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Retained bullets in the head on computed tomography – Get the most out of iterative metal artifact reduction

Florian Berger[a], Tilo Niemann[b], Rahel A. Kubik-Huch[b], Henning Richter[c], Michael J. Thali[a], Dominic Gascho[a,*]

[a] Department of Forensic Medicine and Imaging, Zurich Institute of Forensic Medicine, University of Zurich, Winterthurerstrasse 190/52, 8057 Zurich, Switzerland
[b] Department of Radiology, Kantonsspital Baden, Im Ergel 1, 5401 Baden, Switzerland
[c] Clinic of Diagnostic Imaging, Vetsuisse Faculty, University of Zurich, Winterthurerstrasse 260, 8057 Zurich, Switzerland

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ABSTRACT

Background: Metal artifacts from retained bullets impair the image quality on computed tomography (CT) and may compromise the detection of critical lesions or the bullet path. To reduce metallic artifacts from medical implants on CT, special algorithms have been developed, e.g., iterative metal artifact reduction (iMAR). The aim of this prospective study was to evaluate the application of iMAR in cases of retained bullets.

Materials and methods: In this study, nine different types of projectiles (n = 9) were selected to evaluate the effect of iMAR. The study consisted of two settings. In the first setting, each projectile was fixed on a thin thread and placed in the middle of a water-filled container to demonstrate the effect of iMAR in a homogenous medium. In the second setting, each projectile was placed in the severed head of a pig cadaver as a substitute for human tissue to evaluate iMAR in cases of retained bullets. The raw data from CT scans of both settings were reconstructed with and without iMAR (standard filtered back-projection). The reconstructions with iMAR were calculated using eight different presets provided by the software, namely, neuro-coils, dental fillings, spine implants, shoulder implants, pacemaker, thoracic-coils, hip implants and extremity implants. For each setting, nine reconstructions (n = 9; iMAR: n = 8; without iMAR: n = 1) for each projectile were subjectively evaluated for the image quality and extent of streak artifacts by ten independent and blinded raters (residents: n = 5; radiologists: n = 5). The reconstructions of the second setting were evaluated in a soft tissue window and bone window. A 5-point Likert scale was used for the evaluation of image quality based on the extent of streaks as follows: 1 = severe; 2 = considerable; 3 = moderate; 4 = minimal; and 5 = not apparent.

Kendall's W was used for assessing agreement among the ten raters. The Wilcoxon test was used to reveal whether there was a difference in the subjective evaluations between residents and radiologists. Nonparametric Friedman and post hoc tests were used to analyze the Likert scores. The mean difference was considered significant at the 0.05 level.

Results: The agreement among the raters was reasonably high for all projectiles in both settings. In the phantom setting, the iMAR presets neuro-coils and dental fillings yielded the best results. In the pig's head setting regarding the soft tissue window, the presets neuro-coils and extremity implants were preferred. Regarding the bone window, the presets extremity implants and hip implants had the best results. Statistical significance ($p < 0.01$) between reconstructions without iMAR and neuro-coils or extremity implants was calculated. The iMAR preset spine implants had poor values comparable to reconstructions without iMAR.

Conclusion: The applied iMAR presets revealed different effects on the image quality. Selecting an inappropriate preset (e.g., spine implants) may result in unsatisfactory artifact reduction. The results of this study indicate that the neuro-coils preset is the most appropriate preset for soft tissue, and the preset extremity implants is favorable for bones in cases of retained bullets.

1. Introduction

Utilization of computed tomography (CT) has greatly increased over the past few decades for diagnostic evaluation, and it has become an important radiographic modality in evaluating trauma patients [1]. Compared to other radiographic modalities, such as conventional

* Corresponding author.
E-mail address: dominic.gascho@irm.uzh.ch (D. Gascho).

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radiography, it has the advantage of not only allowing rapid full body examinations but also providing consistent and detailed three-dimensional information [2]. In cases in which a foreign body entered the body, any possibly vital injuries and the introduced foreign body can be effectively visualized on CT [3]. However, metallic hardware frequently results in considerable streaking artifacts on CT due to photon starvation and beam-hardening. These artifacts degrade the image quality and may obscure critical anatomical structures or pathological findings, especially in the region near the metallic foreign body [4,5].

Apart from common medical implants, any foreign bodies with high radiopacities create substantial artifacts on CT, e.g., retained bullets [6]. The number of patients with gunshot wounds and retained bullets continues to increase worldwide with the increase in violence [7]. Over the last 15 years, forensic radiology with postmortem CT has become an established subspecialty, and gunshot injuries are a major focus in this context [8,9]. In the worst case, metallic artifacts due to retained bullets can lead to non-diagnostic images by concealing the relevant pathologies. Furthermore, the reconstruction process may be impaired due to the challenges of accurately detecting the bullet path.

