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Detection of Foreign Bodies in Simulated Wounds Using the Acoustic Emission Method: A Preliminary Study

Otkrivanje stranih tijela u eksperimentalnim ranama metodom akustične emisije: Preliminarno istraživanje

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Summary

Introduction: Shrapnel and ballistic injuries are common in modern warfare, with many foreign bodies (FBs) undetectable by conventional imaging methods like X-ray or MRI. There is a critical need for a reliable, portable, and radiation-free method to detect radiolucent FBs in soft tissues, particularly in resource-limited or battlefield conditions.

Methods: We developed and tested a prototype device using the Acoustic Emission (AE) method**,** which detects transient elastic waves generated when a flexible probe contacts a foreign object. Simulated wound channels were created in bovine muscle tissue, embedding fragments of metal, plastic, glass, and stone. Signals were captured with a microphone, analyzed with spectral tools and Fourier decomposition, and evaluated using fuzzy logic algorithms. Multiple probe configurations and contact conditions were evaluated.

Results: Fragments ≥2.5 mm were detected with >50% accuracy; metal fragments ≥5.0 mm reached 80% accuracy. The detection of plastic fragments was least reliable. Glass and stone fragments showed moderate accuracy that increased with size. Short probes (300 mm, 5.2 mm diameter) produced the most consistent and clear signals. Signal analysis revealed that frequency spectrum width, rather than amplitude, correlated best with fragment type and size. Signal-to-noise ratios improved with gain adjustments and optimized filters.

Conclusion: The AE method shows promise as a diagnostic tool for identifying foreign bodies, including radiolucent fragments, in wound channels. The technique offers a low-cost, portable, and radiation-free alternative suitable for field and emergency use. Further development and clinical validation could improve early detection and management of shrapnel injuries in both military and civilian settings.

Key words: Foreign Bodies/diagnosis; Wounds and Injuries/diagnosis; Acoustic Emission Analysis; Military Medicine; Shrapnel Injuries

Sažetak

Uvod: U suvremenim uvjetima ratovanja ozljede uzrokovane gelerima i projektilima vrlo su česte, pri čemu brojna strana tijela ostaju neotkrivena konvencionalnim dijagnostičkim metodama poput rendgenske snimke ili magnetske rezonancije. Stoga postoji potreba za metodom koja koristi lako pokretan uređaj, ne

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koristi zračenje i pouzdano otkriva radiotransparentna strana tijela u mekim tkivima, osobito u uvjetima s ograničenim resursima ili na bojištu.

Metode: Razvijen je i testiran prototip uređaja koji koristi metodu akustične emisije (AE) temeljen na detekciji prolaznih elastičnih valova koji nastaju pri kontaktu fleksibilne sonde sa stranim tijelom. Simulirani kanali rana izrađeni su u goveđem mišićnom tkivu s umetnutim fragmentima metala, plastike, stakla i kamena. Signali su snimani mikrofonom, analizirani spektralnim alatima i Fourierovom dekompozicijom. Testirane su različite konfiguracije sondi i uvjeti kontakta.

Rezultati: Fragmenti veličine ≥2,5 mm otkriveni su s točnošću većom od 50 %, dok je za metalne fragmente veličine ≥5,0 mm postignuta točnost od 80 %. Otkrivanje plastičnih fragmenata bilo je najmanje pouzdano. Stakleni i kameni fragmenti pokazali su umjerenu točnost koja je rasla s veličinom. Najpouzdanije signale generirale su kratke sonde (duljine 300 mm i promjera 5.2 mm). Analiza signala pokazala je da širina frekvencijskog spektra, a ne amplituda, najbolje korelira s vrstom i veličinom fragmenta. Omjer signal-šum poboljšan je podešavanjem pojačanja i optimizacijom filtara.

Zaključak: Metoda akustične emisije pokazuje potencijal kao dijagnostički alat za prepoznavanje stranih tijela, uključujući radiotransparentne fragmente u kanalima rana. Tehnika predstavlja jeftinu, prijenosnu metodu koja ne koristi zračenja, pogodnu za korištenje na terenu i u hitnim situacijama. Daljnji razvoj i klinička validacija uređaja mogli bi unaprijediti rano otkrivanje minsko-eksplozivnih fragmenata u ratnim ozljedama.

