Reducing metal artefacts and radiation dose in musculoskeletal CT imaging

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CHAPTER 7

OBTAINING OPTIMAL VIRTUAL MONOCHROMATIC DUAL-ENERGY CT IMAGES TO ASSESS BONE UNION IN PATIENTS WITH SUSPECTED NON-UNION OF THE APPENDICULAR SKELETON TREATED WITH DIFFERENT METAL FIXATION IMPLANTS.


Submitted
Chapter 7

ABSTRACT

Purpose: To obtain optimal virtual monochromatic dual-energy CT images to assess bone union in patients with a suspected non-union of the appendicular skeleton treated with different metal fixation implants.

Materials and methods: Fifty patients that were treated for fractures of the appendicular skeleton with suspected non-union were included. Patients were scanned on a Dual-Source CT-scanner using Sn150/100-kVp. Monochromatic images were extracted at 70/90/110/130/150 and 190 keV. In total, 159 orthopaedic trauma surgeons and 12 musculoskeletal radiologists were asked to select the best and worst keV setting to assess bone union in 10 cases. Furthermore, a confidence score from 1-4 in selecting both keV settings was given.

Results: Average optimal keV of surgeons were 145.03, 151.87 ± 10.68 and 151.72 ± 8.51 keV for titanium, stainless steel and combined implants of stainless steel and titanium respectively, compared to 155.69 ± 20.51, 170.67 ± 20.99 keV and 167.08 ± 22.50 keV found by radiologists respectively. Confidence scores and average optimal keVs were higher and average worst keVs were lower for radiologists compared to surgeons in all different hardware (p<0.05). Differences in optimal keV were not statistically significant for different alloys or type of fixation implant in both observer groups.

Conclusions: Optimal monochromatic images to assess bone union in patients with a suspected non-union of the appendicular skeleton varied between 145 and 171 keV. Musculoskeletal radiologists selected higher optimal and lower worst keV settings to assess bone union and were more confident in selecting both keV settings than orthopaedic trauma surgeons in all different hardware.

Keywords: Computed tomography; CT, dual-energy CT; bone assessment; non-union; metal artefact reduction; osteosynthetic implants.
BACKGROUND AND SIGNIFICANCE

In patients with complex fractures of the long bones, Computed Tomography (CT) is often used to assess bone union. Plates and intramedullary nails used for fracture fixation cause metal artefacts, limiting the diagnostic value of CT and impeding a reliable diagnosis regarding bone fracture healing. Especially when dealing with disturbed fracture healing and after multiple surgeries, it is of great importance to optimize CT image quality in order to improve the diagnostic value of CT.

Virtual monochromatic images, extracted from dual-energy Computed Tomography (DECT) scans reduce metal artefacts by reducing beam-hardening artefacts [1–3]. As different metal alloys result in different grades of metal artefacts, optimal monochromatic energies (keV) regarding metal artefact reduction may vary among hardware. Several patient studies focusing on metal artefact reduction in patients with metal fixation implants have investigated optimal monochromatic energies and report a wide range of optimal keVs: 130-148 keV, 95-150 keV, 130 keV, 100-130 keV, and 140 keV [4–8]. Since in most centers orthopaedic trauma surgeons evaluate CT scans of their own patients, next to the reports made by musculoskeletal (MSK) radiologists, we were interested in the opinion of specialists from both disciplines.

The aim of this study was to determine optimal virtual monochromatic images to assess bone union in patients with suspected non-union of the appendicular skeleton treated with different metal fixation implants by orthopaedic trauma surgeons and musculoskeletal radiologists.

MATERIALS AND METHODS

Inclusion
Fifty consecutive patients that were treated for a suspected non-union (a fracture not healed after 6 months time) between November 2015 and November 2016 in our department were included. All patients had hardware in situ. Twenty-five patients had been treated with a stainless steel implant, 17 patients with a titanium implant and 8 patients were treated with a combination of stainless steel and titanium implants. Type of fixation varied. Plate and screw fixation, intramedullary nail fixation or use of only screw fixation was used in 42, 7 and 1 patient(s) respectively. Exclusion criteria were patients with metallic joint replacement prosthesis adjacent to the fracture fixation device of interest.
Image acquisition

Patients were scanned on a Siemens Somaton Force Dual-Source CT-scanner (Siemens Healthcare, Forchheim, Germany) with 100kVp (120 mAs) for tube A and 150kVp (240 mAs) for tube B, using a collimation of 2×96×0.6 mm, a pitch of 0.5, 1.0 mm slice thickness and a rotation time of 1.5 seconds. Images were reconstructed with a sharp reconstruction kernel (Qr54 or Qr59) being most suitable for evaluating osseous structures.

