RESEARCH ARTICLE

Comparative evaluation of soft-tissue foreign body detection using ultrasound and radiography: A phantom study

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Abstract:

Soft-tissue foreign bodies (STFBs) are common clinical presentations requiring accurate imaging for effective diagnosis and management. This experimental phantom study compared the performance of ultrasound and general radiography in detecting STFBs of various materials and depths using anatomically relevant cow-foreleg models. Eight foreign bodies; metallic, organic, and inorganic were inserted at depths of 1, 3, and 5 cm. Image visibility was assessed by two radiologists using standardized scoring criteria, with substantial inter-rater agreement (weighted Cohen's $\kappa = 0.74$). Ultrasound yielded significantly higher visibility scores than radiography, as confirmed by a Wilcoxon signed-rank test ($Z = -2.82$, $p = .01$). A Friedman test showed no significant depth-related differences in ultrasound image quality (χ^2 (2) = 0.57, $p = .75$). Radiographic detection also remained consistent across depths (χ^2 (2) = 4.00, $p = .14$), although it was notably influenced by the radiopacity of the foreign body materials. Overall, the findings support existing evidence that ultrasound provides superior diagnostic performance, particularly when the composition of the suspected foreign body is unknown. This study reinforces the potential role of ultrasound as a first-line imaging modality for suspected STFBs.

Keywords: Phantom study, radiography, soft-tissue foreign bodies, ultrasound

1. INTRODUCTION

Soft-tissue foreign bodies (STFBs), whether introduced intentionally or accidentally, represent a common cause of emergency and outpatient visits, requiring prompt evaluation and intervention (Campbell & Wilbert, 2023). This foreign bodies are categorised by composition; metallic, organic, or inorganic materials and most injuries result from abrasive, blunt, or penetrating trauma (Skinner & Morrison, 2023). STFBs can lead to acute pain, functional impairment, and complications such as inflammation, infection, or allergic reactions (Del Cura et al., 2020). Organic materials, particularly wood, pose significant challenges due to severe inflammatory responses and persistent infections that often resist antibiotic therapy, necessitating timely removal (Campbell & Wilbert, 2023). Accurate detection and extraction are therefore critical to prevent morbidity and avoid further complications.

While superficial STFBs may be removed during routine examination, imaging becomes essential when palpation fails to confirm their presence (Campbell & Wilbert, 2023; Del Cura et al., 2020). Common modalities include general radiography, ultrasound, computed tomography (CT) and magnetic resonance imaging (MRI), which aid in detection and surgical planning by localizing foreign bodies relative to surrounding structures (Voss et al., 2020). General radiography is often the first-line technique due to accessibility and cost-effectiveness, but its utility is limited to radiopaque materials such as glass, metal and stone whereas radiolucent objects like wood and certain plastics remain poorly visualized (Carneiro et al., 2020; Grocutt et al., 2023; Rupert et al., 2020; Voss et al., 2021). Ultrasound complements general radiography by detecting both radiopaque and radiolucent objects, particularly in superficial regions such as the hand and wrist (Grogan & Mount, 2023). Although several studies have assessed ultrasound for STFB detection, methodological limitations including non-representative phantom models and controlled foreign body orientations restrict the generalizability of findings (Alfuraih et al., 2021; Grocutt et al., 2023; Tok & Kadioglu, 2021).

However, critical gaps remain. First, most studies evaluated detection at a single depth, overlooking how varying depths influence diagnostic accuracy, especially for ultrasound. Second, phantom models often lacked anatomical realism, using homogeneous materials that fail to replicate musculoskeletal heterogeneity and bone presence. Third, foreign bodies were frequently aligned parallel to the ultrasound beam, artificially enhancing echogenicity and detectability (Kawalec, 2023). These limitations reduce clinical applicability, as real-world scenarios involve variable depths, heterogeneous tissue structures, and diverse orientations. To address these gaps, this study employs anatomically relevant phantoms incorporating bone tissue and assesses detection of metallic, organic, and inorganic STFBs at multiple depths (1 cm, 3 cm, and 5 cm) using linear ultrasound and radiography. Diagnostic accuracy of both modalities is compared across foreign body types and depths, providing a more realistic and clinically relevant evaluation of imaging performance in STFB detection.

