The detection of wooden foreign bodies: an experimental study comparing direct digital radiography (DDR) and ultrasonography

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Introduction

A presenting problem for patients attending the emergency department (ED) is the assessment and treatment of wooden foreign bodies (FBs). The location of FBs can vary and are often determined by the mechanism of injury. It is important that the most suitable imaging modality is used to detect and localise FBs in order to provide an accurate diagnosis. Plain radiographic imaging is often the first imaging modality of choice as it remains inexpensive and readily available in EDs. This study explores the application of ultrasound imaging in detecting wooden FBs in comparison with direct digital radiography (DDR) as it remains essential to reduce and keep the dose 'as low as reasonably practicable' (ALARP) or even prevent the use of ionising radiation to patients. It is generally accepted that of all wound trauma presenting to the ED, 78% involves wooden FBs.[1, 2] FBs that are easily removed tend to be superficial rather than penetrating. Establishing whether a FB object is near a fundamental structure or not remains paramount. FBs situated within soft-tissues are frequently concealed on first examination. Undetected wooden FBs can cause significant morbidity, repeat visits, leading to increased costs and possible surgery.[3] Despite the various studies exploring the accuracy of radiography, further studies are needed to explore and challenge the diagnostic accuracy advancing technology. This remains paramount because as DDR remains a technological advancement, offering increased levels of spatial resolution and contrast, the exploration of wood detection should continue to be explored, in comparison with other imaging modalities and ensure optimum healthcare delivery. The purpose of this study is to investigate and compare the usefulness of DDR and ultrasonography for the detection of wooden FBs in soft-tissues and evaluate the sensitivity and specificity of each.

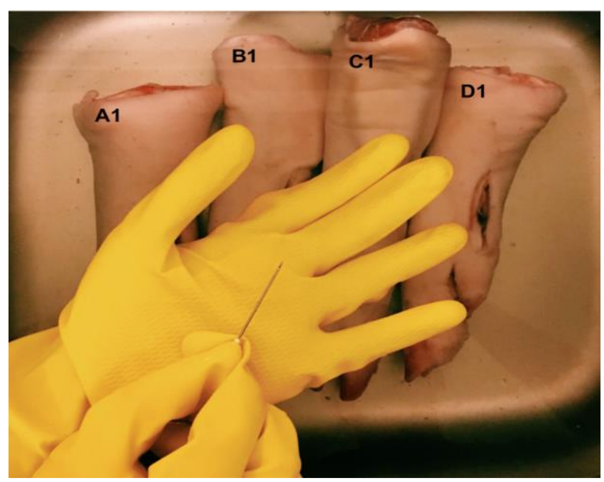
Methods and Materials

Eight porcine feet were used as experimental tools in this study. These were used to closely resemble the appearances of human bone and soft-tissue. All feet were frozen prior to manipulation. Four out of eight feet were imaged using DDR whilst the remaining were imaged using ultrasound. The porcine feet are depicted in figure 1.

Figure 1: Feet specimens used in (A) DDR and (B) Ultrasound.

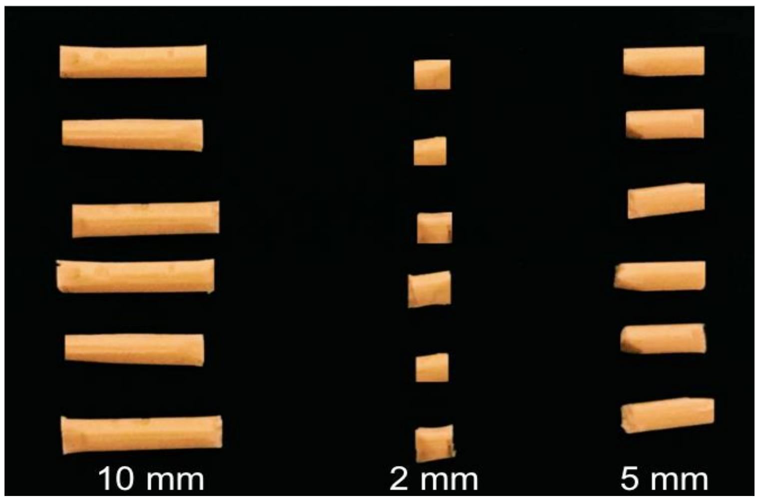
The feet were thawed for approximately 8 hours. Soft-tissue punctures were performed with the feet underwater limiting the amount of air that could track the wound. Three punctures were made in each model using a 19G, 1.5-inch needle in order to mimic soft-tissue damage. This is shown in figure 2. Eighteen ‘splinters’ with a diameter of 2mm made from toothpicks were inserted manually by pushing them along the tracts at all three locations. The selection of sizes resembled a range of wooden FBs identified in previous studies.[4, 5] Although all splinters were manipulated with the needle, A1 and A2 did not have splinters inserted in them. These were used as control groups to test for false-positive results.

