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PICTORIAL REVIEW

Orthopaedic and non-orthopaedic applications of a single-energy iterative metal artefact reduction technique and other metal artefact reduction techniques explained

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ABSTRACT

Metal within the CT field of view causes artefact that degrades the diagnostic quality of the processed images. This is related to the high atomic number of most metals and is due to a combination of beam hardening, scatter, edge effects and photon starvation. Both software and hardware metal artefact reduction (MAR) techniques have been developed. Iterative reconstruction software MAR techniques can be applied on raw CT data sets and show improved image quality in the setting of sparse projection data when compared with filtered back-projection methods. Recently, a novel single-energy iterative metal artefact reduction technique (IMART) was released for use with large orthopaedic devices. The aim of this pictorial essay was to demonstrate the usefulness of IMART in the setting of both orthopaedic and non-orthopaedic metallic objects and devices.

INTRODUCTION

Therapeutic implantable metal prostheses are increasingly common. In the USA, 2.5 million (0.83%) individuals now live with a total hip replacement and 4.6 million (1.52%) individuals live with total knee prostheses.¹ Spinal fusion is becoming more frequent; the number of annual discharges for spinal fusion surgery in the USA has increased from 174,223 to 413,171 (137%) between 1998 and 2008.² In Western Australia, both the incidence and prevalence of pacemakers are on the rise owing to the ageing population, where over 1 in 50 people over 75 years old are living with a pacemaker.³ Similarly, in the USA, between 1993 and 2009, the number of pacemaker insertions increased by 56%, nearing 600,000 per year.⁴

In CT, metal causes artefact which manifests as white and black streaks or, in severe cases, areas of complete information loss. This can limit the identification of pathology in the vicinity of the metal object, precluding diagnostic examination.

The metal artefact is caused by a combination of beam hardening, scatter, edge effects and photon starvation. Beam hardening refers to the preferential attenuation of the lower energy X-rays as the X-ray beam passes through matter, resulting in a “hardened” beam. This results in erroneously low linear attenuation values.⁵ Scatter is predominantly due to Compton interactions of photons. Scattered X-rays reaching the detector are registered as originating from an erroneous point source, thus misrepresenting the imaged object. This results in a Poisson variation of Hounsfield unit values within a homogeneous tissue and is the main contributor to digital noise.⁶ Photon starvation—marked attenuation of the X-ray beam by the extremely high Z-number of metal—causes undersampling of the target region. In reconstruction, the lack of projection data results in “aliasing” artefact, which is worse in the presence of high-frequency objects.⁵ The high contrast between the edge of the metal object and adjacent soft tissues can also introduce lucent streaks, otherwise known as exponential edge-gradient effects.⁷

Figure 1. Image of the pelvis degraded by a metal artefact from a right total hip prosthesis in an 88-year-old male patient (a). Iterative metal artefact reduction technique allowed better assessment of the adjacent greater trochanter and pelvis, femoral musculature (arrowhead) and the wall of the rectum (arrow) (b).

Both hardware and software techniques aimed at metal artefact reduction (MAR) have been developed. Hardware techniques involve altering the acquisition technique. Software techniques, which can be combined with hardware techniques, alter the reconstruction algorithm to ameliorate artefacts. MAR is efficacious in reducing streak artefact and noise around orthopaedic prostheses, dental implants and cerebral aneurysm treatment devices, improving the image quality and diagnostic value.^{8,9} MRI provides an alternate method of assessing for periprosthetic complications, having found most use in the setting of failed metal-on-metal hip prostheses and after spinal surgery. However, its use is still limited by susceptibility artefact from metal, obscuring both the immediately adjacent bone and soft-tissue detail.^{10,11}

MAR for Orthopedic Implants (Philips Healthcare, Cleveland, OH) is an example of a single-energy iterative metal artefact reduction reconstruction technique (IMART). The key feature is the subtraction of metal traces from the original input image from raw CT data prior to entering the iterative reconstruction loop.¹² MAR for Orthopedic Implants may be activated by a toggle box on the radiographer console at the time of

Figure 2. Streak artefact from the right shoulder prosthesis in an 81-year-old female patient obscuring the adjacent bone and musculature (a). The application of iterative metal artefact reduction technique has improved the visibility of these structures (b).

reconstruction, which generates a second set of multiplanar reconstructions to be sent to the picture archiving and communication system. Alternatively, it may be retrospectively applied at the CT console to raw data acquired by Philips CT machines, conferring the ability to limit the reconstructed “scan range” of the corrected images, at the cost of automation. The CT scanning parameters remain the same as in routine scanning. No additional image acquisition is required and therefore, there is no additional radiation dose. The additional reconstruction takes only a few minutes and does not result in a significant additional delay in viewing images on a picture archiving and communication system workstation. Currently, at least three other major CT vendors feature proprietary iterative reconstruction MAR software.

