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A comparison of radiography, x-ray tomosynthesis, and CT for intraorbital metallic foreign body screening --Manuscript Draft--

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Abstract:	Objective Prior to MRI examination, patients are often screened for intraorbital metallic foreign bodies (IMFBs) via questioning, clinical record review, and imaging when appropriate. This work compares the screening performance of digital radiography (DR), digital tomosynthesis (DT), and CT in detecting IMFBs composed of various metals, and identifies their limits of detection. Methods Fragments of aluminum, steel, and cobalt-cemented tungsten carbide were produced. A human skull model, with metal fragments embedded in grapes placed in each orbit, was submerged in a water bath to create a semi-anthropomorphic phantom. Phantom orbit images were acquired with DR, DT, and CT. Six experienced radiologists reviewed images and scored their confidence in detecting IMFBs. ROC analysis was performed and a multi-reader multi-case ANOVA was used to compare the modalities.

	Results Performance comparison across modalities yielded AUC values of 0.90, 0.79, and 0.78 for CT, DT, and DR, respectively. Pairwise comparison revealed that CT was superior to both DT and DR ($p < 0.05$). When stratified by metal type, a significant performance difference among modalities was only observed for steel. Steel fragments of mass 0.8 mg and smaller were not detected using DT or DR, while even the smallest steel fragments of 0.4 mg were detectable with CT. Conclusion CT outperformed DT and DR in detecting IMFBs using a semi-anthropomorphic phantom. This performance difference is largely attributed to differences in detection of steel fragments. Since steel is often ferromagnetic, this distinction is relevant for imaging modality selection for orbit screening prior to MRI.
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Title:

A comparison of radiography, x-ray tomosynthesis, and CT for intraorbital metallic foreign body screening

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Abstract

Objective: Prior to MRI examination, patients are often screened for intraorbital metallic foreign bodies (IMFBs) via questioning, clinical record review, and imaging when appropriate. This work compares the screening performance of digital radiography (DR), digital tomosynthesis (DT), and CT in detecting IMFBs composed of various metals, and identifies their limits of detection.

Methods: Fragments of aluminum, steel, and cobalt-cemented tungsten carbide were produced. A human skull model, with metal fragments embedded in grapes placed in each orbit, was submerged in a water bath to create a semi-anthropomorphic phantom. Phantom orbit images were acquired with DR, DT, and CT. Six experienced radiologists reviewed images and scored their confidence in detecting IMFBs. ROC analysis was performed and a multi-reader multi-case ANOVA was used to compare the modalities.

Results: Performance comparison across modalities yielded AUC values of 0.90, 0.79, and 0.78 for CT, DT, and DR, respectively. Pairwise comparison revealed that CT was superior to both DT and DR ($p < 0.05$). When stratified by metal type, a significant performance difference among modalities was only observed for steel. Steel fragments of mass 0.8 mg and smaller were not detected using DT or DR, while even the smallest steel fragments of 0.4 mg were detectable with CT.

Conclusion: CT outperformed DT and DR in detecting IMFBs using a semi-anthropomorphic phantom. This performance difference is largely attributed to differences in detection of steel fragments. Since steel is often ferromagnetic, this distinction is relevant for imaging modality selection for orbit screening prior to MRI.

Keywords

Intraorbital foreign body, MRI safety, radiography, CT, digital x-ray tomosynthesis

Introduction

Screening patients for potential intraorbital metallic foreign bodies (IMFBs) prior to undergoing MRI examination has been common practice since the 1980s. This practice is attributed to several published cases of injury and one of blindness resulting from MRI scanning of a patient with a previously unidentified IMFB. The first case report in the radiology literature involved a former metalworker who suffered unilateral blindness following an MRI study on a 0.35T imaging system [1]. Despite the increased practice of orbit screening prior to MRI, five additional case studies have been subsequently reported in which patients sustained injuries such as hyphema, increased intraocular pressure, eye pain during MRI examination, blurred vision, and cataract progression [2-6]. In all but one of these cases, case study authors indicated that injuries followed an appropriate screening protocol, but the patients either denied prior intraocular injury [2, 5], reported that previous IMFBs had been removed from the eye [4], or IMFBs were not detected on X-ray screening [3]. The patients in all but one of these case studies were metalworkers or had a known history of IMFB. The other case did not mention procedures for IMFB screening prior to MRI [6].

