Reducing metal artefacts and radiation dose in musculoskeletal CT imaging

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CHAPTER 1

INTRODUCTION AND THESIS OUTLINE

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INTRODUCTION

Clinical problem
Computed tomography (CT) is a widely used imaging modality for postoperative follow-up in patients with metal hardware in situ. These metal implants induce artefacts, which are primarily caused by photon-starvation, beam-hardening, scatter, noise, and edge effects [1]. As such, overall image quality and the diagnostic value of CT are affected since these artefacts impede a reliable evaluation of bone-metal interfaces and bone and soft tissues adjacent to metal hardware. Figure 1 illustrates this clinical problem with severe artefacts in a patient with bilateral metal-on-metal (MoM) total hip arthroplasties (THA) and a patient with an extramedullary plate used for fracture consolidation of the femur.

Large head MoM THAs were thought to enable a longer in situ time due to lower ware rates with an increased range of motion and stability [2]. However, high complication rates due to peri-articular soft tissue masses or so-called pseudo-tumour formation caused by metal on metal wear resulted in high MoM THA revision rates [3,4]. Metal

Figure 1: Metal artefacts impede the diagnostic value of CT in a patient with a/b) bilateral THA and c) femoral plate fixation.
cobalt and chromium particles were accumulated in the hip joint and initiated the formation of pseudo-tumours.

The large metal prosthesis components consisting of a dense cobalt chromium molybdenum alloy result in severe metal artefacts due to photon-starvation. Therefore, in THA imaging the diagnostic accuracy of detecting all sorts of prosthesis-related pathology, such as pseudo-tumours, capsular reactions and other soft tissue and bone pathologies is impeded.

Also, metal implants used for fracture fixation impede the diagnostic value of CT in the radiologic evaluation of bone fracture healing. Especially when dealing with disturbed or delayed fracture healing or so-called “non-union” it is important to reduce artefacts and improve CT image quality adjacent to metal hardware. Differences in metal alloy, shape, size and geometry of metal hardware all influence metal artefact severity [1,5–7].

Another drawback of CT, which impedes it wide clinical use, is radiation exposure. Despite the fact that the risk of radiation induced pathology is limited in the THA population with relatively higher age, the as low as reasonably achievable (ALARA) principle holds. Reducing radiation dose in patients with large unilateral or bilateral hip prostheses can be extra challenging since the influence of metal and relatively large patient diameters will reduce the amount of photons that correctly end up in the right detector. Using low-dose protocols, while maintaining image quality, could increase the acceptance of using CT in clinical routine due to the reduction of radiation exposure to the orthopaedic patient population.

Novel CT-techniques
Over the last decades major improvements of the image reconstruction process have been achieved from standard filtered back-projection (FBP) to iterative reconstruction (IR) and model-based iterative reconstruction (MBIR). Advanced reconstruction techniques incorporate physical data and photon statistics in the image reconstruction process, which may enable a radiation dose reduction while improving or maintaining overall image quality with reduced metal artefacts and low noise levels [6,8,9]. It is known that the use of MBIR improves overall image quality compared to FBP and IR [8,10,11]. Besides improved overall image quality using model-based iterative reconstruction techniques such as IMR at equivalent radiation dose levels, the use of IMR enables a radiation dose reduction also while maintaining image quality compared to IR and FBP.
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The origin of metal artefacts, technical background of commercially available metal artefact reduction algorithms and the diagnostic value of dual-energy CT (DECT) and metal artefact reduction (MAR) software for different metal hardware in current clinical practice is described in more detail in chapter 10. In general, modifying projection data acquisition, image reconstruction and post-processing can reduce metal artefacts. In all these steps, manipulations can be performed to improve overall image quality. MAR techniques focus on tackling these problems, either by minimizing the physical origin of the artefacts or correcting for the artefacts in the image data or projection data. Metal artefact reduction algorithms focus on replacing corrupted projection data or sinogram data, caused by the presence of metal hardware, with averaged or interpolated neighbour data [12]. Major vendors have their own MAR software, which can be used as an add-on. Metal artefacts can also be reduced using DECT. DECT reconstructs images acquired with two photon spectra at different kVp’s. In the early days two conventional CT scans were made sequentially. Nowadays, the spectra are created by either kV switching, using multiple tubes, using a dual-layer detector or using a beam split filter [13–15]. Virtual monochromatic images, extracted from dual-energy computed tomography scans, are known to reduce metal artefacts by decreasing beam-hardening artefacts. These virtual monochromatic images can be extracted from 40 up to 200 keV, where images extracted at energies at 70 keV show similar CT numbers and overall image contrast compared to a conventional 120-kVp polychromatic single energy CT image. Images extracted at higher keVs show reduced artefacts, albeit with reduced overall image contrast [16]. There is no generalized optimal keV for all hardware with respect to metal artefact reduction where literature report a wide range of optimal keVs [7,17–20]. Figure 2 illustrates the principles of dual-source CT and dual-layer detector CT, which were both investigated in this thesis.