With time, several postprocessing methods have been developed for reducing the severity of metal implant artifacts in CT, such as frequency-split metal artifact reduction (f-sMAR), normalized metal artifact reduction (norMAR), and monoenergetic dual-energy CT with energetic extrapolation [10–13]. Each of these methods imposed different challenges in reducing metallic artifacts due to differences in the implant composition and local anatomy [5]. A recently introduced software algorithm for iterative metal artifact reduction (iMAR) has been demonstrated to significantly reduce artifacts caused by medical implants regardless of the affected body region by combining a frequency-split technique with normalized sinogram interpolation [14]. Wuest et al. [15] presented the iMAR technique for metallic artifacts from dental hardware in head and neck CTs and revealed the highest image quality with iMAR compared to filtered back-projection and linear interpolation metal artifact reconstruction. The iMAR technique allows for selection of different reconstruction presets for neuro-coils, dental fillings, spine implants, shoulder implants, pacemaker, thoracic-coils, hip implants and extremity implants. Wuest et al. [15] did not mention the preset they had used in their study, but it can be assumed that the dedicated dental filling preset was used for the iMAR reconstructions. However, a dedicated preset for retained bullets or any other foreign bodies is not selectable in the iMAR software thus far.

To the best of our knowledge, the application of iMAR in cases of retained bullets has not been previously described in the literature. Further, the different effect of iMAR presets on a small metallic objects has not been explored so far. The aim of this prospective study was to evaluate the application of iMAR compared to standard filtered back-projection and define the most appropriate iMAR preset in cases of retained bullets in the head.

2. Materials and methods

2.1. Technical description

As described by Wuest et al. [15], the iMAR algorithm is adapted from two previously introduced metal artifact reduction (MAR) algorithms, namely, norMAR and f-sMAR. Compared to other sinogram inpainting methods, norMAR prevents the introduction of new artifacts tangential to high-contrast objects by first removing high-contrast structures from the sinogram before interpolation and second reinserting them. In the initial unmodified image, soft-tissue pixels are assigned zero Hounsfield units (HU) by thresholding, resulting in a prior image. The initial sinogram is subsequently divided pixel-wise with the prior image followed by linear interpolation on the flat normalized sinogram. The norMAR reconstructions are finally obtained by reconstructing the corrected sinogram and reinserting the metal pixels from the uncorrected images. By contrast, f-sMAR preserves the natural image impression and edge information of the uncorrected image. The latter is known to be affected by pure sinogram inpainting methods, particularly near metal implants. The f-sMAR technique achieves this by combining the high spatial frequencies of the initial image with the low spatial frequencies of the corresponding metal artifact-corrected image. High- and low-frequency images are obtained by Gaussian filtering. On the downside, f-sMAR reinserts high-frequency streak artifacts into the corrected images.

The iMAR technique repeatedly performs the normalized sinogram interpolation and frequency-split operations using the result of each iteration as input for the next iteration. The remaining artifacts of the prior image are thus effectively reduced, and the quality of norMAR is consequently improved in each iteration [15]. The iMAR software provides different presets that are optimized for several common metallic implant types, such as pacemakers, dental fillings, hip implants or spine implants.

2.2. Study design

The Forensic Institute was asked to provide us with projectiles, which are often encountered in practice, made from different materials. Prior to scanning the projectiles, a ballistic expert identified the materials that the projectile jackets and cores consisted of. All projectiles had previously been discharged in firing practice. The following nine projectiles (n = 9; pistol bullet: n = 6 and rifle bullet: n = 3) were selected to evaluate the effect of iMAR on retained bullets:

Pistol bullets:

- 9 × 19 mm Para #1 (Leader FMJ, Leader Trading GmbH, Ratingen, Switzerland):
  jacket: brass; core: lead
- 9 × 19 mm Para #2 (RUAG Pist Pat 41, RUAG Ammotec, Thun, Switzerland):
  jacket: steel; core: lead
- 9 × 19 mm Para #3 (RUAG Action 4, RUAG Ammotec, Thun, Switzerland):
  jacket: brass; core: brass
- 9 × 19 mm Para #4 (Federal Hydra-Shok, Anoka, MN, USA):
  jacket: tombac; core: lead
- 6.35 Browning (Geco FMJ, RUAG Ammotec, Thun, Switzerland):
  jacket: steel; core: lead
- 7.45 mm Browning (Geco FMJ, RUAG Ammotec, Thun, Switzerland):
  jacket: brass; core: lead

Rifle bullets:

- 5.56 × 45 mm NATO #1 (RUAG GP 90, RUAG Ammotec, Thun, Switzerland):
  jacket: steel; core: lead
- 5.56 × 45 mm NATO #2 (RUAG GP 90 LSP, RUAG Ammotec, Thun, Switzerland):
  jacket: steel; core: lead
- .223 Remington (PPU FM3, Prvi Partizan, Užice, Serbia):
  jacket: tombac; core: lead

The study consisted of two settings. In the first setting, each projectile was fixed with a thin thread in the middle of a water-filled container to demonstrate the effect of iMAR in a homogenous medium. In the second setting, each projectile was placed in the severed head of a pig cadaver through the foramen magnum as a substitute for human tissue to evaluate iMAR in cases of retained bullets (Fig. 1). The raw data from CT scans of both settings were reconstructed with and without iMAR (standard filtered back-projection). The reconstructions with iMAR were calculated using eight different presets for medical implants as provided by the software, namely, neuro-coils, dental