Screening a patient for IMFBs prior to MRI can consist of clinical screening (including asking questions about history of metalworking, eye injury, and subsequent treatment), review of the patient record and past imaging exams, and/or non-MRI imaging-based screening. In the United States, current

guidance documents from the American College of Radiology (ACR) indicate that patients who have sought medical attention for orbital trauma by a potential IMFB should be cleared by an orbit radiograph or assessment of a prior CT obtained after the orbital trauma event (it is noted that MRI alone is insufficient to clear orbits) [7]. An expert consensus document from 10 North American radiologists recommends screening with orbit radiographs or low dose orbit CT and/or reviewing a recently obtained head CT if there is suspicion for IMFBs [8]. Image based screening can also be used in cases where the patient is obtunded or otherwise unable to provide reliable history.

Several investigations have compared the sensitivity of projection x-ray and CT for IMFB screening in phantoms, cadaver models, or retrospective patient studies [9-15]. Though IMFB size, composition, and imaging protocols vary, this body of work has demonstrated that CT has higher sensitivity than x-ray [9, 10, 12, 14], and CT can facilitate identification of smaller IMFBs than x-ray [9, 10, 14, 15].

In practice, IMFB screening varies across sites. Imaging-based screening is utilized based on site-specific criteria with differing preferences across sites for 1-view radiograph, 2-view radiographs, or CT [16]. Imaging-based screening may be used if a patient is a prior metalworker, has high risk of orbital trauma, or has known past orbital trauma. Important considerations in establishing an IMFB screening protocol include sensitivity for detection of IMFBs, radiation dose, imaging exam cost, and the risks and costs of false positive and false negative screenings.

Digital x-ray tomosynthesis (DT) is an image acquisition and reconstruction approach available on some clinical digital radiography (DR) systems. It involves sweeping the x-ray tube in an arc with respect to the patient and the detector, acquiring projection images at a range of angles for reconstruction into a stack of in-focus tomographic planes parallel to the detector plane [17]. This image acquisition and planar reconstruction approach holds potential for clearer visualization of IMFB presence and location compared to projection radiography, with lower radiation dose and cost than CT imaging.

This study explores the sensitivity of DR, DT, and CT for IMFB screening, and investigates the limits of detection for several metal fragment materials using these three modalities in a human skull phantom model. Radiologists independently evaluated metal presence, scored their interpretation confidence, and provided feedback on exam appropriateness.

Methods

Metal fragments and head phantom preparation

Shaved fragments of aluminum, steel, and cobalt-cemented tungsten carbide (hereafter referred to as “carbide”) were created. Radiographs of an initial subset of fragments placed on glass slides and a 2cm acrylic phantom were acquired to gain a baseline understanding of fragment detectability on radiographs, then a wider size range of fragments were created for skull phantom imaging. The number, mass, and approximate volumes of the full set of fragments are detailed in **Table 1**. These fragment size ranges were selected with the goal that for each material, some fragments would be detectable with DR, DT, or CT, and others would be undetectable. Fragment size range was limited by material properties and the fragment shaving process.

A semi-anthropomorphic phantom was created by placing a human skull model into a water bath. Metal fragments were embedded in table grapes, with one fragment in each grape. Additional

grapes with no metal fragments were also imaged as negative controls. The grapes were placed into the skull orbits and the model was submerged in a water bath, as shown in **Figure 1**.

Image acquisition

DR and DT acquisitions were performed on a GE Discovery XR656 in the posterior-anterior (PA) orientation at the wall stand (**Figure 1b**). DR acquisition parameters were as follows: kVp=80, mAs=18, SID=1.83m. DT acquisition parameters were kVp=75, mAs/view=2.5, tomography angle=40°, tomography time=11.4s. DT reconstruction was performed with slice locations at 20-130mm from the detector at 3mm intervals.

CT acquisitions on a GE Revolution used a similar phantom set-up as DR and DT, but the skull model was rotated 90° in the water bath to simulate a supine patient. The axial CT protocol used kV=100, manual mAs=145, acquisition slice thickness=0.625mm, reconstruction slice thickness=0.625mm (Bone reconstruction kernel) and 5mm (Standard kernel). MIPs were reconstructed with 5mm thickness and 2mm spacing. The CTDI for this acquisition was 6.74 mGy.