Figure 2: Illustration of conventional single-source, dual-source and dual-layer detector CT.
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Potential clinical value
Patients may benefit from the possible improved overall image quality due to the reduction of metal artefacts and use of (model-based) iterative reconstruction. CT scans of patients with THA and patients with metal fixation hardware may be evaluated with less distorting artefacts and image noise, which could improve the diagnostic value of CT. In this way, soft tissue and bone pathology and malfunctioning of prosthetic hardware could be assessed with a higher diagnostic confidence, which thereby improves clinical decision-making. Furthermore, reducing CT radiation could reduce the incidence of radiation-induced pathology.

By better understanding the cause of metal artefacts, differences in metal artefact severity and ways to reduce artefacts, imaging protocols can be adjusted from acquisition to reconstruction and visualization parameters for specific hardware. Modifying these parameters is of great importance in musculoskeletal CT imaging involving metal hardware. By use of model-based iterative reconstruction, MAR software and use of dual-layer detector or dual-source DECT, image quality may be further improved with reduced metal artefacts and radiation exposure.

By quantitatively and qualitatively assessing image quality in phantom, human cadaver and patient studies the potential clinical value of these techniques individually and when combined is thoroughly investigated in this thesis. First, phantom studies, using a THA phantom and a femur fracture phantom, were executed to quantify the value of new techniques compared to existing techniques used in clinical practice. Second, a human cadaveric study was executed to validate phantom results and to further optimize CT acquisition and reconstruction. Third, the clinical value and possibilities regarding metal artefact reduction and radiation dose reduction was investigated in patients treated for fractures of the appendicular skeleton with suspected non-union and in THA patients. By conducting these studies, imaging acquisition and reconstruction were tailored based on the type and size of metal hardware in these patient groups.
THESIS OUTLINE

This thesis focuses on the clinical value of novel CT techniques including model-based iterative reconstruction, metal artefact reduction software and use of dual-energy CT in reducing metal artefacts and radiation dose in musculoskeletal CT imaging based on phantom (Part I), human cadaveric (Part II) and patient studies (Part III) respectively. The final chapter consists of a review on metal artefact reduction techniques in musculoskeletal CT imaging.

Part I
Chapter 2 - The combined use of iterative model-based reconstruction (IMR) and orthopaedic metal artefact reduction (O-MAR) in reducing metal artefacts and improving image quality was quantified. A large head metal-on-metal total hip arthroplasty was inserted in a THA phantom, which was filled with water. Outcome values such as CT-number accuracy, noise values, signal-to-noise-ratios (SNR) and contrast-to-noise-ratios (CNR) were measured in water and in hydroxyapatite pellets, which represent bone.

Research question: Does the combined use of IMR and O-MAR reduce metal artefacts and improve overall image quality compared to IR and FBP combined with O-MAR?

Chapter 3 - The use of IMR enables a radiation dose reduction. The next step was to determine the possibility to lower radiation dose while maintaining image quality or improving image quality involving metal artefacts. Quantitative measures of image quality, in terms of CT number accuracy, noise, SNR and CNR values were compared at different dose levels with FBP, iDose⁴ and IMR alone and when combined with O-MAR in a THA phantom while inserting a commonly used total hip prosthesis. In this setting, CT radiation dose was reduced up to 80% compared to current clinical practice.

Research question: Does the use of IMR and O-MAR enable a CT radiation dose reduction in a THA phantom?