Figure 2: A 19G, 1.5-inch needle used to create punctures to mimic FB injury.



Three wooden FBs were inserted in each foot; 10 mm wooden splinters in B1 and B2, 2 mm in C1 and C2 and 5 mm in D1 and D2. Each splinter was carefully positioned either 'behind bone', 'near bone' and 'distant from bone'. This was repeated for the second set of porcine feet (A2, B2, C2 and D2), which were to be scanned using ultrasound. These locations represent possible localization of FBs.[6-9] To mimic absorption of body fluids, all splinters were soaked in water for approximately 24 hours before they were inserted in the feet. These can be seen in figure 3.

Figure 3: Wooden splinters of varying sizes used in this study.



Ethical and infection control considerations

This study was exempt from the institutions research ethics committee. This was recognised in a similar study utilising cadavers[10]. In this study, departmental approval was sought and approved by the local hospital due to the use of both radiography and ultrasonography equipment. Adherence to infection control measures was applied. For example, plastic was used to cover the imaging detector preventing it from being contaminated with specimen substances. Gloves and aprons were worn to avoid contamination from specimen substances throughout the experiment. Equipment was later cleaned with hospital approved cleaning solutions in order to prevent cross-contamination.

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Equipment and parameters

Six X-ray exposure factors were deemed appropriate for the experiment using DDR. These were 55 kVp/2 mAs, 55 kVp/3.2 mAs, 60 kVp/1.6 mAs, 60 kVp/2 mAs, 60 kVp/3.2 mAs, and 63 kVp/1.6 mAs. Varying kVp and mAs was an important consideration in this study in order to maximise radiographic contrast and found to be useful in a previous study.[10 (p.224)] Further, whilst Sheridan and McNulty utilised this approach when comparing computed radiography (CR) and indirect digital radiography (IDR), few studies have explored varying kVp and mAs with DDR, thus enhancing originality. A ceiling-mounted Bucky Star X-ray tube by Xograph Healthcare was used for all DDR radiographic exposures. The DDR wireless detector was a DX-D 30C (35 x 43cm). A General Electric (GE) Logiq E9 ultrasound machine was used for all ultrasound scans. The frequencies selected for ultrasound were 4 MHz, 5 MHz, 9 MHz, 11 MHz, 13 MHz and 15 MHz Ultrasonography was performed using pulsed-wave ultrasound. The linear ultrasound probe, GE ML6-15-D is a wide footprint linear matrix array transducer, producing high frequencies ranging from 4.5-15 MHz. Further, a curvilinear transducer was used utilising frequencies between 1-5 MHz as this has been found in other comparison studies.[11] The smallest hockey stick probe, a high-resolution linear probe, was also used. This had the smallest and narrowest field of view. Further, ultrasound scans were performed in more than 2 planes; transverse, longitudinal and oblique, however only the transverse and longitudinal planes were utilised in the study, as oblique planes did not provide any additional information. Similarly with DDR and in accordance with the Trust's departmental protocols, only DP and lateral projections were undertaken. Generally accepted X-ray parameters were utilised, as identified with the literature.[12,13] Table 1 provides the reader with the scoring criteria used by the researcher during this experiment.

Table 1: Criteria for scoring the visibility of FB.

