Reducing metal artefacts and radiation dose in musculoskeletal CT imaging

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CHAPTER 8

IMPROVED DIAGNOSTIC CONFIDENCE IN EVALUATING SUSPECTED NON-UNION OF THE APPENDICULAR SKELETON USING VIRTUAL MONOCHROMATIC DUAL-ENERGY CT.

J.C.E. Donders, R.H.H. Wellenberg, G.J. Streekstra, M. Maas, P. Kloen

Submitted
ABSTRACT

Objectives: To determine whether virtual monochromatic dual-energy CT imaging improves the diagnostic confidence in evaluating suspected non-union of the appendicular skeleton treated with titanium or stainless steel intramedullary nails and plates.

Methods: Forty-one patients with a clinical suspected non-union of the appendicular skeleton with hardware in place were included. Patients were scanned on a Siemens Somaton Force dual-source CT-scanner using 100/Sn150kVp. Images extracted at 70 keV served as reference. High 130 or 150 keV images were extracted in patients with titanium and stainless steel hardware respectively. A musculoskeletal radiologist and orthopaedic trauma surgeon rated image quality, degree and location of consolidation, non-union type and diagnostic confidence using Likert scales.

Results: Diagnostic confidence improved from 1.43 to 2.37 in high (130 and 150) keV images compared to 70 keV images (p<0.001). Overall diagnostic confidence was higher in intramedullary nails than plates (p<0.05). No significant difference in diagnostic confidence was seen between titanium and stainless steel hardware. Likert scores with respect to image quality improved from 0.88 to 1.83 (p<0.001). Intra class correlation (ICC) on degree of consolidation improved from 0.573 (p<0.005) in 70 keV images to 0.664 (p<0.001) high keV images. No improved agreement between observers was seen regarding location of consolidation and non-union type.

Conclusions: Diagnostic confidence and overall image quality improved using high keV images extracted at 130 and 150 keV compared to 70 keV monochromatic images in evaluating fractures of the appendicular skeleton with suspected non-union treated with titanium and stainless steel intramedullary nails and plates.

Keywords: CT; dual-energy CT; non-union; osteosynthetic fixation; metal artefacts.
INTRODUCTION

A non-union is defined as a fracture that has not healed within 6-9 months. There is however no clear point in time when a non-union loses its capacity to heal. As many studies already pointed out, the underlying causes of disturbed fracture healing are diverse (e.g. poor fixation, infection, high energy fracture, osteoporosis) and multifactorial including patient factors such as smoking, age, diabetes mellitus, steroid use [1–4]. Treatment of a non-union is usually surgical and involves a combination of optimizing biology, stability, debridement and release of surrounding soft tissues [3–10]. With increasing insight in the underlying events of non-union development and improvements in treatment, there is still a need for adequate and timely diagnosis.

To help prevent unnecessary and costly surgery, a radiologic test with high sensitivity and specificity enhances the diagnostic confidence. Radiography and CT are both used on non-union diagnostics [11–13]. Bhattacharyya et al. showed that computed tomography (CT) has 100% sensitivity for detecting tibia non-union; however, it is limited by a low specificity of 62% [14]. In CT, implants used for internal fixation of fractures and non-unions cause metal artefacts due to photon-starvation, scatter and beam-hardening [15–17]. Visibility of fractures or non-union lines adjacent to hardware is therefore compromised, which negatively affects the diagnostic value of CT.

Virtual monochromatic images computed from Dual-Energy Computed Tomography (DECT) reduce metal artefacts. It does so by reducing beam-hardening artefacts using extrapolated data at higher monochromatic energies [18]. With respect to intramedullary implants and extra medullary plates, various “optimal” monochromatic energies are reported in literature ranging between 95-150 keV [16,18–24]. The possible enhancement of the diagnostic value of DECT compared to conventional CT in evaluating bone healing in the presence of metal (stainless steel or titanium) hardware may facilitate non-union diagnostics. To the best our knowledge, there are no studies investigating the diagnostic value of DECT in patients treated for fractures of the appendicular skeleton with suspected non-union. The main goal of this study was therefore to determine whether virtual monochromatic DECT imaging improves the diagnostic confidence in patients treated for fractures of the appendicular skeleton with suspected non-union.
MATERIALS AND METHODS

A total of 41 consecutive patients treated for a fracture of the appendicular skeleton with suspected non-union were included. Exclusion criteria were a history of a pathologic fracture, obvious loosening or failure of hardware on plain radiographs. Indication for the DECT was to gain optimal information whether fracture bridging or (previous) non-union was present or not. Patients were treated with varying type of internal fixation where some patients underwent multiple surgeries. Sixteen patients were treated with titanium hardware of which 5 were intramedullary nails and 11 were plates. Twenty-five patients were treated with stainless steel hardware of which 2 with an intramedullary nail and 23 with plate fixation. All patients were scanned on a Siemens Somaton Force Dual-Source CT-scanner (Siemens Healthcare, Forchheim, Germany) with tube currents of 100-kVp for tube A (240 mAs) and 150-kVp for tube B (120 mAs), using a collimation of $2\times92\times0.6$ mm, a pitch of 0.5, 1.5 mm slice thickness.