Thin 1.0 mm axial slices were loaded on a Syngo Via workstation (version 3.0.0.16 Siemens Healthcare, Forchheim, Germany) in the CT Dual-Energy application. Virtual monochromatic images were extracted at monochromatic energies of 70, 90, 110, 130, 150 and 190 keV. Images at 70 keV served as a reference since CT numbers and overall image contrast in 70 keV monochromatic images are similar to polychromatic 120-kVp images.

Images extracted at the six different keVs were processed using Horos V2.1.0 DICOM software. First, all 6 monochromatic images were previewed at once in a 3x2 viewing matrix using a bone window (400 window level/1600 window width). Most relevant axial, coronal or sagittal slices to assess bone union were selected and movies were extracted and saved in high quality (2656x1337 pixels; frame rate 10 images/second). By simultaneously evaluating all 6 keV in a 3x2-viewing matrix, impact of high and low keV settings and differences between keV settings can be evaluated in more detail. The order of the 6 different keVs in the 3x2 viewing matrix was randomized and the keV settings were blinded (Fig. 1). All movies were uploaded on YouTube whereas Survey Monkey was used as an online survey platform to present the cases to the observers.

Image quality scoring

Members of the Science of Variation Group (SOVG) consisting of orthopaedic and trauma surgeons or residents and musculoskeletal radiologists (MSK) radiologists or radiology residents with an interest in MSK radiology were invited to participate in the online survey. The SOVG studies variation in definition and treatment of human illness without financial incentives. The only incentive is group authorship. All observers were randomly assigned to 1 of the 5 surveys containing 10 cases per survey each. Before starting the survey, observers were informed with detailed instructions. First, observers were instructed to evaluate the movies in full screen, on a desktop/laptop using a fast Internet connection. They were allowed to pause the movie using the ‘space bar’, go through movie frames back and forward using
‘,’ and ‘.’ and skip 5 seconds back or forward using ‘ß’ or ‘à’. The survey could be interrupted and restarted at any time. Observers were instructed to focus on the balance between metal artefacts reduction while limiting the loss of overall image contrast. Observers were asked to select the best and worst keV setting to assess bone union in each of the 10 cases. Furthermore, a confidence score from 1 (not certain at all) to 4 (completely certain) had to be given in selecting the best and worst setting to assess bone union.

Statistical analysis
Shapiro Wilk test and visual inspection of data were performed to determine whether data were normally distributed. Paired sample t-test was used to compare average optimal keVs and confidence scores between both observer groups. Wilcoxon signed rank test was used to compare worst keVs between both observer groups since data were not normally distributed. Differences in outcome in optimal keV, worst keV and confidence for different metal implants within observer groups were compared using Kruskall-Wallis analysis. A significance level of 5% was used for all tests, and all tests were two-tailed. The statistical package used for analyses was SPSS software, version 24.

RESULTS

In total 159 orthopaedic trauma surgeons and 12 musculoskeletal radiologists completed the survey. On average it took the observers approximately 18 minutes to evaluate the 10 cases.

Figure 1: Example of the six different keV settings randomly placed in the 3x2-viewing matrix.
Surgeons
Average optimal keVs as chosen by the orthopaedic trauma surgeons for titanium implants (Ti), stainless steel implants (SS) and combined implants of stainless steel and titanium (SS+Ti) were 145.03 ± 13.39 keV, 151.87 ± 10.68 keV and 151.72 ± 8.51 keV respectively (Fig. 3). Differences in optimal keV were not statistically significant for different alloys or type of fixation implant. For each metal, 190 keV was selected as the optimal keV setting most frequently (Fig. 2). There was however more dispersion in selecting the optimal keV compared to the worst keV where in only 34.74%, 38.54% and 40.00% of the cases the highest keV of 190 was selected for titanium implants, stainless steel implants and combined implants of stainless steel and titanium respectively. Surgeons selected in 75.37%, 79.26% and 85.66% of the cases 70 keV as worst keV setting for titanium implants; stainless steel implants and combined implants of stainless steel and titanium respectively.

Radiologists
Average optimal keVs as chosen by the radiologists were 155.69 ± 20.51 keV, 170.67 ± 20.99 keV and 167.08 ± 22.50 keV for titanium implants, stainless steel implants and combined implants of stainless steel and titanium respectively (Fig 3). Differences in optimal keV were not significant for different alloys or type of fixation implant. In titanium implants, 150 keV was selected as the optimal keV in most cases (37.5%) where in case of stainless steel implants (59%) and combined implants (47.4%) 190 keV was selected as the optimal keV most frequently (Fig. 2). Radiologists selected 70 keV as worst keV in almost all cases (97.5%) where in only in 3 cases 90 or 130 keV was selected as being the worst keV setting to assess bone union.