Chapter 4 - The value of the novel dual-layer detector approach with respect to metal artefact reduction was quantified in this chapter. Furthermore, a thorough quantitative evaluation on the performance of virtual monochromatic imaging as a tool for metal artefact reduction in different hardware may improve its clinical value. Metal artefact reduction was quantified in the CT imaging of different unilateral and
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bilateral hip prostheses types composed of different metal alloys using dual-layer detector spectral CT imaging at various monochromatic energies (keV).

Research question: Does the use of high keV monochromatic images, extracted from dual-layer detector spectral CT reduce metal artefacts using a THA phantom with different unilateral and bilateral total hip prostheses?

Chapter 5 - In large orthopaedic implants and implants with a high density the value of virtual monochromatic imaging with respect to MAR can be limited. However regarding smaller fixation implants and more specifically regarding fracture visualization adjacent to metal fixation implants, choosing the right protocol is less straightforward. Therefore, the aim of chapter 5 was to quantitatively assess CT image quality and fracture visibility using virtual monochromatic imaging and iterative metal artefact reduction (iMAR) in a femoral bone fracture phantom with titanium and stainless steel fixation implants of different thicknesses.

Research question: Which technique, MAR software or virtual monochromatic imaging, is superior in CT image quality and fracture visibility in a femoral bone fracture phantom with external titanium and stainless steel fixation implants of different thicknesses?

Part II
Chapter 6 - As different metal alloys result in different grades of metal artefacts severity, it is likely that implant specific CT imaging protocols are needed to achieve optimal monochromatic energies with respect to metal artefact reduction. In this chapter, metal artefact reduction was quantified in relevant bone and soft tissue structures using virtual monochromatic dual-source CT images in intramedullary and extramedullary fixation implants placed in a cadaveric lower leg. Non-metal cadaver scans were used as a reference.

Research question: Can we quantify and optimize metal artefact reduction in relevant bone and soft tissue structures using virtual monochromatic dual-energy CT images in intramedullary and extramedullary fixation implants placed in a cadaveric lower leg?

Part III
Chapter 7 - Despite the fact that quantitative measures are of increasing importance in medical imaging, assessing diagnostic quality remains essential before implementing novel CT techniques in clinical practice. Therefore we requested
observers to select optimal and worst virtual monochromatic reconstructions to assess bone union in patients with fractures of the appendicular skeleton. An online survey platform with large observer groups was used including musculoskeletal radiologists and orthopaedic and trauma surgeons.

Research question: Can we obtain 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?

Chapter 8 - Monochromatic images extracted at 130 and 150 keV in case of titanium fixation implants and stainless steel fixation implants respectively were further analysed in this chapter. The diagnostic value of high (130 or 150) keV virtual monochromatic imaging in patients treated for fractures of the appendicular skeleton with suspected non-union was investigated compared to 70 keV images. Images were subjectively evaluated on image quality, degree and location of consolidation, non-union type and overall diagnostic confidence.

Research question: Does high keV monochromatic DECT imaging improve the diagnostic value of CT in patients with suspected non-union of the appendicular skeleton treated with different metal fixation implants?

Chapter 9 - Based on phantom results, a clinical validation study was executed in order to determine minimal acceptable radiation dose levels based on qualitative and quantitative image quality measures in patients with unilateral or bilateral MoM THA. CT values, noise and contrast-to-noise ratios were measured in regions of interest placed in muscle, fat and bladder whereas subjective image quality was evaluated based on 7 aspects in full-dose and low-dose images. Radiation dose was reduced in four different patient groups where each patient received a full-dose CT scan and a low-dose CT scan with 20%, 40%, 57% or 80% reduced CT radiation dose.

Research question: Can we reduce CT radiation dose in patients with unilateral or bilateral MoM THA using IMR and O-MAR?

Chapter 10 - Based on relevant literature and research conducted in the previous chapters we conducted a review on metal artefact reduction techniques in musculoskeletal CT imaging. An overview of the origin of metal artefacts, technical background of commercially available metal artefact reduction algorithms and the diagnostic value of dual-energy CT and MAR software for different metal hardware in current clinical practice is provided in this final chapter.
REFERENCES