Score	Observation
1	Excellent visibility

2	Good visibility
3	Poor visibility
4	Not Visible

Results

No foreign objects were detected in A1 and A2 (control specimens) thus received scores of 4 for both DDR and ultrasonography. This increases the reliability of the study, as there were no false-positive diagnoses when searching for foreign bodies. Based on the grading criteria, a FB was classed as detected only if it had been given a score of 1 or 2.

FB detection using direct digital radiography

When utilising DDR for the detection of FBs there was a 95.8% non-detection rate (foot B1). Further, no FBs were detected in muscle near and behind bone in both projections for all exposures using DDR. The detection in muscle distant from bone for foot B1 was 12.5%, whereby visualization was detectable in the dorsi-plantar (DP) projections (63%). All FBs in C1 and D1 were not detected. These are illustrated by figures 5, 6 and 7.

FB detection using ultrasonography

Similarly, no FBs were found in foot A2 using ultrasound. Ultrasound had a detection rate of 50% in foot B2, receiving scores 1 and 2. The detection rate in muscle near bone was 87.5% and was equally detected in the longitudinal and transverse planes. 56.3% of the FBs inserted in muscle distant from bone were detected, of which 62.5% and 50% were found in transverse and longitudinal views respectively. Ultrasound detected the 2 mm FBs in muscle distant from bone in foot C2 (11.1% detection rate), which all received scores of 2. No FBs were detected in muscle behind and near bone. The detection rate of FB in muscle distant from bone was 25%. Contrary to DDR, the detection rate for ultrasound was 22.2% in foot D2. There was a 66.7% detection rate of the FB in muscle behind bone, which received scores of 1 and 2. However, the FBs in muscle near bone and distant from bone remained undetected. Ultrasound of the FB (yellow arrows) in B2 is demonstrated in figure 4. A FB is shown as a linear echogenic structure in muscle near bone (A) using low frequency of 4 MHz in muscle near bone. Image B shows the FB distant from bone as hyperechoic with acoustic distal shadowing (identifiably by the letter x) using 15 MHz on transverse section. A FB is also shown as a linear echogenic focus in image C.

The image scores obtained were analyzed using R and Welch's two-sample *t*-test. The significance level was taken at 5%. The analysis demonstrated statistical significance $p < 0.001$ ($t = 6.21$, df = 148). Results imply that the overall mean score of ultrasound is significantly lower than that of DDR, which provides significant evidence to reject the null hypothesis. Welch's two-sample unequal variance *t*-test was performed at each site of FB insertion. There is a significant difference in the mean scores of each modality when comparing scores of B1 & B2, C1 & C2 and D1 & D2. This is demonstrated in table 2.

Table 2: *t*-test and *p* - values on individual feet when comparing DDR and ultrasound

Foot Specimen (DDR/US)	Degrees of Freedom (df)	*t* statistic	*p* value
A1/A2	N/A	N/A	N/A
B1/B2	73	2.93	0.002
C1/C2	35	4.76	< 0.001