2. MATERIALS AND METHODS

Three cow-foreleg phantoms were used, each embedded with eight soft-tissue foreign bodies (STFBs): two metallic (office pin, aluminium shard), two organic (cactus spine, wooden splinter), and four inorganics (glass shard, small stone, pencil lead, plastic fragment). These materials were selected based on commonly reported STFB injuries. Foreign bodies were inserted at depths of 1, 3, and 5 cm, with each foreleg representing a single depth. Both ultrasound and general radiography were performed on all phantoms, yielding 24 images were independently assessed by two radiologists using a validated scoring system adapted from Alfuraih et al. (2021).

Fresh cow-forelegs were obtained from a local slaughterhouse, transported on ice, and stored frozen until imaging. Three forelegs (Leg A, B, C) were incised to depth of 1, 3, and 5 cm, respectively, following the method described by Tok & Kadioglu (2021). Incision depths were determined using pre-marked indicators on the knife and forceps, to ensure consistent depth during foreign body inserting. Each foreign body was inserted individually using forceps, and orientation were randomised to simulate clinical variability. All insertions were performed by a co-researcher to ensure blinding of the sonographer, radiographer and primary researcherr. Prior to ultrasound and general radiographic image acquisition, the cow-forelegs were thawed at room temperature for approximately 12 hours to preserve soft-tissue characteristic similar to in vivo condition, as recommended by USDA FSIS (2023).

All materials measured ≤3 cm, reflecting commonly encountered STFB sizes (2 - 4 cm). Selected materials were able to penetrate soft tissue and represented the major clinical categories of metallic, organic, and inorganic foreign bodies (Table 1).

Table 1. Classification of soft-tissue foreign body materials

Classification	Type	Material	Radiographic property
Metallic	Metal	Office pin	Radiopaque
	Metal	Aluminium shard	Low radiopacity
Organic	Wood	Cactus spine	Radiolucent
	Wood	Splinters	Radiolucent
Inorganic	Glass	Glass shard	Radiopaque
	Stone	Small stone	Radiopaque
	Graphite	Pencil lead	Radiopaque
	Plastic	Plastic fragment	Radiolucent

Note: Classification based on material composition and radiographic visibility.

Ultrasound was performed by a sonographer with more than 15 years of clinical experience, to ensure consistent image acquisition, using a Samsung RS85 Prestige system with a 3–12 MHz linear transducer. Depth was adjusted manually. Each phantom was scanned in longitudinal and transverse planes to optimize visualisation, following recommendations by Grocutt et al. (2023) and Tok & Kadioglu (2021). Images were exported directly from the system.

General radiography was performed using a Carestream ceiling-suspended X-ray system with a Fuji Computed Radiography (FCR) imaging plate. The imaging plate surface and housing were inspected for physical damage, scratches, or debris, and was erased prior to image acquisition to remove any residual latent image from previous exposures. Anteroposterior (AP) and lateral projections were acquired in a single imaging plate, at a source-to-image distance (SID) of 100 cm. The initial exposure was set at 63 kVp and 4.0 mAs, followed by two reduced-kVp settings (53 kVp and 45 kVp) to enhance contrast for low-density materials (Sy et al., 2022). Metallic foreign bodies, high density material, required a higher kVp (63 kVp) for adequate penetration. While the organic materials such as wood, which are low-density, required a lower kVp (45 kVp) to improve contrast between the material and surrounding soft tissue. Inorganic materials, with intermediate in density, were imaged at medium kVp (53 kVp) to achieve balanced penetration and contrast. As each phantom contained various foreign body types and materials, the same imaging protocol was applied to all phantoms for consistency.