Radiologist reader study

In this IRB-approved study, six radiologists reviewed all images independently. Radiologists had 17, 12, 12, 11, 6, and 5 years of experience, respectively, and the group included four neuroradiologists, one emergency radiologist, and one breast radiologist. A reader study spreadsheet contained rows instructing radiologists to review a specific orbit (L or R) in a specific image. In all, radiologists reviewed 72 images/volumes in total (24 each for DR, DT, and CT), with two orbits containing independent metal fragments or no metal fragment in each image/volume. For each radiologist this resulted in 144 orbit evaluations, resulting in 864 “cases” for analysis, where a case is an individual radiologist evaluation of a single orbit. No information was provided to readers regarding number and types of metal fragments used in the acquisitions, repeat acquisitions, or presence of negative controls.

For each case, radiologists evaluated their confidence in the detection of metal presence on a Likert scale from -3 to +3, where -3 indicated “metal fragment definitely not present,” 0 indicated “can’t make a call,” and +3 indicated “metal fragment definitely present.” They were asked to make a forced choice decision with the question “Is metal present in the orbit?” with answer options Yes and No. They were asked “Is this examination technically adequate for the purpose of detecting metal in the orbit?” with the answer options Yes, Unsure, and No. Readers were given an opportunity to enter free-text comments following review of each image.

Statistical analysis

Descriptive statistics were used to summarize the reader study results. To compare modality performance, a multi-reader multi-case ANOVA was conducted considering all metal types, and stratified by metal type [18]. This analysis consisted of calculating the ROC curve for each modality and reader, based on the radiologist’s confidence (scale -3 to +3) and the ground truth of metal fragment presence. An ANOVA test was used to investigate whether there was a difference in the AUC across modalities, while adjusting for each reader and case [19]. In this statistical analysis, a “case” refers to a fragment of a specific size and type, and two images of the same re-positioned fragment are replicates of the same case. Both cases and readers were assumed as random as they were only a sample of possible radiologists and fragments, and an interaction between them was included in the model.

Pairwise tests were also performed to compare across modalities. When stratifying by metal type, adjustment for multiple comparisons was performed using a Bonferroni correction. A p-value <0.05 was considered significant, and all analyses were performed using R (version 4.2.1).

Results

Aluminum, steel, and carbide detection on DR, DT, and CT

Example images of aluminum, steel, and carbide fragments acquired via DR, DT, and CT are depicted in **Figure 2**. The full range of carbide fragment sizes were detected across all modalities, while aluminum fragments were typically not detected, except for the largest fragment on CT. The detection of steel was variable by modality and fragment size. The average reader confidence in detecting metal fragments of various materials and sizes on the three modalities is plotted in **Figure 3**.

For aluminum fragments, only the largest fragment size on CT was confidently identified. For smaller fragments, radiologists were on average more confident that the fragment was not present using CT compared with the other modalities. For carbide fragments, all fragment sizes were detected across tested modalities, with higher confidence on CT and DT compared to DR, on average. In the detection of steel fragments, those with mass of 0.8 mg or less were only identified using CT (average confidence score > 0). For larger steel fragments, confidence was on average higher for CT and DT than DR. In negative control samples, radiologists on average were more confident that a fragment was definitely not present when using CT, followed by DT, then DR.

ROC analysis comparing DR, DT, and CT

The ROC curve comparing overall detection of all metal fragments is shown in **Figure 4a**. After adjusting for readers and cases, the AUC was significantly different across modalities ($p=0.019$). The AUC for CT was 0.900, which was significantly higher than those for DT (0.791) and DR (0.775) with p-values 0.024 and 0.010, respectively. There was not a statistically significant difference in AUC between DR and DT. Overall, CT outperformed the two other modalities for detecting metal fragments in the orbit.

ROC analysis was performed to compare each modality for each metal type depicted in **Figures 4b-d**. A significant difference in AUC across modalities was detected for steel fragments ($p=0.021$), though not for aluminum or carbide fragments. In a pairwise comparison, the AUC was significantly higher for CT compared with DT and DR for steel fragment detection ($p=0.015$ and 0.027).