D1/D2	35	3.33	0.001

Figure 4: Detection of wooden foreign bodies utilising ultrasonography

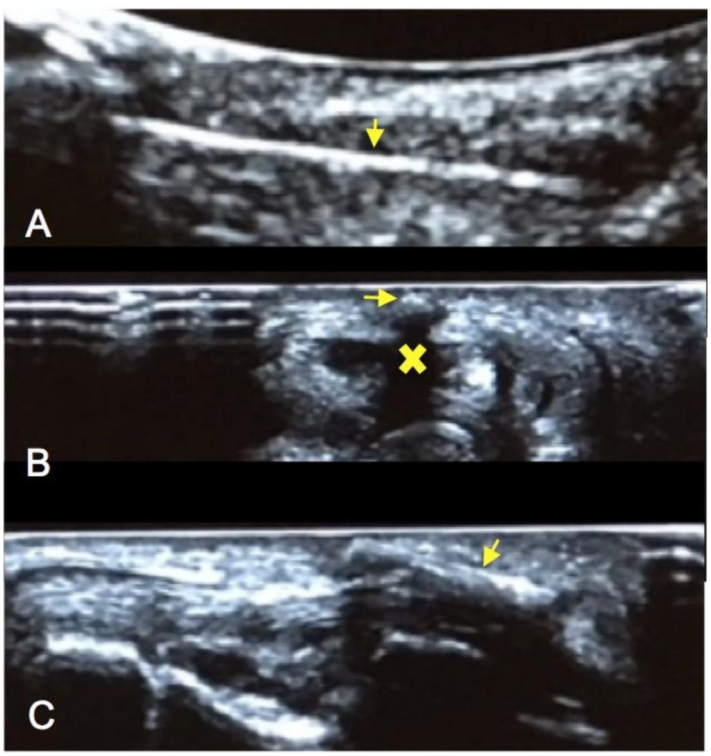

Figure 4: Ultrasound of the FB (yellow arrows) in B2. Image A depicts FB as a linear echogenic structure in muscle near bone using low frequency of 4 MHz. Image B shows the FB distant from bone as hyperechoic with acoustic distal shadowing (depicted by letter x) using 15 MHz on transverse section. Image C Shows FB as a linear echogenic focus (yellow arrow).

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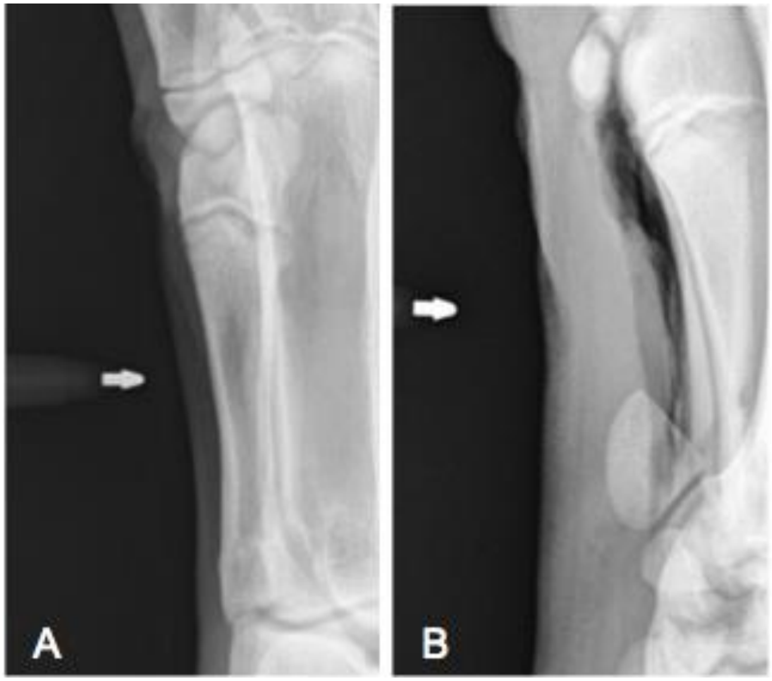

Figure 5: Projection imaging of A1. (A) Dorsi-plantar and (B) lateral radiographs with a radiopaque marker pointing at the suspected point of FB entry. No FB can be delineated in muscle distant from bone, thus there are no false positive diagnoses.

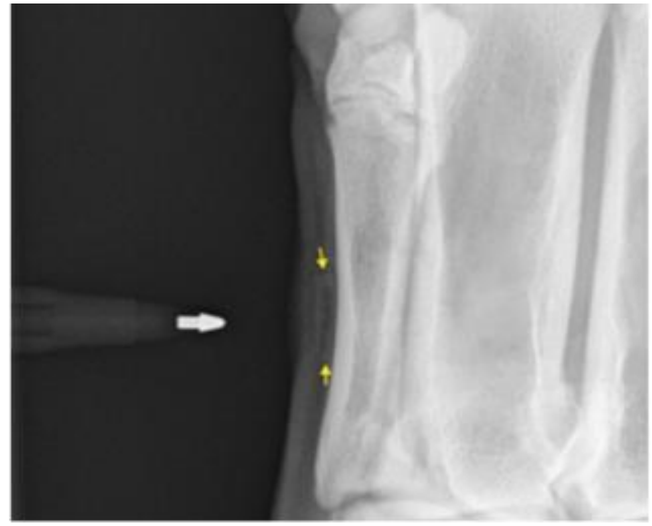

Figure 6: 10 mm FB situated in muscle distant from bone in B1 obtained using 60 kV/1.6 mAs. DP foot radiograph shows an isodense structure with air (yellow arrows) on the lateral aspect of