Two radiologists, each with more than 15 years of clinical and ultrasound imaging experience, independently scored all images while being blinded to the foreign body type and depth. The separation of roles between the sonographer and radiologists was implemented to minimise bias and ensure an objective evaluation of modality's performance. Images were provided in JPEG format via Google Forms, and scoring was conducted using the foreign bodies visibility criteria, ranging from 0 (no foreign body detected) to 5 (excellent visibility), adapted from Alfuraih et al. (2021; see Table 2).

Table 2. Scoring criteria (Adapted from Alfuraih et al., 2021)

Score	Quality	Description
4	Excellent	Excellent visibility with clear detail resolution and good demarcation from surrounding tissues.
3	Good	Clear visibility with good detail resolution and adequate demarcation from surrounding tissues.
2	Fair	Limited visibility with insufficient detail resolution and poor demarcation.
1	Poor	Poor visibility with no meaningful detail resolution and unclear demarcation from surrounding tissues.
0	Invisible	No foreign body detected.

All analyses were performed using IBM SPSS Statistics version 29. Inter-rater reliability between the two radiologists was assessed using Cohen's Kappa, with interpretation as follows: ≤0.20 (poor), 0.21–0.40 (fair), 0.41–0.60 (moderate), 0.61–0.80 (substantial), and ≥0.81 (excellent). Substantial agreement or higher permitted averaging of the raters' scores.

The Friedman test, a non-parametric alternative to repeated-measures ANOVA, was used to compare visibility scores across the three depths for each imaging modality. Statistical significance was set at $p < 0.05$. The Wilcoxon signed-rank test, the non-parametric equivalent of the paired t-test, was used to compare ultrasound and radiography scores, with significance similarly defined as $p < 0.05$.

This study received approval from the Universiti Teknologi MARA (UiTM) Ethics Committee (Reference: FERC/FSK/MR/2025/00013) and was conducted in accordance with institutional and research ethics guidelines.

3. RESULTS AND DISCUSSION

Inter-rater reliability for image quality scores was assessed using weighted Cohen's Kappa (Table 3). The two radiologists demonstrated substantial agreement, $\kappa = .74$, 95% CI [0.59, 0.89, p<.001. Modality-specific analyses also indicated substantial agreement for ultrasound ($\kappa = .75$, 95% CI [0.53, 0.96], p<.001) and radiography ($\kappa = .70$, 95% CI [0.49, 0.92], p<.001). Because the agreement met the recommended threshold, scores from both raters were averaged for subsequent analyses (Ranganathan et al., 2017). Both raters, with more than 15 years of clinical experience, were aware of the presence of foreign bodies but blinded to material types. High agreement is likely attributable to their comparable experience and the use of a standardized scoring framework, which enhances reliability (Alfuraih et al., 2021; Luiz et al., 2021; Neto et al., 2022).

Table 3. Inter-rater reliability between Radiologist 1 and Radiologist 2

Measure of Agreement	Value	Asymptotic Standard Error	Approximate T	Approximate Significance
Kappa	0.74	0.08	7.29	< .001

Interpretation: Agreement is substantial according to Landis & Koch criteria (κ = 0.61–0.80).

A Friedman test was conducted to examine the effect of foreign body depth (1 cm, 3 cm, and 5 cm) on ultrasound image quality scores (Table 4). Results indicated no statistically significant differences across depths, χ^2 (2) = 0.57, p = .75. Median scores were highest at 1 cm and 3 cm (Mdn = 4.00) and slightly lower at 5 cm (Mdn = 3.88), suggesting a minor decline with increased depth that did not reach statistical significance. Therefore, the null hypothesis was retained, indicating that depth had no significant effect on ultrasound image quality.

The slight decline in image quality with depth aligns with established principles; high-frequency linear probes provide excellent resolution but reduced penetration, and objects deeper than 2 cm are more challenging to visualize due to attenuation (Grogan & Mount, 2023; Campbell & Wilbert, 2023). Sample size may also have contributed to the non-significant results. Three cow-forelegs (n=3) were used in this study, limiting statistical power. Larger studies, such as Voss et al. (2021) with n = 34, offer greater generalizability, though the current sample aligns with prior phantom studies (Grocutt et al., 2023; Tok & Kadioglu, 2021).