Metallic medical prostheses and devices are becoming more prevalent in the ageing population and the accompanying artefact can often obscure bone and soft-tissue detail in the close vicinity. The aim of this pictorial essay was to demonstrate the usefulness of this tool in ameliorating the metal artefact from orthopaedic devices, and also non-orthopaedic devices, to allow assessment of otherwise obscured regions.

Figure 3. Artefact from bilateral hip prostheses completely obscuring the pelvis in an 81-year-old female patient (a). After the application of iterative metal artefact reduction technique, the rectum and sigmoid colon are more readily appreciable and decentring of the head of the right femoral prosthesis (arrow) is more evident (b).

Figure 4. Anterior cervical discectomy and fusion were previously performed in this 71-year-old female patient (a). The application of iterative metal artefact reduction technique has allowed partial assessment of the paravertebral muscles and improved detail within the spinal canal (b).

APPLICATIONS

Orthopaedic

Metal artefact from joint replacements and internal fixation devices (such as screws, plates and rods) is frequently encountered in CT. The artefact is more severe when multiple metallic objects lie in the same plane such as in patients with bilateral joint replacements. The artefact makes detection of peri-prosthetic complications or adjacent bone or soft-tissue lesions difficult. For example, periprosthetic lucency, reproductive organs, bladder and lower gastrointestinal tract can all be obscured by artefact from hip joint replacements. Detection of a collection or mass in the pelvis or chest or identification of lymphadenopathy in the pelvis, inguinal and axillary regions may be compromised. IMART is effective in the amelioration of metal artefact, allowing better assessment of bony and soft-tissue detail. This is applicable in the setting of large joint prostheses (Figures 1 and 2), especially bilateral implants (Figure 3), spinal surgery (Figures 4 and 5) and external fixation (Figure 6).

Non-orthopaedic

Although IMART is primarily for use with orthopaedic implants, there are other situations in which the technique is effective. These include, but are not limited to cerebral aneurysm clips and coils (Figure 7), dental amalgam (Figure 8), venous access ports (Figure 9) and pacemakers (Figure 10).

DISCUSSION

Software techniques

The presence of metal alters the CT number of surrounding structures in the same axial plane through corruption of the CT data. Software techniques aim to either correct or replace the corrupted data.

Adaptive filtered back projection

In the sinogram inpainting method, any ray sums considered corrupted by the metal artefact are disregarded. Replacement values are then interpolated from adjacent healthy data.^{8,9}

Figure 5. Post-operative assessment after lumbar laminectomy and fusion in a 28-year-old female patient: pedicular screws caused artefact which obscured the posterior spinal canal and operation site (a). With the use of iterative metal artefact reduction technique, the epidural fat (arrow), ligamentum flavum and facet joints are now visible (b).

Figure 6. External fixation of the lower limb in a 10-year-old female patient has caused extensive streak artefact (a). The application of iterative metal artefact reduction technique has resulted in a marked reduction in streak artefact, with recovery of the bony and muscular detail (b).

Adaptive filtering methods use a statistically based approach to account for local noise characteristics, striking a balance between streak artefact and spatial resolution.⁶ Combinations of these techniques exist.¹³ Filtered back-projection MAR techniques have generally had more success with reduction of artefact arising from large implants rather than small implants because of blurring caused by loss of edge information.⁸

Iterative reconstruction

Standard iterative reconstruction MAR techniques segment and remove metal traces, using iterative methods to reconstitute the artefact-affected pixels.^{12,14} The advantages of iterative techniques include fewer streak artefacts and similar image quality at a lower dose compared with filtered back-projection techniques.

Figure 7. Left middle cerebral artery aneurysmal clip metal artefact obscuring the adjacent brain parenchyma in a 32-year-old male patient (a). An area of hypodensity in the left medial temporal lobe has been shown to be artefactual (arrowhead) after the application of iterative metal artefact reduction technique (IMART) (b). IMART has also revealed an area of hypodensity in keeping with a recent infarct surrounding the surgical clip in the left temporal lobe (arrow) which was not previously visible (b).

The techniques can be applied on raw CT data. A metal deletion technique has shown promise, especially in the setting of small, stationary implants.¹⁴

Similar to other iterative methods, the first step of the IMART loop is the creation of a “tissue-classified” image from the raw image by setting all pixels in the soft-tissue range to an averaged value. IMART is unique in that in the first iteration of the algorithm, the metal traces are replaced with soft-tissue values before the creation of the tissue-classified image. The image is then forward projected and an error sinogram is generated by subtraction. Simultaneously, a “metal-classified” image is also created using preset Hounsfield values to segment the image and set non-metal values to 0. The metal-classified image is used as a mask to remove the non-metal traces from the error sinogram, which is then back projected to form the correction image. Subtracting the correction image from the original input image yields an output image, which then re-enters the iterative loop as the input image.¹²

Figure 8. Dental material in an 81-year-old male patient obscuring the jaw muscles and oral cavity (a). The application of iterative metal artefact reduction technique has decreased the artefact and allowed partial assessment of the musculature and skin (b).