Axial images were loaded on a Syngo Via workstation (version 3.0.0.16 Siemens Healthcare, Forchheim, Germany). Virtual monochromatic images extracted at 70 keV served as a reference since CT numbers and image contrast are comparable to 120-kVp polychromatic images. In patients with titanium implants and stainless steel implants monochromatic images were extracted at 130 and 150 keV respectively. Monochromatic energies of 130 and 150 keV were chosen based on own experiences and previously reported keVs by similar studies including patients with metal fixation hardware of the long bones [16,19-22].

All images were evaluated on 5 aspects (Table 1) by a musculoskeletal radiologist (MM, observer 1) with 21 years experience and by a fellowship trained orthopaedic trauma surgeon (PK, observer 2) with 16 years experience. Overall image quality was scored using a 4-point Likert scale with a score of 0 meaning severe artefacts with a poor diagnostic quality; a score of 1 moderate artefacts with an impaired diagnostic quality; a score of 2 in case of minor artefacts with good diagnostic quality; a score of 3 meaning absence of artefacts with an excellent diagnostic quality. Consolidation of fractures or non-union was given on a 5-point scale: 0: less than 10% consolidation (no bone healing); 1: meaning 10%-30% consolidation (only single isolated bridges visible); 2: 30%-50% consolidation (several centres of ossification with bridging, but large, noticeable gaps in the preformed defect); 3: 50%-80% consolidation (advanced bone bridging, but residual gaps both, in the centre of the defect and cortically) or 4: 80%-100% (complete consolidation).
Location of consolidation was only scored for plate fixation. A score of 0 was given for no consolidation; a score of 1 for bridging directly under the plate; a score of 2 for bridging directly opposite from the plate; a score 3 for patchy/scattered (or circumferentially) bridging; and a score of 4 for bridging obliquely across from the plate. Non-union type was scored as follows: 0: bone union; 1: atrophic non-union; 2: hypertrophic non-union or 3: oligotrophic non-union. Overall diagnostic confidence in evaluating fracture consolidation was scored as follows: 0: poor evaluation with no confidence; 1: impaired evaluation with low confidence; 2: good evaluation with medium confidence or 3: excellent evaluation with high confidence. KeV settings were blinded and the order of presentation of the different keV’s (70 and 130 or 150) was randomized to minimize bias. We furthermore precluded the consecutive presentation of 70 and high keV images of the same patient.

Due to relatively small sample sizes, the Wilcoxon signed rank test was used to compare subjective image quality scores by the two observers in 70 keV and high 130 or 150 keV images. Spearman correlation and two-way random intra-class correlation (ICC) were used to determine correlation of outcome values and agreement between both observers. Fisher’s Exact test was used to determine statistical differences in outcome values for different groups including titanium and stainless steel implants, intramedullary nails and plates.

RESULTS

Image quality of high keV images was rated higher or equally compared to standard 70 keV images in the vast majority of cases (Figure 1). Observer one rated the image quality of the high keV images equally to those at 70 keV in only 34% of the cases. In almost two thirds (66%) of the cases the high keV were rated better compared to 70 keV images. The second observer rated the image quality of the high keV images equal (27%) or better (61%) compared to 70 keV images. Mean Likert

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<thead>
<tr>
<th>Aspect</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Image quality (0-3)</td>
</tr>
<tr>
<td>2</td>
<td>Degree of consolidation (0-4)</td>
</tr>
<tr>
<td>3</td>
<td>Location of consolidation (0-4)</td>
</tr>
<tr>
<td>4</td>
<td>Non-union type (0-3)</td>
</tr>
<tr>
<td>5</td>
<td>Overall confidence level of the diagnosis (0-3)</td>
</tr>
</tbody>
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score improved from 0.88 to 1.83 with respect to image quality, which was highly statistically significant ($p<0.001$). Image quality of titanium (Ti) hardware was rated higher than stainless steel (SS) hardware in 70 keV images ($p<0.05$). In high keV images, there was no statistical difference in image quality between titanium and stainless steel implants. Image quality of intramedullary nails was rated higher than plates in 70 keV images ($p<0.05$), which is illustrated in Figures 2 and 3. In high keV images, there was no statistical difference in image quality between intramedullary nails and plates (Figure 1).