Additionally, the use of a high-end ultrasound system (Samsung RS85 Prestige) may have reduced depth-related degradation. Its advanced beam-forming technology, attenuation compensation, and AI-assisted optimisation likely enhanced visibility at deeper levels. Emerging AI tools that assist in structural detection and noise reduction may also contribute to more stable performance across depths, thereby diminishing detectable differences (Shin et al., 2020). These technological features help improve shadowed regions, where attenuation and posterior acoustic shadowing are commonly produced by foreign bodies (Carneiro et al., 2020). Proper optimisation of imaging parameters further enhances penetration and image quality, potentially minimising depth-driven variability (Zander et al., 2020). Overall, while depth-related attenuation trends were present, they did not significantly influence ultrasound detection performance within the tested depth range.

A Friedman test also evaluated the effect of foreign body depth on radiography image quality (Table 4). Results showed no statistically significant differences across the three depths, χ^2 (2) = 4.00, p = .14. Median scores were identical at all depths (Mdn = 0.00), indicating no effect of depth on radiographic visibility. The null hypothesis was therefore rejected.

This aligns with radiography's principle of detecting foreign bodies primarily based on radiopacity rather than depth. Radiopaque materials absorb more X-ray photons and are easily visualized regardless of insertion depth, whereas radiolucent materials remain difficult to detect (Mowery & Singh, 2022). Exposure parameters such as kVp and mAs influence image contrast; in this study, a 15% kVp reduction enhanced contrast for low-density foreign bodies (Sy et al., 2022). Despite this adjustment, the number of detectable foreign bodies remained unchanged, supporting the conclusion that depth alone does not substantially affect general radiography detection. These findings align with previous observations suggesting that radiography's effectiveness is largely determined by material density rather than depth, emphasizing the modality's limitation in detecting radiolucent objects regardless of insertion depth (Hammoud et al., 2024).

Table 4. Friedman Test for ultrasound and general radiography image scores across varying depths

Imaging Modality	N	Chi-Square	df	Asymptotic Significance
Ultrasound	8	0.57	2	0.75
General Radiography	8	4.00	2	0.14

Note: Friedman test was used to compare image visibility scores across three depths (1 cm, 3 cm, and 5 cm). Statistical significance was set at p < 0.05.

A Wilcoxon signed-rank test (Table 5) was used to compare ultrasound and general radiography scores, as the ordinal data did not meet the assumptions required for a parametric paired t-test. Ultrasound demonstrated higher median scores (Mdn = 3.25, IQR = 4.00) compared with general radiography (Mdn = 0.00, IQR = 3.00). The difference between the two modalities was statistically significant, Z = −2.82, N = 24, p = .01, indicating superior diagnostic performance of ultrasound for detecting soft-tissue foreign bodies. Accordingly, the null hypothesis was rejected.

Table 5. Wilcoxon signed-rank test for averaged ultrasound and general radiography scores

Variable	Ultrasound median (IQR)	Radiography median (IQR)	Z	p-value
Soft tissue foreign body detection score	3.25 (4.00)	0.00 (3.00)	-2.82	0.01*

*Wilcoxon signed-rank test; p < 0.05 indicates statistical significance.

Ultrasound demonstrated superior performance compared to radiography, which can be attributed to its enhanced soft tissue visualisation, multiplanar imaging capabilities, and ability to detect both radiopaque and radiolucent foreign bodies, particularly those located superficially (Carneiro et al., 2020; Vishwanath et al., 2020; Voss et al., 2021). The presence of posterior acoustic shadowing further improves identification by increasing diagnostic confidence and sensitivity (Del Cura et al., 2020; Grocutt et al., 2023). In contrast, radiography relies primarily on the radiopacity of materials. Dense foreign bodies such as metal, glass, and stone demonstrate high X-ray attenuation and are readily detected, whereas radiolucent materials including wood and many plastics, are frequently missed, resulting in lower visibility scores and a higher likelihood of undetected foreign bodies (Voss et al., 2021).