Figure 9. A chest port in a 10-year-old patient caused streak artefact that has made assessment of the adjacent liver parenchyma impossible (a). Iterative metal artefact reduction technique has markedly improved the streak artefact; even the internal architecture of the port has become visible (b).

Hardware techniques

Examples of hardware solutions include gantry tilting, increasing the photon flux and dual-energy and spectral CT techniques.

Metal artefact is most apparent in the axial scanning plane. Using a tilted axial gantry technique changes the plane of the metal artefact, allowing evaluation of structures adjacent to the metal object. This has limited usefulness in the setting of dental implants, heart valves and knee prostheses.^{15,16}

Using a high peak kilovoltage (kVp) without changing the overall dose reduces beam hardening at the expense of some soft-tissue contrast and has been used in the assessment of cardiac valvular prostheses.¹⁷

Dual-energy imaging uses two kVp data sets to computationally simulate a monochromatic beam, effectively eliminating the beam-hardening artefact and allowing more accurate subtraction of specific densities. The data sets can be acquired using a single source with fast kVp switching, a dual-source/dual-detector system or a dual-layer single detector able to separate high- and low-energy photons. Further software processing can reduce the streak artefact induced by the reconstruction process.¹⁸

Impact on image quality and workflow

IMART is most useful when the soft-tissue pathology is likely to lie in close proximity to the metal or between metal objects. Especially in the setting of bilateral joint prostheses and spinal surgery, the intervening tissue may be completely obscured on the non-corrected images and assessable only on the corrected images.

A phantom study has demonstrated that IMART confers a reliable, modest improvement in image quality around the hip,

Figure 10. A left chest wall pacemaker in a 90-year-old male patient has produced extensive streak artefact (a). Iterative metal artefact reduction technique has resulted in a marked reduction of streak artefact (b).

Figure 11. An earring in a 29-year-old male patient has produced some metal artefact degradation at the level of the middle cranial fossa (a). This artefact has been exacerbated by iterative metal artefact reduction technique (b) because of the direct contact of the earring with air.

spinal and dental implants and in the accurate representation of metal object size. The same study noted that the wide variance of tissue density in the thorax at lung, bone and soft tissue interfaces contributed to increased distant streak artefact.¹⁹ Jeong et al²⁰ showed improved image quality in the context of spinal and hip joint prostheses compared with standard iterative reconstruction without IMART. Clinically, IMART has been shown to be beneficial for structure delineation and dosimetry in the planning of pelvic radiotherapy in patients with hip joint prostheses²¹ and does not affect spinal stereotactic body radiation therapy treatment planning.²²

MRI remains the most viable alternative, but accessibility and cost preclude routine use, especially in rural and regional areas (Figure 11).

As with other MAR techniques, there are limitations to the use of IMART. When metal traces are in direct contact with air, the adjacent artefact is reduced, but a distant streak artefact is often created (Figures 11, 12 and 13). In our experience, if the metal object is at least deep to the skin, only minimal streak artefact is produced (Figure 10). It is recommended that all external metal objects be removed from the plane of scanning if possible, even when using IMART. Because of the induced distant streak artefact, it is important that both the IMART images and the uncorrected images are interpreted in tandem to avoid misinterpreting distant artefact.

Figure 12. An underwire brassiere has caused only minor artefact in this 63-year-old female patient (a). Iterative metal artefact reduction technique (IMART) has worsened the streak artefact instead (b). Arrows indicate streak artefact produced by the IMART.

Figure 13. The metal artefact created by a combination of an external electrocardiogram device, wires and spinal fusion screws in a 90-year-old male patient has caused extensive streak artefact (a). Whilst the paraspinal tissues have become more visible after the application of iterative metal artefact reduction technique, streak artefact has been created (arrowhead) or altered (arrow), leading to obscuration of the mediastinal structures (b).

Because of the need to review both sets of data to avoid misinterpretation of distant streak artefact, the additional IMART images result in increased storage requirements and radiologist viewing time. Both of these factors can be ameliorated by limiting the range of the IMART reconstructions to the plane of the metal objects. This translates to only a minor increase in the reporting time as a focused review of areas can be made. In our experience, the recovery of soft-tissue detail in the setting of spinal surgery and large joint prostheses, especially when bilateral, and the potential for uncovering pathology in other situations justify the mild workflow impact.

SUMMARY

CT continues to be a rapidly evolving modality. Technological advances are focused on not only improvements in spatial and temporal resolution, but also reconstruction technique,

especially in regard to dose reduction and MAR. Metal artefact from medical devices is increasingly common. This single-energy IMART is shown to confer radiation dose neutral improvement in image quality, in the form of decreased noise and metal streak artefact, allowing better interpretation of studies that would otherwise be non-diagnostic. It is particularly useful when the tissue of interest lies between two metallic objects.

KEY POINTS

- Metal artefact can obscure pathology, especially in the close vicinity of the metal object. This is especially relevant in the assessment for periprosthetic complications.
- Numerous software and hardware MAR solutions exist.
- Single-energy MAR is beneficial in improving the image quality for not only orthopaedic, but also non-orthopaedic devices and objects.

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