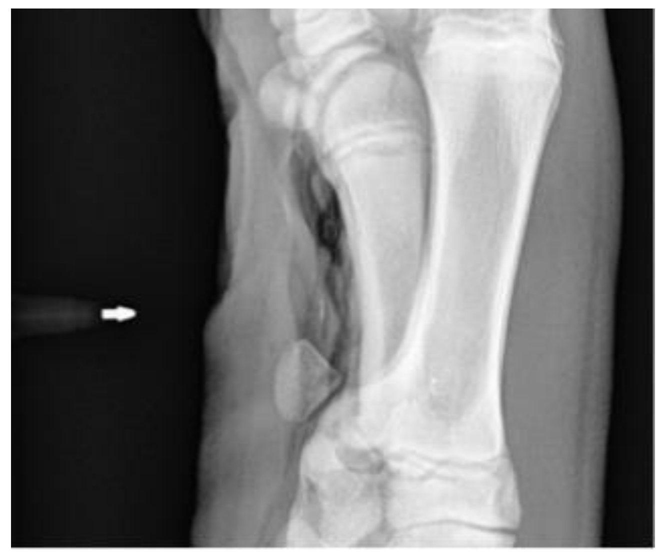

Figure 7: 10 mm FB situated in muscle distant from bone in B1 obtained using 60 kVp/1.6 mAs. Lateral radiograph showing no FB present.

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Discussion

There are several imaging modalities which can be used for the diagnosis of radiolucent FBs (matter with limited X-ray attenuation, limiting radiographic visibility).[16] Ultrasound has a reported sensitivity of 30% for the detection of wooden FBs in this study. Ultrasound demonstrated improved results, whereby dimensions were visible in comparison to DDR. The study, however, demonstrated limitations with ultrasound when detecting FBs with dimensions of 2 x 1 mm. Further, the FB placed in muscle behind bone in foot B2 was only detected once using 3 MHz on the longitudinal section. This is an anomaly as FBs are visualised better at higher frequencies. In short, the results identify ultrasonography to have improved diagnostic accuracy than DDR, as the overall sensitivity for DDR was 4.17%. The overall specificity of both imaging modalities was 100%; however, the main disadvantage of ultrasonography occurs if air is present during evaluation. Entries of air from manipulation are seen radiographically and thus important to reflect upon. It is important to acknowledge that the intake of air may have proved problematic when aiming to identify FBs in some radiographic planes.

The results show that FBs inserted into muscle distant from bone resulted in the successful detection using ultrasound. This is important because it is among the most common sites for acute injuries involving FBs.[17] It was also found that all FBs embedded behind bone were not visualised using ultrasound. The findings in this study indicate that evaluation of foreign objects should begin at a high frequency of at least 9 MHz to enable good visibility,[18, 19] however, frequencies from 4 MHz can also be used as it has the capacity to penetrate at a higher level for FBs embedded in muscle near to bone.

DDR is currently the preferred imaging method in detecting radiopaque FBs and constitutes the first tool at investigating FB detection protocol.[20] When a disease is queried by a referring clinician, general radiography of the foot is generally indicated; however, superimposition of structures and the minimal information of soft tissues make it limited for use. Whilst DDR provides higher image quality with sound osseous anatomy, this study identifies the inability to give the exact identification, shape and dimension of wooden FB objects, therefore modalities such as ultrasound should act as a supplementary or primary investigation in order to

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deliver important information leading to optimal treatment/management of the patient. Ultrasound is not superfluous, as DDR does not always deliver accurate definition of FBs.