Overall sensitivity of each modality

Based on radiologists' forced-choice assessments, the sensitivity of each modality for the detection of metal fragments in this phantom model is shown in **Table 2**. The sensitivity of CT for detecting fragments was 80.9% overall (100% carbide/96.9% steel/25% aluminum). In comparison, 55.4% of fragments were detected with DR (100% carbide/55.2% steel/0% aluminum) and 53.9% were detected with DT (100% carbide/51% steel/2.1% aluminum). Steel fragments smaller than 1.4 mg were not detected by the majority of readers on DT or DR, while even the smallest steel fragment of 0.4 mg could be detected by the majority of readers on CT.

Perceived exam sufficiency and radiologists' comments

For each orbit reviewed, radiologists were asked whether the examination was technically adequate for the purpose of detecting metal in the orbit (Yes/Unsure/No) and given an opportunity to respond with free comments. The number of orbit images for which 3 or more radiologists responded "Unsure" or "No" was 5 for DR, 3 for DT, and 0 for CT. Two out of six radiologists included comments on the desire for a lateral projection on DR to increase their confidence. One radiologist indicated that they preferred DT over x-ray for several acquisitions, and indicated that the coronal MIP reconstruction in CT was particularly helpful for screening for small fragments (the corresponding images where this comment was made contained the smallest steel fragments).

Discussion

The purpose of this study was twofold: first, to improve understanding of the detectability of IMFBs composed of different materials using x-ray based imaging modalities (DR, DT, and CT) in a phantom model; and second, to understand how the sensitivity of DT compares with that of DR and CT in detecting IMFBs. Detectability of steel fragments varied among fragment sizes and imaging modalities. Using CT, all steel fragments were detected by most radiologists (mass range 0.4-5.9 mg, approximate volume range 0.05-0.75 mm³), in agreement with two past studies identifying an approximate limit of detection of 0.06-0.07 mm³ for steel fragments in CT [9, 10]. Sensitivity for the smallest fragments in this work may have been improved compared to past studies due to the inclusion of thin-slice images and MIPs. In the present work, reader confidence was maximized for steel fragments of mass 1.4 mg (~0.18 mm³) and above. Using DR and DT, steel fragments ≤0.8 mg (~0.1 mm³) were not detected (average reader confidence <0), while those ≥1.4 mg (~0.18 mm³) were consistently detected (average reader confidence between +2 and +3). These DR and DT results agree well with several studies in the literature suggesting a detection threshold in the range of 0.12-0.2 mm³ for steel and iron fragments on film and CR-based planar radiography in cadaver and phantom models [9, 14, 15].

As expected when considering the low density and atomic number, aluminum fragments were least likely to be confidently identified in this study. For the range of aluminum fragment sizes in this study, only the largest fragment (mass 2.7 mg, volume 1 mm³) was identified by most readers on CT, and none were identified by the majority of readers on DR and DT. In the context of orbit screening, this may be considered acceptable, as injury risk from a small paramagnetic IMFB is minimal. Due to low magnetic susceptibility and small size, a paramagnetic IMFB is unlikely to be subject to torque or translational forces stronger than gravity [20, 21] or to undergo potentially harmful heating during a typical MRI exam [22-24]. In addition, to our knowledge, there are no published case studies of injury from an IMFB that was known to be paramagnetic. Carbide fragments ranging in mass between 0.2-8.1 mg (approximate volume 0.014-0.59 mm³) were identified with 100% sensitivity across all evaluated modalities. Because steel and Co-cemented tungsten carbide are typically ferromagnetic, these materials are higher risk for causing injury if an IMFB is present, so their higher detectability on imaging screening is reassuring.

It is worthwhile to consider these results in the context of IMFB fragment sizes in past case studies of orbit injury from MRI, as well as cases where no injury occurred despite IMFB presence. The fragment sizes in this work have approximate calculated volumes ranging from 0.05-0.75 mm³ for steel, 0.037-1 mm³ for aluminum, and 0.014-0.59 mm³ for carbide. In clinical case studies of IMFB-related injury from MRI, IMFB fragment sizes were larger than the fragments in this study, with quoted sizes of 1x1mm [3], 1-2mm [4], 3mm diameter [5], 6mmx0.8mm [6], and 2x3.5mm [1]. In one case study where

IMFBs were detected on MRI for two patients without resulting injury and were later removed, ferromagnetic IMFBs (likely iron or steel) were measured to have volumes of 0.017mm^3 and 0.04mm^3 , smaller than the steel fragments in this work [25]. In another study where an IMFB was discovered on MRI but no injury occurred, the IMFB was not removed [26]. It was estimated to be a sphere with diameter 3.5mm, and was suspected to be a BB pellet, which commonly have a ferromagnetic iron core with a paramagnetic zinc or copper coating. The IMFBs in these case studies confirm the relevance of the fragment sizes studied in this work. However, a clear link still cannot be made between fragment size/composition, detectability on screening modalities, and likelihood of injury from MRI, due to the variety of physical and clinical factors that play a role in whether injury occurs.