Same scores regarding degree of consolidation were seen in 70 keV and high keV images in 41% (observer 1) and 66% (observer 2) of the cases. There was a clear visible trend for both observers to lower the degree of consolidation in the high keV images (when they were different between low and high keV). When categories were grouped into two groups instead of 4 (consolidation<50% and equal/more than 50%), indicating treatment or no treatment, same scores were seen in 30/41 cases in 70 keV images and 31/41 cases in high keV images, resulting in an improvement in intra class correlation (ICC) between observers from 0.573 ($p<0.005$) in 70 keV images to 0.664 ($p<0.001$) high keV images.

With respect to location of consolidation in the 34 patients with plate fixation, observers rated equally in 47% and 50% of the cases in 70 and high keV images respectively. Location of consolidation changed in 38% and 35% of the cases for observer 1 and 2 respectively when switching to higher keVs. Same scores with respect to non-union type were seen in 14/41 cases and 12/41 cases in 70 and high keV images respectively. This shows that there is a large discrepancy in location of consolidation and type of non-union between both observers.

In 70 keV images, subjective scores were statistically different between observers regarding image quality ($p<0.005$) and non-union type ($p<0.05$). In high keV images, subjective scores were statistically different between both observers with respect to image quality ($p<0.005$), location of consolidation ($p<0.05$) and non-union type ($p<0.05$).

Overall diagnostic confidence with respect to the aforementioned aspects improved in 63% and 68% of the cases and remained equal in 29% and 27% of the cases in high keV images compared to 70 keV images for observer 1 and 2 respectively. In the remaining 7% and 5% of the cases, the diagnostic confidence of the high keV images was scored 1 point lower than 70 keV images. Similar to what was seen with
For the purposes of this study, let’s assume that the diagnostic confidence improved from 1.43 to 2.37 in high keV images compared to 70 keV images (Figure 1)(p<0.001). Overall diagnostic confidence was rated higher in intramedullary nails than plates in both high keV and 70 keV images (p<0.05). No significant difference in diagnostic confidence was

![Image quality and diagnostic confidence](image)

Figure 1: Mean Likert scores with respect to image quality (1) and diagnostic confidence (6) for both observers in 70 keV and high keV images are shown. Average scores are presented for 4 groups including: titanium intramedullary nails, titanium extramedullary plates, stainless steel intramedullary nails and stainless steel extramedullary plates. Likert scores were generally lower for observer 2 compared to those of observer 1.
seen between titanium and stainless steel hardware. Image quality and diagnostic confidence were positively correlated. Spearman correlation between image quality and diagnostic confidence was 0.766 (p<0.001) and 0.625 (p<0.001) in 70 and high keV images respectively for observer 1. Correlation was 0.544 (p<0.001) and 0.588 (p<0.01) in 70 and high keV images respectively for observer 2.

**DISCUSSION**

Our study reveals that diagnostic confidence (p<0.001) and overall image quality (p<0.001) improved using high keV images extracted at 130 and 150 keV compared to 70 keV monochromatic images in evaluating fractures of the appendicular skeleton with suspected non-union treated with titanium and stainless steel intramedullary nails and plates. Metal artefacts, caused by titanium and stainless steel intramedullary nails and plates were reduced in high keV images by eliminating beam-hardening artefacts. Figure 4 illustrates that relevant findings, such as hardware failure, is better assessable high keV images than in 70 keV images.

Radiography and conventional CT are both used in non-union imaging, however a general consensus in the assessment of fracture healing in the first place is lacking [11–13,25]. Various quantitative methods and qualitative scores have been proposed to increase the intra- and interobserver reliability to determine fracture union [26–30]. To prevent unnecessary surgery or prolonged pain and disability, an improvement of CT image quality and diagnostic confidence is mandatory to facilitate clinical decision making in these complex cases.

Since a clear improvement of overall image quality and diagnostic confidence was seen when switching from 70 keV to high (130 and 150) keV images, we expected an improved agreement between observers regarding degree and location of consolidation and non-union type also. This improvement was only minor and applied to only several cases. There was poor agreement between observers with respect to degree of consolidation using 5-point Likert scale. However, when dividing degree of consolidation in 0-50% and 50-100%, which indicates treatment or no treatment, intra class correlation (ICC) on degree of consolidation improved from 0.573 (p<0.005) in 70 keV images to 0.719 (p<0.005) high keV images.