Detection of low contrast FBs such as wood on DDR images also depends on exposure factors.[21] Studies have concluded that DDR has superior image quality to other projection imaging due to higher detective quantum efficiency (DQE) and contrast enhancement.[22] The evaluation of 2 mm and 5 mm wooden splinters showed similar attenuation to soft-tissue structures and thus cannot be distinguished between wood and muscle for FB diagnosis. However, exposure factors did offer adequate identification and clear visualisation of the shape of the foreign body inserted in muscle distant from bone on DP projections in this study. Immediate detection allows for early treatment planning and reduces the risk of additional complications in relation to FB migration such as infection, localised cellulitis or abscess formation.[23, 24, 25] Further, if the FB has been present for a few days or weeks, a hypoechoic inflammatory reaction may occur.[26, 27] Reactions to inflammations, oedema and abscess have ultrasonic manifestations, thus, reactions in a cadaver specimen limit the applicability of the results in this study to real life situations. Studies conducted on live samples may offer a better understanding towards the behaviour and detection of wooden FBs. The detection rate of FBs could have been greater if the operator was highly experienced in ultrasound.[28] A high-frequency linear transducer was needed to optimise near-field spatial resolution. Further, the size estimation could be affected by the presence of tissue reaction; however, due to the nature of the specimen this factor was not taken into consideration.[29]

It is important to recognise that ultrasound evaluation of musculoskeletal injuries is of paramount significance to healthcare professionals, in which they have acknowledged this utility following the use of laptop-sized ultrasound units. These are able to achieve high image quality for examining musculoskeletal systems, as long as high-frequency (10-12 MHz) transducers are used. The more recent availability of these ultrasound units has made even more interest in sonographic reinforcement of the physical examination, although currently these machines are used mainly for basic evaluation of free fluid in the abdomen in trauma cases, and are not labelled by the vendors for musculoskeletal imaging. Yet, as technology continues to improve, it may not be uncommon for ultrasonography to be the first imaging modality of choice in the emergency department for patients suspected of having wooden FBs.

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Conclusion

To conclude, several factors contribute to the usefulness of DDR and ultrasound as medical imaging modalities. Ultrasound offers superior detail relative to FB description, which, in this study demonstrates enhanced diagnosis, making it a clinically effective approach in comparison to DDR. In events where suspicion for a wooden FB is high and plain radiographs remain negative, ultrasound should be considered by the referrer. Such clinical evaluations and utilisation of ultrasonography may identify and localize a wooden FB object, which limits infection, whilst facilitating an appropriate treatment plan for the patient. The results of this research may aid operators in the justification procedures of medical exposures in order to keep the dose as 'low as reasonably practicable', whilst also aiding surgical planning. However, further studies will be required to refine the outcomes of this study, due to the number of methodological limitations acknowledged. FBs of size 2 mm and 5 mm resulted in false-negative outcomes thus verifying that these sizes were too small for detection. Additionally, due to the radiolucent nature of wooden splinters, the range of exposure factor combinations selected demonstrates the limitations with DDR in delineating these FBs. On the other hand, ultrasound provided a larger number of true-positive outcomes.

Limitations

It is important to acknowledge the post-processing algorithms in both DDR and ultrasound equipment. In response to the work undertaken by Sheridan and McNulty[10], Hughes[28] recognises the potential impact of post-processing algorithms in such research. In their study, Sheridan and McNulty examined the detection of glass FBs by comparing CR and IDR. The authors, in a follow-up communication acknowledge no attempt of adjusting algorithmic settings upon assessing the visibility of FB objects.[29] The authors importantly recognise this as an underexplored area of radiographic practice. Similarly, the researchers in this study made no attempt to alter the pre-set algorithms for both DDR and ultrasonography equipment. The authors methodologically acknowledge the importance of post-processing algorithms clinically and because it remained underexplored in this experiment, it remains a significant limitation of this experiment. Lastly, it is important to recognise that the author(s) did not attempt to 'window' or 'invert' the X-ray images on PACS. This is an important limitation to consider methodologically, thus cautious when interpreting the findings presented in this small scale experimental paper.

Recommendations

This study explores the use of 3 ultrasound transducers in the detection of wooden FBs. It is important to acknowledge that whilst many EDs may have ultrasound equipment, ED departments may need to consider purchasing transducers that will offer alternate ultrasonic properties in order to best evaluate wooden FB objects.

This study also aims to provide a platform for future research and build on the existing limitations identified within the methodology. This paper offers practitioners and researchers a critical lens of detecting wooden FBs using ultrasound.

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