The performance of DT for IMFB detection was of interest in this study and was compared with DR and CT, modalities which are more thoroughly studied and well-understood for IMFB screening. The results of ROC analysis (**Figure 4**) and the sensitivity measure based on radiologist forced-choice decision (**Table 2**) demonstrate that for IMFB screening, the performance of DT is very similar to that of DR and under-performs CT in the phantom model and fragment materials/sizes studied. The reader confidence curves in **Figure 3** show that when IMFBs are large enough for detection with DT and DR, DT does tend to provide the reader with greater confidence than DR. This is likely related to the 3D information about fragment location provided in a tomographic reconstruction.

Several limitations of this study are noted. First, fragments could only be created and tested within a limited size range. In fragment fabrication, we aimed to include fragments of each material small enough to be undetectable and large enough to be detectable on each modality, though we met limitations in shaving aluminum fragments that were large enough to be confidently detected on all modalities and carbide fragments that were small enough to go undetected. Second, we did not test the force, torque, and heating of the fragments used in this experiment in an MR environment. Third, this study was performed in a simplified phantom model. This should be kept in mind when considering these results in the context of orbit screening decisions for human patients, as anatomical noise, a more complex orbit anatomy, and patient motion may additionally impact IMFB detection. Last, in this study, default facial bone protocols were used for DR and DT. Though the techniques used align with commonly recommended orbit screening protocols [16], protocol optimization was outside the scope of this work and may contribute to improved performance, particularly for DT, as to our knowledge this application of the modality has not been studied or optimized.

Injury risk, imaging costs, radiation dose, and modality sensitivity/specificity should all play a role in developing IMFB screening procedures prior to MRI. However, there are also the questions of how the information resulting from imaging-based screening is managed and the risks of inaccurate screening results. The likelihood of IMFB movement and injury based on IMFB material, size, location, orientation, and time in place is only vaguely understood from scattered clinical case studies and animal/phantom studies over the past 40 years. Other factors have also changed since the first studies of orbit injury from IMFBs in MRI. For example, modern higher field scanners with steeper spatial static magnetic field gradients may introduce higher injury risk if IMFBs are present. Overall, the question of whether IMFBs that cannot be detected on x-ray modalities have potential to cause orbit injury in an MRI environment is challenging to study and remains unclear. The results of this study, which provide information about the comparative performance of three screening imaging modalities and the detectability of multiple IMFB materials and sizes in a phantom model, can help inform screening

protocols and provide insight into the types and sizes of IMFB that can be detected using x-ray based orbit screening.

Take Home Points

- CT outperforms digital tomosynthesis and digital radiography for detection of intraorbital metallic foreign bodies in a semi-anthropomorphic phantom. Digital tomosynthesis and digital radiography show similar performance.
- The limit of detection of steel fragments was identified as <0.4 mg on CT and between 0.8 and 1.4 mg on DT and DR in this phantom model.
- The limit of detection of aluminum fragments was identified between 1.2 and 2.7 mg on CT and >2.7 mg on DT and DR in this phantom model.
- The limit of detection of cobalt-cemented tungsten carbide fragments was identified as <0.2 mg on CT, DT, and DR in this phantom model.
- The results of this study can be used alongside considerations of cost, radiation dose, and the risks and costs of false positive and false negative screenings, to determine the preferred approach for orbit screening.

