be 31.23 mGy*cm (range 27.16 - 35.3 mGy*cm).

Due to the differing methods of acquisition, direct comparison between radiation output measures is not feasible between radiography and CT. However, the dose from the scout or topogram images may be compared. The mean total dose recorded for four view radiography was 0.199 dGy*cm^2 (range 0.167 – 0.232). This compares with the average combined scout exam dose for CBCT of 0.236 dGy*cm^2 (range 0.226 – 0.242) and 0.916 dGy*cm^2 for the single MSCT topogram (range 0.782 – 1.120). However, the CBCT scout and MSCT topogram images are non-diagnostic and are only used for planning the volume acquisition.

DISCUSSION

The pattern of scattered exposure varies across modalities, with higher doses to the neck in CT, and higher doses to the chest in CBCT and radiography. This is most likely due to the different patient positioning by modality, with the neck closest to the beam source in MSCT, and the chest closest to the source and receptor in CBCT and radiography. MSCT of the wrist is typically performed with the patient prone resulting in shielding of the thyroid and other anterior structures by the scanner table. However, as the radiation source rotates around the patient, there may also be substantial dose to the posterior aspect of the patient for MSCT, without reduction in scatter from the table. This is not the case for CBCT or radiography, where the patient is positioned so that the radiation source is closest to the anterior or lateral margins of the patient.[25] Scattered dose to the head and orbits would presumably be higher in MSCT of the wrist than in the other modalities, based on the proximity of the head to the x-ray source during exposure. The overall profiles of exposure here would appear to confirm this, with MSCT scattered doses increasing in relation to proximity to the scanner gantry as opposed to the peak exposure at the chest with radiography and CBCT. However measurements of dose to the head were not performed.

A typical pathway of diagnosis for scaphoid injuries will include two or three radiography examinations at 10 to 14 day intervals if the initial exam is negative.[9] The use of cross-sectional imaging at an early stage can negate the need for these repeated examinations and greatly reduce the delay to confirmed diagnosis and over treatment costs.[12] CBCT has been found to be comparable to MSCT in reliably demonstrating scaphoid injury and so could negate the need for repeated radiography exams.[26,27]

A study comparing effective dose in three and four view radiography against MSCT for wrist injuries reported a mean effective dose of 0.1 mSv for MDCT against 0.01 mSv for x-ray.[28] As CBCT uses multiple x-ray sources along the Z-axis the profile of irradiation and dose varies in comparison to MSCT, due to overlap of exposure from two sources.[29] Furthermore, the specific fixed length of CBCT scans and differences of beam geometry can prevent direct comparisons with MSCT based purely of CDTIvol values. The use of a dedicated CBCT dose index (CBCTDIw) has been proposed that could better allow evaluation of dose.[30]

Another study compared effective doses in wrist phantoms across MSCT and CBCT devices found an average effective dose of 0.0086 mSv from MSCT compared to 0.0007 to 0.0024 mSv for CBCT and 0.0009 mSv for two-view radiography, albeit at six to 12 times the mAs used in this study.[13] However this study only looked at dose to the wrist and not to the body. Surface doses to the wrist and ankle have also been evaluated, with greatly reduced doses to the extremities in CBCT when compared to MSCT. [31] The greater dose burden from MSCT compared to CBCT in these studies align with the results presented here.

LIMITATIONS

Due to the prone positioning used in MSCT, it is likely that ESD would be higher at the head and associated structures (such as the eye lens and salivary glands) due to the proximity of anatomy to the x-ray source. It is also possible that the patients' head would affect the scattered ESD to the regions measured here. However, due to availability a head phantom was not used either as a ESD measuring tool nor scattering medium in this study.

We used a survey meter sensor positioned at three locations for measurement of scattered ESD at the anatomical regions of radiosensitive structures. However, measurements were not made at the location of individual structures (such as breast tissue or abdominal viscera), but rather at the anterior surface of the torso phantom at locations reflecting sensitive structures. As such, effective doses were not established by this study. Further study using thermo-luminescent dosimeters (TLDs) or similar sensors positioned within anatomical phantoms at the regions of radio-sensitive structures would give further data on effective dose and prevent any issues of angular dependence on sensor placement in relation to beam geometry.

The anatomical wrist phantom used in this study was not designed as an image-quality tool for CBCT or MSCT, and was used purely as a method of producing radiation scatter equivalent to patient anatomy.

CONCLUSION

While a CBCT scans of the wrist carries a significantly higher scattered radiation dose to the neck, chest, and abdomen than the four view scaphoid radiography series, they also carry a significantly lower scattered radiation dose than MSCT of the wrist of equivalent diagnostic value. The pattern of scattered dose varies between modalities, with the neck receiving the highest scatter dose in MSCT and the chest in CBCT and radiography. The use of CBCT for scaphoid injury could negate the need for repeated delayed scaphoid radiography and with ongoing MRI capacity challenges could enable earlier conclusive diagnosis of scaphoid injury.

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Table 1: Exposure factors by modality

Table 2: Comparison of factors in CT

Table 3: Total exam scattered dose in mGy

Figure 1: Sensor positions on Anthropomorphic Torso Phantom relating to A- Neck, B- Chest, and C- Abdomen

Figure 2: Top - CT positioning of torso and wrist phantom, Bottom - volunteer as positioning standard

Figure 3: Top – Radiography positioning of torso and wrist phantom (Lateral view) with dose sensor at thyroid position. Bottom – volunteer as positioning standard

Figure 4: Entrance surface doses by region of phantom compared across modalities