Ključne riječi: strana tijela/dijagnoza; rane i ozljede/dijagnoza; analiza akustične emisije; vojna medicina; minsko-eksplozivne ozljede

Introduction

The ongoing Russian aggression against Ukraine has led to widespread destruction and a profound humanitarian crisis.[1,2] The Russian military has employed a wide range of weaponry, including missiles, artillery systems, and prohibited munitions such as cluster and phosphorus shells, often deliberately targeting infrastructure and civilian areas.[3] As a result, shrapnel injuries have become highly prevalent, accounting for 56.7% of all reported war-related injuries and most commonly affecting the limbs and torso.[4] Multiple and combined injuries make up 27.4% of these cases, while limb injuries are the most frequent, occurring in 57.1% of patients. Head injuries, primarily caused by mines and explosive trauma, are reported in 26.6% of cases.[4]

Due to the diversity of foreign bodies (FBs) and the materials involved, many fragments are not detectable on X-ray, complicating diagnosis and treatment. Shrapnel injuries are characterized by the variability in fragment mass, shape, material, velocity, and kinetic energy—factors that determine the extent and nature of tissue damage. This variability, combined with differences in anatomical structure and physiology, makes predicting fragment behavior particularly difficult. Wound channels are typically irregular and deformed at the entry point rather than conical in shape.[5,6]

Shrapnel fragments may be regular or irregular in shape, and may be composed of various materials, not limited to metal. Regularly shaped fragments are often found in pre-fragmented munitions such as grenades and fragmentation shells.[7] Current detection methods include X-ray, MRI, magnetic detectors, ultrasound, and visual inspection. However, each has limitations, especially for fragments that are radiolucent or non-magnetic. For example, X-rays may fail to detect up to 25% of glass fragments and up to 93% of wooden FBs.[8]

Recently, magnetic search methods have become more popular, particularly those employing strong neodymium magnets with breaking forces of 100–150 kg (and 200–300 kg for deeper fragments).[9,10] However, some diagnostic methods are contraindicated for certain injuries, and others fail to detect specific materials entirely. These limitations significantly reduce the effectiveness of medical care in both military and emergency settings, underscoring the need for a new, simple, and reliable diagnostic approach that does not depend on X-ray or MRI technology.

This study investigates the feasibility of using Acoustic Emission (AE) technology to detect foreign bodies, particularly radiolucent fragments, embedded in wound channels. AE signals are generated when a flexible probe comes into intermittent contact with a foreign object. We aimed to develop and test a prototype diagnostic tool capable of identifying such fragments in soft tissue using this method.

Materials and methods

Acoustic Emission method - Theoretical background

This study applied the Acoustic Emission (AE) method to detect foreign bodies in wounds by capturing transient elastic waves generated during interactions between a probe, tissue, and embedded fragments.[11,12] These mechanical stress waves, with both longitudinal and shear components travel through solid media and are highly sensitive to material boundaries and internal structures. Unlike conventional sound waves in air, AE signals are short in duration, high in frequency, and highly dependent on the material properties through which they propagate.

AE analysis focuses on waveform characteristics such as amplitude, rise time, duration, and frequency content, all influenced by material type and wave attenuation. The method allows for the estimation of emission energy and localization of the wave source. It is particularly effective for detecting short-lived signals generated by localized stress events**,** such as when a probe contacts a foreign body. Since materials differ in properties like elasticity, density, and acoustic attenuation, each interaction produces a distinct AE signature.[11,13]

In practice, a flexible, elastic probe was inserted into simulated wound channels. When the probe contacted foreign objects, it produced changes in vibration patterns. These were captured by a microphone, amplified, and analyzed via an oscilloscope. Signals were recorded both during continuous motion and at the point of contact. Fourier analysis was used to decompose the signals into frequency components, revealing material-specific oscillation patterns. Features such as sharp spectral peaks, high intensities, and harmonic structures helped distinguish foreign bodies from biological tissue. To improve classification accuracy, fuzzy logic algorithms were used to assess amplitude and frequency ratios, enhancing identification of both the material type and fragment size. Fuzzy logic, unlike rigid yes/no rules, can weigh multiple signal features and express results in degrees of certainty, which is particularly useful for interpreting AE signals affected by noise and tissue variability.

Description of the device prototype

The prototype device used to examine wound channels consists of two main components: a disposable probe and a reusable unit equipped with a microphone and signal processing software (Figure 1).

The disposable component inserted into the wound consists of a flexible tube containing the probe. It is designed for single use to minimize tissue trauma and reduce the risk of complications. The probe is flexible enough to conform to the shape of the wound channel. As the probe advances, it interacts with the channel walls and any embedded structures, including foreign objects, generating acoustic emissions.

These emissions are transmitted through the probe to the reusable unit, where they are captured by a MAX9814 microphone with an amplifier board and automatic gain control (frequency range: 20 Hz to 20 kHz). The resulting signals are amplified and displayed using a Rigol DS1064 oscilloscope and further processed by a dedicated device running specialized spectral analysis software.

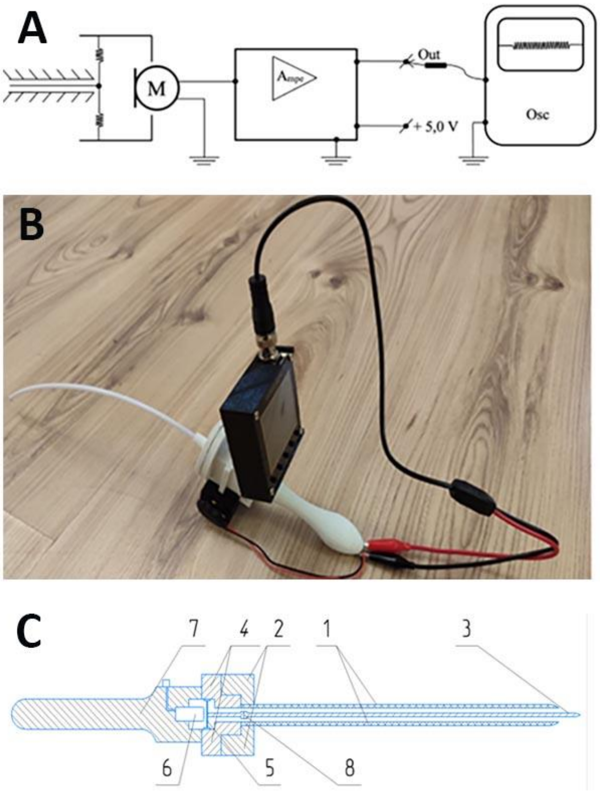


Figure 1 A) Schematic diagram of the device for haptic noise-emission detection of embedded fragments. Legend: M – Microphone, Ampe – Amplifier, Osc – Oscilloscope. B) External view of the device designed to locate foreign bodies in gunshot wounds. C) Schematic representation of the probe without the protective sheath. Legend: Reusable parts; 4 - fastening element (threaded connection point), 5 – noise-generating membrane (receives vibrations from probe/shell and oscillates), 6 – microphone (picks up vibrations/noise and converts to electrical signals), 7 – handle, 8 – connection element (links reusable and disposable parts). Disposable parts: 1 – flexible tube (Teflon sheath protecting the probe in the wound channel), 2 – fastening element (connects tube to the reusable part), 3 – elastic metal wire probe, Ø 0.5 mm, extends beyond the sheath and vibrates on contact, 8 – connection element (common to both parts, ensures assembly).

Slika 1. *A) Shematski prikaz uređaja za haptičku detekciju signala i pronalaženje fragmenata. Legenda: M – mikrofon, Ampe – pojačalo, Osc – osciloskop. B) Vanjski izgled uređaja namijenjenog lociranju stranih tijela u prostrijelnim ranama. C) Shematski prikaz sonde bez zaštitne ovojnice. Legenda: Višekratno upotrebljivi dijelovi: 4 – fiksacijski element (navojna spojna točka), 5 – membrana za generiranje signala (prima vibracije sonde/zaštitnog omotača i oscilira), 6 – mikrofon (bilježi zvučni signal i pretvara ga u električne signale), 7 – ručka, 8 – spojni element (povezuje višekratno i jednokratno upotrebljive dijelove). Jednokratno upotrebljivi dijelovi: 1 – fleksibilna cijev (teflonska ovojnica koja štiti sondu u kanalu rane), 2 – fiksacijski element (spaja cijev s višekratnim dijelom), 3 – elastična metalna žičana sonda, Ø 0.5 mm, koja izlazi izvan ovojnice i vibrira* pri kontaktu, 8 – spojni element (zajednički za oba dijela, omogućuje sklapanje).

Experimental Procedure

We evaluated the probe using simulated wound channels created in bovine muscle tissue, both with and without foreign bodies. In some models, bone fragments were added to simulate environments with varied mechanical properties. Foreign bodies were embedded by creating tissue cavities and inserting shrapnel, replicating realistic injury scenarios.

The tested foreign bodies included plastic, glass, metal, and stone fragments. A plastic fragment (10.0 × 5.5 mm) with a rough surface was produced via 3D printing, modeled from a metal cluster munition fragment. The 3D scan and design were performed using a Revopoint Trackit 3D scanner and Revo Design software.

Two types of glass fragments were tested. The first, a rounded tempered glass piece (6.5 × 1.0 mm), simulated fragments typically produced by vehicle glass breakage. The second was a polished, oblong fragment (3.0 × 12.0 mm), chosen for its potential to penetrate deeper tissue layers. Additional sharp-edged glass fragments (1.0 × 5.0 mm) with flat surfaces and brittle properties were also examined.

Metal and stone fragments were tested in two size categories. Medium fragments (2.5–10.0 mm) had elliptical to rounded shapes with faceted, rough surfaces. Small fragments (0.8–1.5 mm) were rounded and exhibited quasi-brittle behavior. Surface roughness was assessed using a microscope. Probe-fragment interaction was influenced by both geometry and surface texture.

For each material type, 20 fragments were tested, classified into four categories: plastic, glass (two types), and natural minerals. Metal fragments were also examined but not included in the main analysis. Each fragment was tested repeatedly, and duplication of measurements was performed on a sample of 50 fixed records, with each measurement consisting of automatic 2.0 s signal capture. In total, each material group yielded approximately 1000 frames for analysis. Accuracy values (e.g., >50%) refer to the proportion of correct determinations of fragment type based on characteristic acoustic emission (AE) patterns. Thus, “accuracy” is defined here as the frequency of correct classification of fragment type relative to the total number of test frames.

To assess the diagnostic value of AE signals, we conducted controlled experiments varying two key factors: fragment type and contact conditions. Materials were tested across all four categories, and probe contact was repeated under different angles and forces to reflect clinical variability. These tests allowed us to evaluate how material composition and interaction dynamics affected acoustic signatures.

AE signals were influenced by probe motion within the sheath, movement in the wound canal, and environmental acoustic noise. To minimize these effects, we calculated the ratio of maximum amplitude at the base frequency at the moment of contact with a foreign body to the averaged amplitude of the background spectrum in the absence of contact. This improved signal-to-noise discrimination and reduced false positives from probe instability or tissue friction. Band-pass LC filters were applied to attenuate predictable noise frequencies, while the membrane chamber and microphone were noise-insulated to reduce environmental interference. Laboratory tests indicated that external noise levels above –25 dBA distorted spectral patterns, so measurements were performed under controlled, quiet conditions. We recognize that unpredictable ambient noise remains a limiting factor, which we note as a study limitation. Future work will explore neural network–based filtering to further improve noise isolation.

Each contact between the probe and a foreign object produced a distinct AE pattern, visible on the oscilloscope and analyzed spectrally at both low and high frequencies (Figure 2). The device measured average amplitude at set frequencies, spectrum width, fundamental tones, and harmonics under defined contact scenarios. The time of signal generation was recorded to allow localization of the fragment before removal.

Spectral analysis was performed without tissue dissection, enabling laparoscopic-style manipulation. Signal processing used enhancement filters and Fourier-based spectral tools integrated into the oscilloscope system, which also enabled data export. Final signal analysis was conducted using Statgraphics+ statistical software.

Statistical analysis included variance analysis and validation of sample homogeneity using the ω-criterion, suitable for small sample sizes (n=20 per group). Cluster analysis and regression modeling (nonlinear second-order models) were used to detect patterns linking fragment characteristics (size, shape, surface roughness) with spectral AE signatures. Correlation coefficients for base excitation frequencies are reported in the Results section. These procedures provided sufficient replication for reliable detection of consistent patterns despite modest sample sizes.

Identification was evaluated in two aspects: (1) the ability to confirm the presence of a foreign body within the wound, and (2) the ability to classify the fragment type, particularly for non-metallic materials (glass, plastics, minerals). Larger fragments were generally identified with higher accuracy due to their greater mass and stronger AE signatures. Localization within the wound was determined by the insertion length of the probe; in future versions, a graduated scale will be incorporated to facilitate clinical use.

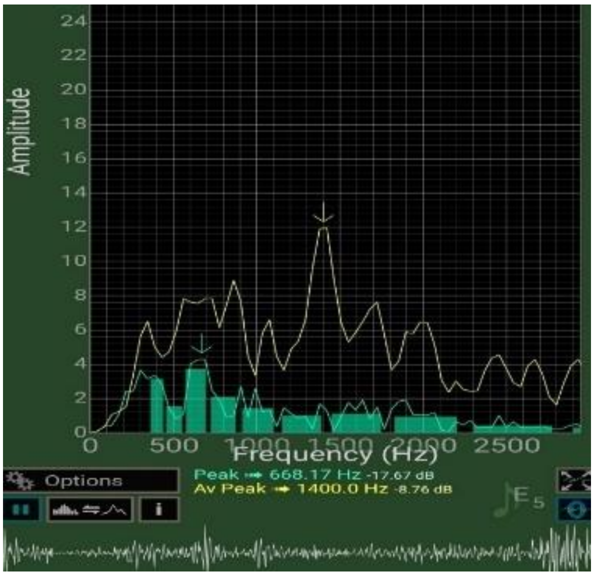


Figure 2 Representative spectrogram illustrating changes in acoustic emission as the probe advances through a wound channel; the arrow marks the moment of contact with a foreign body.

Slika 2. *Reprezentativni spektrogram koji prikazuje promjene akustične emisije dok sonda napreduje kroz kanal rane. Strelica označuje trenutak kontakta sa stranim tijelom.*

Results

Almost all fragments used in the study were identified with a probability greater than 50% at sizes of 2.5 mm and above (Figure 3). The highest identification accuracy, reaching 80%, was achieved for metal fragments measuring 5.0 mm or larger. In contrast, plastic fragments exhibited the lowest identification accuracy, even at relatively large sizes (5–10 mm). Mineral and glass fragments showed intermediate performance, with identification accuracy improving consistently as fragment size increased (Figure 3).

Accuracy in identifying smaller fragments, within the 0.9–1.5 mm and 1.2–2.5 mm size ranges, was relatively low across all materials. However, cluster analysis confirmed that mineral and glass fragments in these size ranges were identified more reliably than the plastic ones. This difference is likely due to the distinct elastic properties of the materials, which influence their acoustic emission behavior.

To investigate the effect of fragment surface characteristics on probe-tip response, transient acoustic signals were recorded and summarized in Table 1. The dynamic behavior of the elastic probe, particularly its elasticity coefficient, is governed by its geometric parameters, notably length (l) and diameter (d). These design features must balance two practical requirements: maximizing signal informativeness and minimizing overall device complexity. Therefore, several probe configurations were tested, as shown in Table 1.

These experiments allowed us to identify general trends regarding optimal spectral clarity and signal repeatability. Although complete results are not presented in this article, the data support the conclusion that the most effective probe configuration for signal clarity is a short probe with a length of 300 mm and a diameter of 5.2 mm.

Comparison of the transient signal patterns with corresponding oscillograms and probe oscillation spectra revealed distinct differences in near-resonant frequency zones. Significant signal attenuation was observed, attributed to the damping effect of the surrounding biological tissue. These changes emphasize the importance of considering not only the mechanical dynamics of the probe but also the influence of the tissue environment.

To address signal attenuation and improve the signal-to-noise ratio, gain coefficients were increased, and dedicated signal filters were implemented. These modifications led to a more accurate spectral pattern detection and enhanced repeatability, providing insights that help inform optimal strategies for signal acquisition in such experimental setups.

Because the depth of probe insertion significantly affects its interaction with embedded fragments, impacting both the signal-to-noise ratio (denoted as *lp*) and the effective length of the cantilever section (*lm*), a probe length of *lp* = 300 mm proved to be more reliable in experimental procedures.

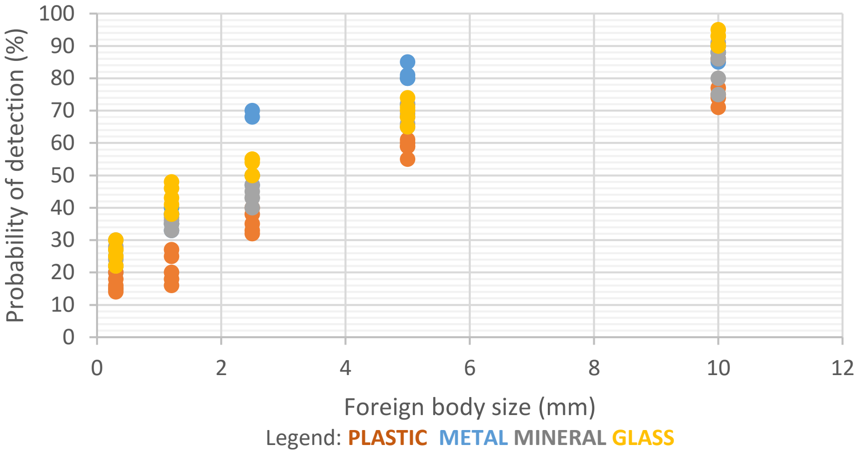
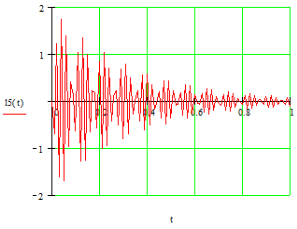
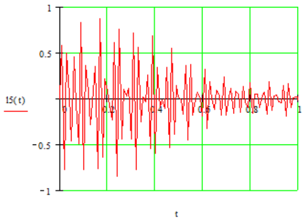
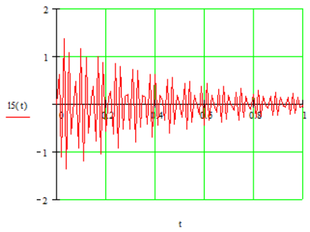
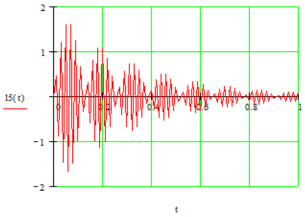


Figure 3 Probability (in %) of accurate identification of foreign fragments in the muscle simulator at depth l_m=50 mm.
Slika 3. *Vjerojatnost (u %) točne identifikacije stranih fragmenata u mišićnom simulatoru na dubini* l_m *= 50 mm.*

Table 1 Transient signal patterns from the probe contact with tissue surfaces under varying conditions.
Tablica 1. *Prolazni uzorci signala nastali pri kontaktu sonde s površinama tkiva u različitim uvjetima.*

#	Conditions *Uvjeti*	Device parameters *Parametri uređaja*	Sample of diagram *Primjer dijagrama*	Conclusions *Zaključci*
1	Low speed (1 cm/s), contact with soft tissue *Mala brzina (1 cm/s), kontakt s mekim tkivom*	Metal probe, small diameter (d = 0.5 mm), length = 0.3 m *Metalna sonda, mali promjer (d = 0,5 mm), duljina = 0,3 m*		Low-amplitude noise with fixed frequencies and no peak *Šum niske amplitude s fiksnim frekvencijama i bez vrha*
2	Low speed (1 cm/s), contact with bone tissue *Mala brzina (1 cm/s), kontakt s koštanim tkivom*	Metal probe, large diameter (d = 0.9 mm), length = 0.3 m *Metalna sonda, veliki promjer (d = 0,9 mm), duljina = 0,3 m*		Peak amplitudes at contact; wide noise spectrum at resonant frequencies *Vršne amplitude pri kontaktu; širok spektar šuma na rezonantnim frekvencijama*
3	High speed (4 cm/s), contact with soft tissue *Velika brzina (4 cm/s), kontakt s mekim tkivom*	Metal probe, small diameter (d = 0.5 mm), length = 0.8 m *Metalna sonda, mali promjer (d = 0,5 mm), duljina = 0,8 m*		Frequency spectrum changes: bursts appear due to contact with channel walls *Promjene frekvencijskog spektra: naleti se javljaju zbog kontakta sa stijenkama kanala*

#	Conditions *Uvjeti*	Device parameters *Parametri uređaja*	Sample of diagram *Primjer dijagrama*	Conclusions *Zaključci*
4	High speed (4 cm/s), contact with bone tissue *Velika brzina (4 cm/s), kontakt s koštanim tkivom*	Metal probe, small diameter (d = 0.5 mm), length = 0.8 m *Metalna sonda, mali promjer (d = 0,5 mm), duljina = 0,8 m*		Smaller amplitude bursts; lower signal-to-noise ratio *Manja amplituda rafala; niži omjer signala i šuma*

Discussion

This preliminary study demonstrates that the AE method can effectively detect foreign bodies in wound channels, including radiolucent materials such as plastic and glass. The technique relies on analyzing distinct spectral and amplitude characteristics of acoustic signals generated when a flexible probe makes mechanical contact with embedded objects. This approach shows a strong potential for battlefield and emergency medical settings, where access to advanced imaging modalities is limited.

The results indicate that the fragment size significantly affects detection accuracy**.** Fragments ≥2.5 mm were identified with over 50% probability, while metal fragments ≥5.0 mm achieved up to 80% accuracy. Plastic fragments were the most difficult to detect, even at larger sizes, likely due to their low acoustic impedance and weak emission signals. In contrast, mineral and glass fragments demonstrated moderate detectability, with accuracy improving consistently with size. These findings suggest that a frequency bandwidth is a more reliable diagnostic marker than amplitude alone.

Probe design also played a key role in signal clarity and repeatability. A shorter probe (300 mm in length, 5.2 mm diameter) provided the best performance by enhancing resonance and minimizing background noise caused by tissue damping. This supports established the principles of mechanical wave propagation, where probe geometry and material properties influence signal behavior.

Advanced signal analysis techniques**,** including the discrete singularities method and cluster analysis, improved the classification of AE signals. While amplitude showed weak correlation with fragment type or size, the width of the frequency spectrum at the point of contact was consistently linked to both parameters. Regression analysis confirmed a strong relationship between spectral width and fragment characteristics, underscoring the value of refined signal processing in complex biological environments.

These findings compare favorably with conventional diagnostic tools. Standard modalities such as X-ray and MRI often fail to detect non-metallic fragments, especially plastic or wood, while ultrasound can be unreliable for deep or irregularly shaped objects.[14-16] Optoacoustic imaging shows promise but is limited by technical complexity and availability. In contrast, the AE-based approach offers a low-cost, portable, and radiation-free alternative that could complement the existing technologies, particularly in military and resource-constrained environments.

Despite the encouraging results, this study has limitations. The range of tested materials and fragment sizes was restricted, and experiments were conducted in bovine muscle tissue, which does not fully replicate human anatomy. Further research should include a broader array of materials, in vivo validation, and analysis of factors such as wound geometry, fluid content, and tissue heterogeneity.

Future improvements may involve incorporating fuzzy logic algorithms, enhancing signal consistency through controlled mechanical excitation, and applying machine learning for real-time classification. These advancements could significantly boost the accuracy and clinical utility of AE-based foreign body detection.

In summary**,** this study supports acoustic emission as a promising method for detecting embedded foreign bodies, especially those invisible to conventional imaging. The frequency spectrum width serves as a reliable indicator of the presence, type, and size of fragments. The developed prototype—featuring a flexible probe with real-time spectral analysis—represents a valuable diagnostic tool for both military and civilian medical applications. With continued development and validation, this technique could greatly improve early diagnosis and treatment planning in trauma care.

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