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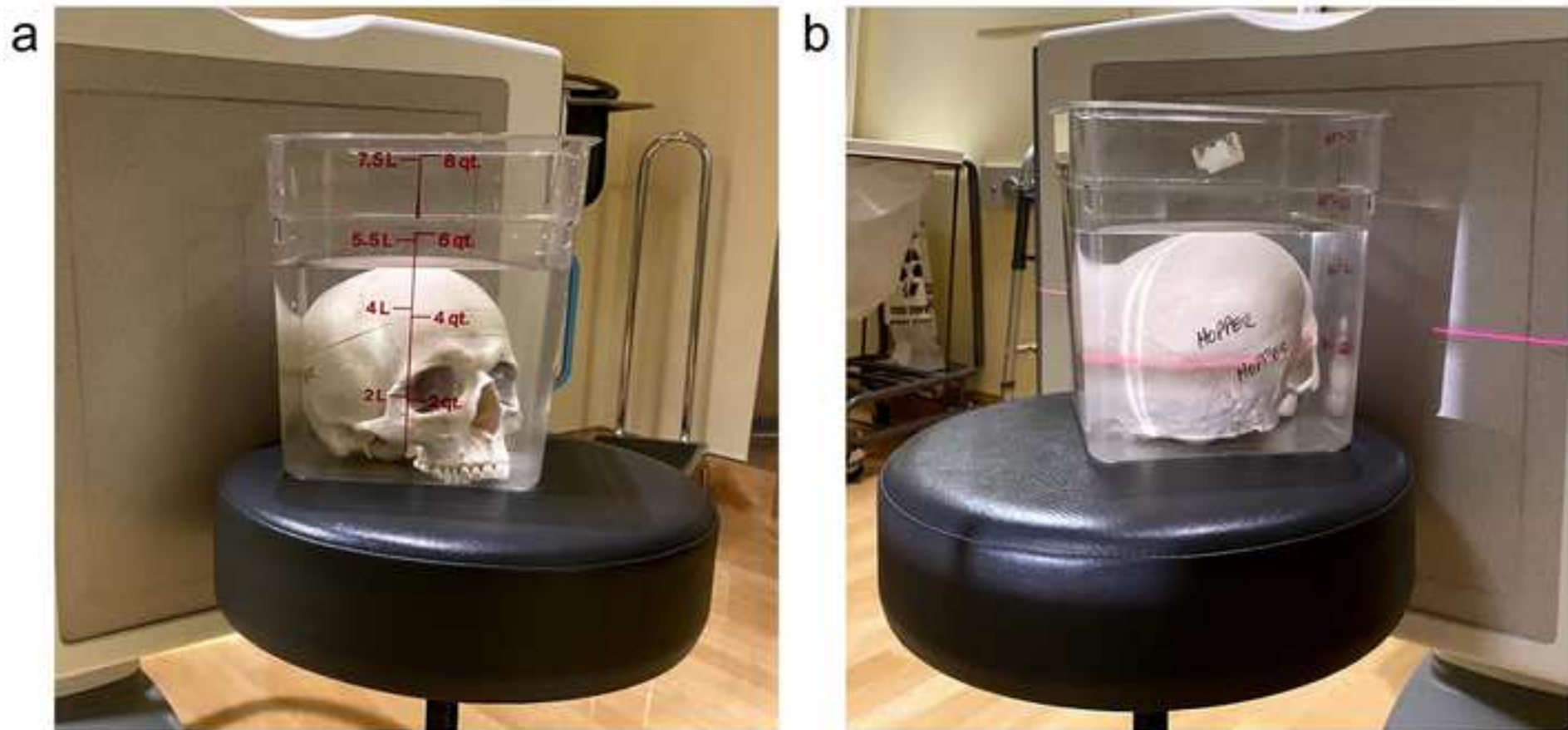