In literature, none of the studies evaluated the degree of consolidation, location of consolidation, or non-union type using DECT. Several studies showed that virtual monochromatic images computed from dual-energy CT (DECT) reduce metal artefacts. These studies all state that high keV images improve overall image quality
and diagnostic quality by reducing beam-hardening artefacts compared to 64, 68, 69 or 70 keV images, which approximate conventional 120-kVp images. In post-mortems, Filograna et al. (2015) rated the degree of artefacts and overall image quality using a four-point Likert scale. Image quality was scored higher for the optimal keV of 137.1 ± 4.9 keV (130-148 keV) compared to 64, 69, 88, 105, and 120 keV and single energy CT with no difference seen with 130 keV [19]. Zhou et al. (2011) found that 130 keV provided the optimal image quality for total, internal, and external metal orthopedic hardware compared to 40, 70, 100, 160 and 190 keV. Image quality was evaluated based on a 4-point Likert scale with respect to artefacts and evaluation of adjacent bone and soft tissue structures [16]. In a patient study, including patients with hardware in the appendicular skeleton, Bamberg et al. (2011) quantified beam-hardening artefacts by measuring the most hypodense streak and rated artefacts

![Figure 2: Images extracted at a) 70 and b) 150 keV are shown in a patient with an external femoral stainless steel plate fixation. Severe artefacts were reduced and visibility of the fracture clearly improved in the 150 keV image compared to the 70 keV reference image. Image quality and diagnostic confidence were both rated higher in high keV images compared to 70 keV images by both observers. Correct positioning of patients within the smallest field-of-view of the high kVp tube is essential. Metal artefacts were only reduced within this field-of-view of 300mm, which can be observed at the lateral side in the 150 keV image.](image-url)
and diagnostic interpretability on a 5-point Likert scale. An optimal monochromatic energy of 120 keV was found, ranging from 95-190 keV. Artefacts were not completely eliminated but were substantially reduced, the image quality improved by 49% and the diagnostic value was enhanced by approximately 44% [21]. In our study, not all artefacts were reduced completely either. However, in high keV images average image quality and diagnostic confidence scores were 108% and 66% higher respectively compared to 70 keV images. Neuhaus et al. (2017) showed that use of 105 and 140 kV reduced artefacts significantly in smaller implants, while maintaining tissue contrast [20]. Density, standard deviation and width of the most pronounced hypodense artefact were measured in the artefact close to the implant and were compared to measurements in reference area. Artefacts and diagnostic quality in the assessment of bone and soft tissue adjacent to the relevant hardware were

Figure 3: Images extracted at a) 70 and b) 130 keV are shown in a patient with an intramedullary titanium nail placed in the tibia. Minor artefacts as well as overall image contrast are reduced in the 130 keV image. Image quality and diagnostic confidence was rated similar in both images by both observers.
subjectively rated using a 5-point Likert scale. Artefacts were significantly reduced at higher monochromatic energies, which improved the assessment of hardware and adjacent soft tissue and bone structures. In patients with osteosynthesis hardware in place, Mangold et al. (2014) showed that in 130 keV images metal artefacts were substantially reduced based on quantitative CT measurements. No subjective image quality scoring was performed in this study. Meinel et al. (2012) found that optimal keVs within the range of 100-130 keV improves image quality and diagnostic quality based on a visual analogue scale ranging from 0-10 in a patient study including patients with hardware in the appendicular skeleton. A more accurate assessment of fracture consolidation was seen in 8 patients. Overall image contrast decreases in high keV images, which may limit the diagnostic value of CT especially in assessing the consolidation of fractures where the high-contrast depiction of the trabecular bone structure is essential [22]. Using higher keV images provides limited additional artefact reduction while overall image contrast decreases even further. For this reason, we chose to use 130 and 150 keV images.

This study has some limitations that need to be addressed. First, in clinical practice fracture healing is assessed by combining clinical and radiographic data. Clinical signs of union include improved weight bearing and mobility, increased range of motion and less pain. This background information, which often helps decision-making in daily practice, was not available to the observers. Second, there was no gold standard, i.e. we did not know whether the bone had indeed healed or not at the time of the CT. However, the absence of clinical signs and gold standard applied to both 70 keV and high keV images. Observers were blinded for 70 and high keV results but one could easily identify high keV images due to reduced artefacts and overall image contrast. An extensive training session for both observers could have enhanced the agreement between both observers with respect to some evaluated aspects. The poor agreement between both observers, consisting of an experienced MSK radiologist and experienced orthopedic trauma surgeon, suggests that multidisciplinary consultation between both disciplines enhances a reliable diagnosis to improve clinical decision-making.

CONCLUSION

Our study reveals that diagnostic confidence and overall image quality improved using high keV images extracted at 130 and 150 keV compared to 70 keV monochromatic images in evaluating fractures of the appendicular skeleton with
suspected non-union treated with titanium and stainless steel intramedullary nails and plates. Overall diagnostic confidence was rated higher in intramedullary nails than plates where no significant difference in diagnostic confidence was seen between titanium and stainless steel hardware. Use of dual-energy facilitates clinical decision-making whether to revise the fracture fixation.

REFERENCES


Figure 4: In this patient, screw failure was only observed in the high keV image, shown in Figure 4b, indicated by the red circle.


Chapter 8