Within both groups there was no statistical significant difference in optimal keVs between intramedullary nails and plates. Radiologists chose higher optimal keVs for intramedullary nails as well as for plates with average optimal keVs of 166.19 ± 24.53 and 165.79 ± 20.82 keV compared to 148.18 ± 8.82 keV and 149.75 ± 12.25 keV respectively as chosen by the surgeons (p<0.05). In short, average optimal keVs chosen by the radiologists were higher than those chosen by surgeons for both titanium implants (p<0.05) and stainless steel implants (p<0.001). Average worst keVs chosen by the radiologists were lower than those selected by surgeons for all different hardware (p<0.01). Radiologists were more confident in selecting optimal and worst keVs for all different hardware (p<0.005). Differences between surveys were not investigated since all 50 cases were randomly divided over the 5 surveys with 10 cases each.
DISCUSSION

Implants used for fracture fixation cause metal artefacts and impede a reliable diagnosis of bone fracture healing in musculoskeletal CT imaging (Fig. 4). Options to reduce these artefacts are continuously being explored and improved, allowing better diagnostic evaluation to guide treatment. A significant improvement came with the ability to extract virtual monochromatic images from dual-energy CT by reducing beam-hardening artefacts [1–3]. However, as implants vary in alloy (stainless steel vs. titanium), but also have different sizes, shapes, position (extramedullary vs. intramedullary) and geometry they cause difference artefacts. As a result “optimal” keVs for metal artefact reduction may vary.

Results of this study showed that there is indeed a variety in “optimal” keVs as chosen by surgeons vs. radiologists to assess bone union when there is hardware in situ. Average optimal keVs vary between 145 and 171 keV in different hardware.

Figure 2: Number of times (N) that surgeons and radiologists selected a certain optimal keV, worst keV and additional confidence scores for titanium implants (Ti), stainless steel implants (SS) and combined implants of stainless steel and titanium (SS + Ti).
and observer groups. Other studies have suggested that use of highest keV levels of 190 is suboptimal due to loss of overall image contrast and suboptimal evaluation of fractures [7]. It seems that most observers in our study did not encounter this as a limitation since 190 keV was selected as the optimal keV most frequently. The large variance in selecting an optimal keV was expected since differences between high keV settings (130-150-190) were hard to discern. Most artefact reduction and the largest improvements in overall image quality are seen in the lower region going from 70 keV to approximately 110 keV [1]. Therefore, selecting the worst keV setting with most severe artefacts was much easier than selecting the optimal keV setting. Interestingly, both observer groups were least confident in choosing the optimal and worst keV in case of titanium implants. What surprised us was the fact that 70 keV was selected by the surgeons as being the optimal keV in 6% of the cases. A possible explanation for this could be the loss of overall image contrast at higher keVs or the fact that observers are used to evaluate cases with artefacts with a similar appearance as 120-kVp polychromatic images. As mentioned before,

Figure 3: Average optimal keV, worst keV and confidence scores selected by surgeons and radiologists for titanium implants (Ti), stainless steel implants (SS) and combined implants of stainless steel and titanium (SS + Ti).
both observer groups most frequently selected 190 keV as optimal keV. This can be explained by the fact that all 6 settings were viewed simultaneously in a 3x2-matrix, which could ‘draw’ the observers to the setting with the least image contrast. Losing image contrast is a potential downside of metal artefact reduction at high keVs. On the other hand, the study design was blinded and randomized and observers were able to simultaneously evaluate all keV settings, therefore making it easier to notice differences in MAR and overall image contrast in different keV settings.