Figure 2

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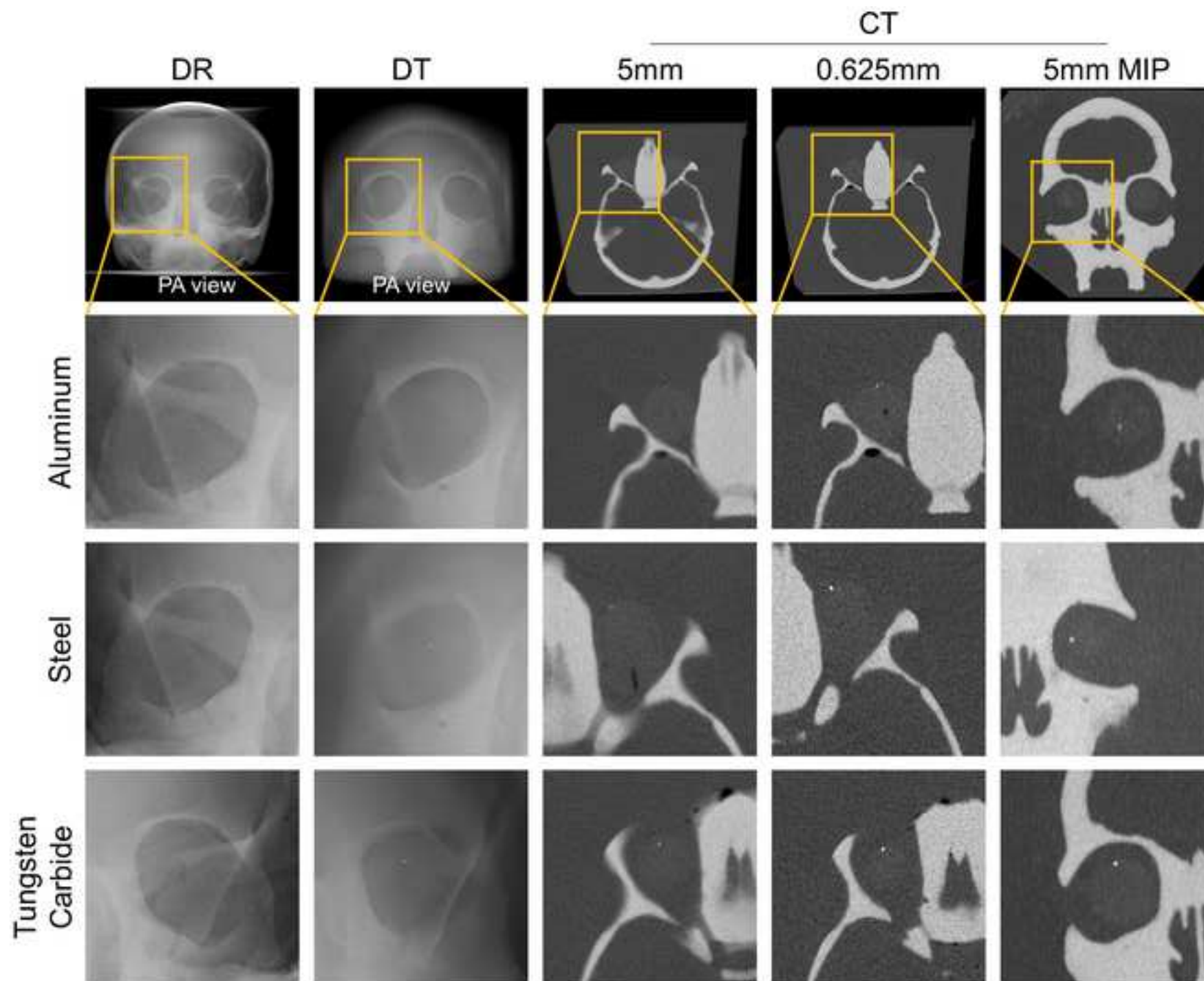