The findings of this study are consistent with Voss et al. (2021), particularly regarding the material-dependent nature of detectability. Consistent with their observations, ultrasound displayed superior performance for radiolucent materials and maintained high detection rates for foreign bodies located within the first 4–6 cm, a depth range previously identified as optimal for high-frequency linear transducers (Lee et al., 2025). The studies support the conclusion that ultrasound's diagnostic value is influenced more by material composition than by depth, provided the object remains within the effective penetration range of the transducer.

Earlier research by Manthey et al. (1996) reported poor ultrasound sensitivity and considerable difficulty in detecting radiolucent materials, while radiography showed excellent detection of radiopaque objects but failed entirely to identify radiolucent foreign bodies such as wood, plastic, and cactus spines. The authors attributed ultrasound's limited performance to the technological constraints of earlier-generation systems, including inadequate management of acoustic shadowing, heterogeneous tissue backgrounds, and attenuation.

The improved outcomes observed in this study compared to Manthey et al. (1996) likely reflects major advancements in ultrasound technology over the past three decades. The Samsung RS85 Prestige system used in this study incorporates advanced beam-forming, attenuation compensation, speckle-reduction algorithms, and AI-assisted optimisation. These features appear to mitigate the confounding effects of soft-tissue interfaces and acoustic artefacts, contributing to more consistent detection across depths and reinforcing ultrasound's role as a highly effective modality for foreign-body identification.

This technological contrast is further highlighted by the performance of general radiography in the present study. Radiography detected fewer foreign bodies (N = 9) than ultrasound (N = 15), despite the application of three different exposure settings. Adjustments to exposure parameters influenced only visibility scores rather than the number of foreign bodies detected, supporting previous findings that detectability is driven primarily by material composition rather than radiographic exposure selection (Carneiro et al., 2020; Mowery & Singh, 2022). Only three radiopaque foreign bodies; an office pin, a glass shard, and a small stone were consistently visualised across all kVp and mAs combinations and at varying depths, although visibility diminished as kVp and depth increased. Conversely, radiolucent soft-tissue foreign bodies were undetectable regardless of exposure settings or depth, as shown in Figure 1.

These findings support ultrasound as the preferred first-line imaging modality for STFB detection, particularly when the composition of the foreign body is unknown or radiolucent. As shown in Figure 2, ultrasound reliably demonstrate various range of STFB, including radioapaque and radiolucent materials, with high sensitivity. Ultrasound offers real-time, non-invasive imaging and non-ionising radiation, making it particularly suitable for evaluating musculoskeletal injuries of the hands, wrists, and other soft tissues (Alfuraih et al., 2021; Grogan & Mount, 2023; Tok & Kadioglu, 2021). Overall, the results of this study reinforce the clinical value of ultrasound over general radiography for comprehensive detection of soft-tissue foreign bodies.

Figure 1. Anteroposterior (AP) and lateral projections of the cow foreleg phantom acquired with 45 kVp/4.0 mAs (A), 53 kVp/4.0 mAs (B), and 63 kVp/4.0 mAs (C), demonstrating three radiopaque foreign bodies; an office pin, a glass shard, and a small stone (arrow from top to bottom).

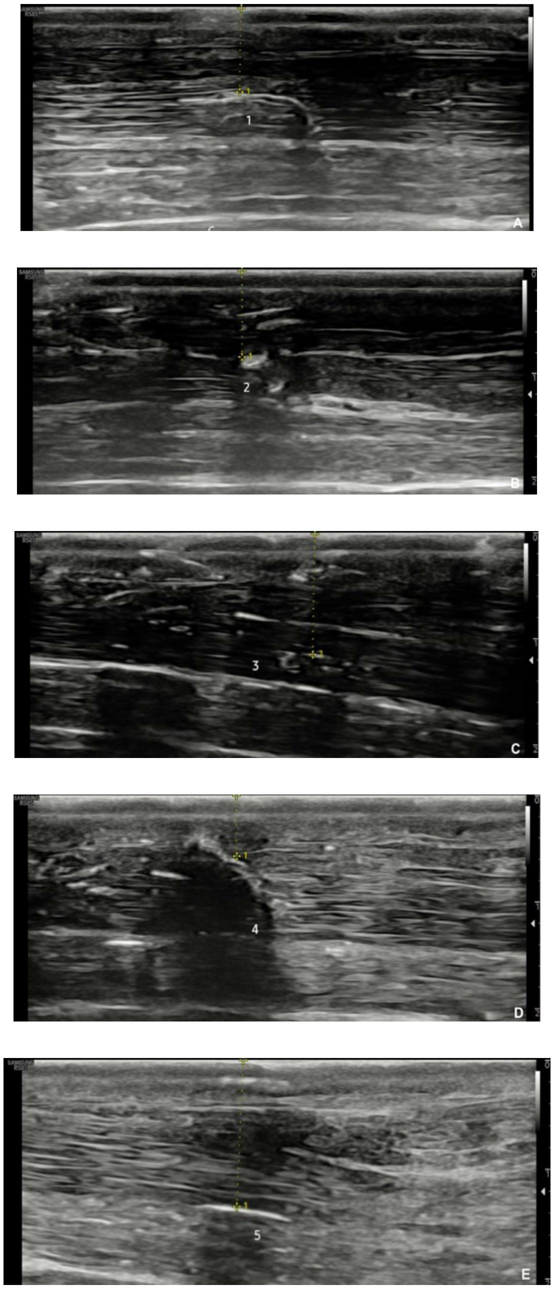

Figure 2. Ultrasound images (A-E) demonstrating the detection of various soft-tissue foreign bodies (STFBs) embedded within the foreleg phantom. Each image shows the foreign body as a hyperechoic structure with posterior acoustic shadowing or artefacts, aiding identification.

Although this study provides valuable insights into the effectiveness of ultrasound and general radiography for detecting STFB of varying depths and materials, several limitations should be acknowledged. First, the sample size was small (n = 3), which may have reduced the statistical power of the findings. Additionally, although eight foreign body types were included, they do not represent the diversity of STFB materials encountered in real clinical settings. Clinically, STFBs may involve a much broader range of radiolucent, radiopaque, and specialised materials, such as carbon-fibre fragments, depending on the mechanism of injury. Consequently, while the findings offer meaningful insight into STFB imaging and detectability, their generalisability to all clinical scenarios is limited. Second, the study utilized cow-foreleg phantom models. Although these phantoms approximate human forearm anatomy, they do not replicate the dynamic characteristics of live tissue, such as patient motion, pain response, and swelling. Unlike clinical settings, phantoms are static and free from motion artefacts which may limit the applicability of results to real-world conditions. Third, the absence of clinical validation represents another constraint. Controlled phantom environments do not account for practical challenges such as patient movement or incorrect positioning, both of which are critical in musculoskeletal imaging and can lead to diagnostic errors. Additionally, variability in image review conditions may have influenced interpretation. Image scoring was performed at different times, locations, and on different display screens, introducing potential inconsistencies due to variations in resolution, brightness, and ambient lighting. Lastly, the incision depth was estimated by marking the knife and forceps with a marker to indicate the level of penetration. Although this method provided a practical reference, it lacked the precision of direct measurement. Future studies should consider using a calibrated digital calliper or depth gauge to obtain accurate measurements from the surface to the deepest point, thereby enhancing the consistency and reproducibility of the results.

4. CONCLUSION

As a conclusion, ultrasound demonstrated superior performance over general radiography in detecting soft tissue foreign bodies (STFB). Although ultrasound image quality decline slightly with increasing depth, this difference was not statistically significant. In contrast, radiographic detection remained consistent across depths but was strongly influenced by material radiopacity, highlighting its limitations for identifying radiolucent foreign bodies. These findings support ultrasound as a more reliable modality for STFB detection, particularly when foreign body composition is unknown. Despite limitations such as small sample size and limited clinical variability, this study reinforces the potential of ultrasound as a first-line imaging technique in suspected STFB cases.

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