Several other groups have investigated the benefit of dual-energy CT in metal artefact reduction. So far there is no consensus regarding an optimal keV for all metal hardware. Obviously, lightweight alloys such as titanium and relatively smaller implants result in less severe metal artefacts. In these cases optimal keVs are found between approximately 95-150 keV [4–8]. Filograna et al. (2015) focused on the value of DECT regarding MAR in post-mortems with mainly fixation implants using 100-140Sn kVp dual-source CT. They found an optimal keV of 137.1 ± 4.9 keV (130-148 keV) based on images extracted at 64, 69, 88, 105, 120, and 130 keV and at optimal selected keV selected by the observers. Image quality was scored higher for the optimal keV compared to 64, 69, 88, 105, and 120 keV and single energy CT with no difference seen with 130 keV [4]. Zhou et al. (2011) investigated image quality in 47 patients with various fixation implants in the extremities and vertebrae. They found an optimal keV of 130 chosen from 40, 70, 100, 130, 160 and 190 keV using 80-140 kVp dual-source CT. A monochromatic energy of 130 keV showed the optimal quality for total, internal, and external metal orthopaedic devices [6]. Bamberg et al. (2011) found an optimal keV of 119.5 ± 13.5 keV ranging from 95-150 keV in patients with various metal hardware and 13/31 patients with hardware in the appendicular skeleton. Images extracted at 64, 69, 88, 105 keV and a manually adjusted optimal energy were investigated. Image quality was rated superior to the standard image in 29/31 high keV images and diagnostic value was rated superior in 27 patients [5]. Meinel et al. (2012) found optimal keVs within the range of 100-130 keV, based on phantom and patients studies. Tube voltages of Sn140/100 kVp yielded superior results over Sn140/80 kVp for the different prosthesis included. Images extracted at 64, 69, 88, 105, 120 and a freely adjusted keV were included. [7]. In high keV images, a more accurate assessment of fracture consolidation was seen in 8 patients. Increasing the keV beyond 120 keV showed less artefacts but a lower diagnostic quality than the manually adjusted keV. At higher keV, overall image contrast decreases, 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 [7]. Neuhaus et al. (2017) suggest using an average monochromatic energy of 140 keV, (chosen from 64, 70, 105, 140, 200 and an optimized keV) extracted from 120-kVp dual-layer detector CT acquisitions. In smaller implants, use of 105 and 140 keV reduced artefacts significantly while maintaining tissue contrast [8]. Mangold et al. (2014) included 50 patients with fracture fixation using consecutive 140 and 80 kVp single energy acquisitions. A monochromatic energy of 130 keV was used and compared to polychromatic results. Metal artefacts were substantially reduced as determined by measuring circular lines surrounding bone and the implant [9]. No optimization of monochromatic energies

Figure 4: Monochromatic images extracted at 70, 90, 130 and 190 keV are shown from left to right respectively for: a) A titanium intramedullary nail placed in the tibia and b) Stainless steel plate fixation for fixation of distal tibia non-union and tibiotalar arthrodesis. Less artefacts are seen with the intramedullary titanium implant, with almost no artefact reduction observed at higher keVs. For the stainless steel implant, each increasing keV step results in additional artefact reduction.
was performed since only 130 keV images were extracted in this study. The lack of a sharp dual-energy reconstruction kernel for bone limited the assessment of bony structures in this study.

Our CT acquisition protocols are comparable to other studies. We chose to use tube voltages of 100/150 kVp over 80/150 kVp since metal artefacts were less severe in this setting based on earlier experiences. Furthermore use of Tin (Sn) filtration increases the spectral separation and reduces CT radiation dose [10–12]. Since only beam-hardening artefacts are reduced in high keV monochromatic images, more severe photon-starvation artefacts remain visible in the resultant image. In this way not all artefacts were removed, which was mainly the case in stainless steel implants. The use of additional MAR software may be more beneficial in these cases. However, it is known that the use of MAR software could induce secondary artefacts [2,13–16] mainly in relatively smaller hardware such as plates and screws as compared to total joint prosthesis.

This study has several limitations. First, the online survey did not allow tools that are used for conventional reading by radiologist such as scrolling, windowing and switching between various multiplanar reconstructions. We selected the most optimal (axial, coronal or sagittal) views, in which all observers were able to go through individual movie frames. We also used the bone window setting, which is most suitable for evaluation of osseous structures. Second, although we used high quality videos and zoomed in on relevant areas in all individual settings, the individual videos in the survey could not be watched full screen. Nevertheless, conditions were the same for all observers. Third, the orthopaedic trauma surgeon observer group was much larger compared to the radiology group. However sufficient responses were collected and cases with Ti, SS, and SS+Ti implants were evaluated at least 19 times by the radiologists group.

CONCLUSION

Optimal monochromatic images to assess bone union in patients with suspected non-union of the appendicular skeleton varied between 145 and 171 keV. No significant difference in optimal keV was seen regarding alloy type or type of fixation implants in both observer groups. Musculoskeletal radiologists selected higher optimal keV settings and lower worst keV settings to assess bone union in all hardware and were more confident in selecting both settings than orthopaedic trauma surgeons.
REFERENCES