Figure 3

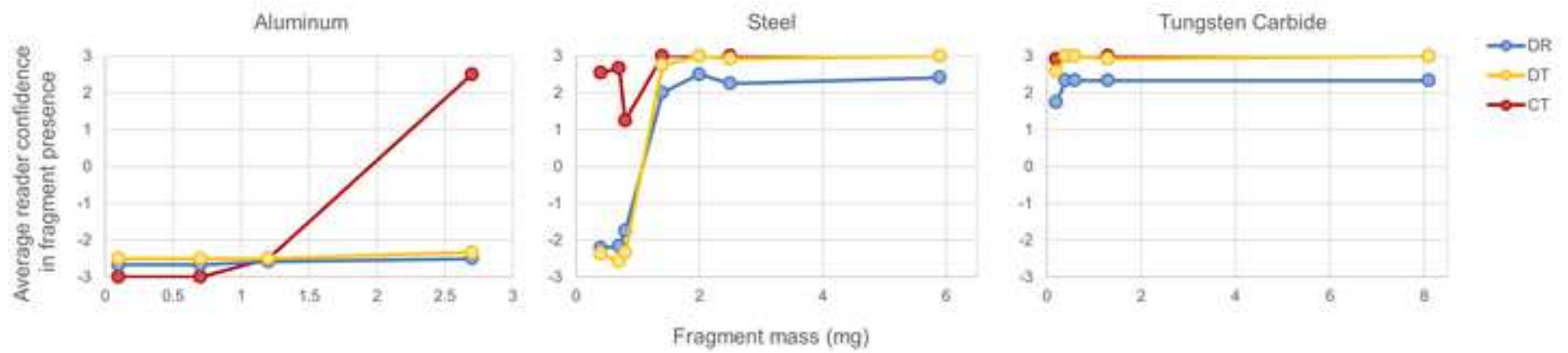
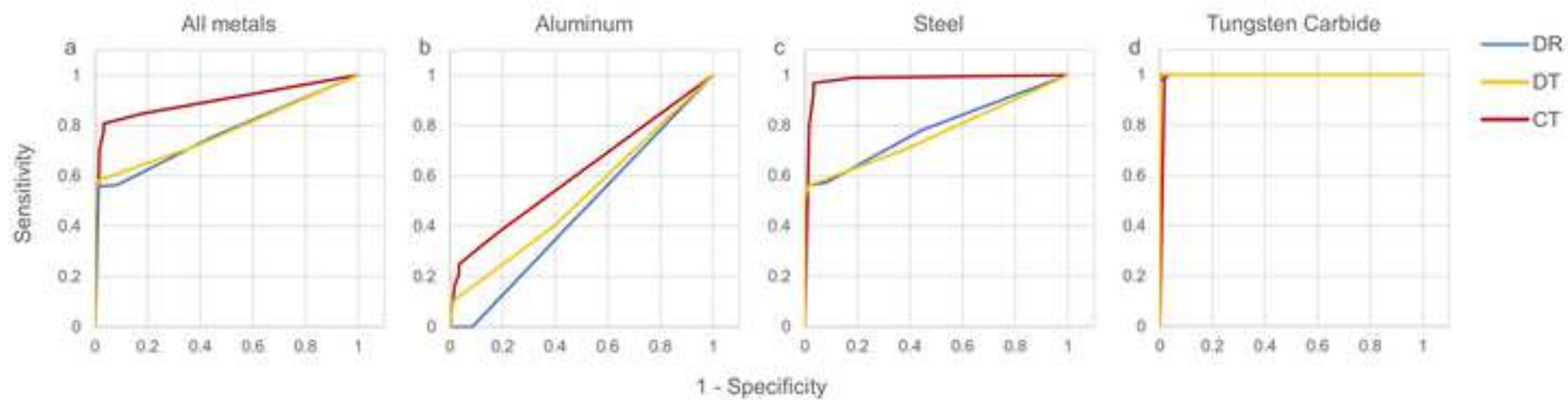


Figure 4



Aluminum (N=4) $\rho=2.7 \text{ g/cm}^3$ Z=13		Steel (N=8) $\rho\approx 7.9 \text{ g/cm}^3$ $Z_{\text{eff}}\approx 25-26$		Co-cemented Tungsten Carbide (N=5) $\rho\approx 14.5 \text{ g/cm}^3$, $Z_{\text{eff}}\approx 39$	
Measured mass	Approximate volume	Measured mass	Approximate volume	Measured mass	Approximate volume
0.1 mg	0.037 mm ³	0.4 mg	0.051 mm ³	0.2 mg	0.014 mm ³
0.7 mg	0.26 mm ³	0.4 mg	0.051 mm ³	0.4 mg	0.028 mm ³
1.2 mg	0.44 mm ³	0.7 mg	0.089 mm ³	0.6 mg	0.041 mm ³
2.7 mg	1.0 mm ³	0.8 mg	0.10 mm ³	1.3 mg	0.090 mm ³
		1.4 mg	0.18 mm ³	8.1 mg	0.59 mm ³
		2 mg	0.25 mm ³		
		2.5 mg	0.32 mm ³		
		5.9 mg	0.75 mm ³		

Table 1: Measured mass and approximate volume of each fragment. ρ : density, Z: atomic number, Z_{eff} : effective atomic number

	Overall	Aluminum	Carbide	Steel
CT	80.9% (62.3, 99.5)	25.0% (0, 74.0)	100% (100, 100)	96.9% (90.4, 100)
DT	53.9% (30.0, 77.9)	2.1% (0, 7.4)	100% (100, 100)	51.0% (14.7, 87.4)
DR	55.4% (31.9, 78.9)	0% (0, 0)	100% (100, 100)	55.2% (21.2, 89.2)

Table 2: Sensitivity values (95%CI range noted in parentheses)

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: