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FORENSIC TAPHONOMY OF MASS GRAVES – IMPORTANCE OF QUANTIFYING SKELETAL REMAINS FRAGMENTATION

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FORENZIČKA TAFONOMIJA MASOVNIH GROBNICA – ZNAČAJ KVANTIFIKOVANJA FRAGMENTOVANOSTI SKELETNIH OSTATAKA

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FORENSIC TAPHONOMY OF MASS GRAVES – IMPORTANCE OF QUANTIFYING SKELETAL REMAINS FRAGMENTATION

ABSTRACT

This study investigates the varying degrees of body fragmentation across 13 mass grave sites, utilizing data from 10 commingled secondary mass grave sites and two primary sites associated with the 1995 Bosnian war, along with one secondary mass grave site from Serbia. The aim was to analyze differences in body fragmentation levels among mass graves, particularly focusing on variation between mass graves of similar origin and taphonomy.

To assess the degree of fragmentation and commingling within each grave, we introduced a *fragmentation index* (FI) representing the ratio between the number of complete bodies and the number of body parts from the same mass grave. Our findings revealed significant variations in body fragmentation among different sites. Specifically, FI values for secondary sites with similar formation histories ranged from 0.01 to 0.59 (with a maximum value of 1), while the two primary sites exhibited values of 0.92 and 0.90, respectively.

The differing levels of fragmentation among similar secondary sites suggest potential differences in peri-mortem circumstances for the deceased. Consequently, we explored whether the "body fragmentation index" could help in understanding the manner of death. Remarkably high levels of body fragmentation (FI values below 0.1) observed in some secondary sites may indicate that body disarticulation was likely caused peri-mortem by explosives, landmines, mortars, or tank fire, all indicative of a combat scenario.

Moreover, we examined how the FI affected the accuracy of estimating the *minimum number of individuals* (MNI) by evaluating MNI error. This entailed comparing MNI estimates for different sites with DNA identification results from the same sites and correlating that error with FI. Our results demonstrated a strong negative correlation between FI and MNI error.

Keywords: *mass graves, taphonomy, fragmentation, peri mortem circumstances, MNI error*

Research Field: Medicine

Specialized scientific field: Skeletal biology

Research subfield: Forensic anthropology

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FORENZIČKA TAFONOMIJA MASOVNIH GROBNICA – ZNAČAJ KVANTIFIKOVANJA FRAGMENTOVANOSTI SKELETNIH OSTATAKA

REZIME

Ova studija analizira različite stepene fragmentiranosti tela između 13 masovnih grobnica od kojih su dve primarno, a 11 sekundarno ukopane. Jedna sekundarna masovna grobnica je iz Srbije dok su ostale povezane sa ratom u Bosni 1995. Godine. Cilj istraživanja jeste kvantifikacija i analiza razlika u nivoima fragmentacije tela između masovnih grobnica sa posebnim fokusom na razlike između masovnih grobnica sličnog porekla i tafonomije.

Da bismo utvrdili stepen fragmentacije i dezartikulacije kostiju unutar svake grobnice, uveli smo *indeks fragmentacije* (FI), koji predstavlja odnos između broja celih tela i broja delova tela iz iste masovne grobnice. Naši su nalazi otkrili značajne varijacije u fragmentaciji tela među različitim masovnim grobnicama. Konkretno, vrednosti FI za sekundarne lokacije sa sličnim uslovima formiranja bile su od 0,01 do 0,59 (sa maksimalnom vrednošću od 1), dok su za dve primarne lokacije vrednosti IF iznosile 0,92 i 0,90.

Različiti nivoi fragmentacije među sličnim sekundarnim masovnim grobnicama sugerišu na moguće razlike u peri-mortem okolnostima preminulih. Stoga smo istražili da li indeks fragmentacije tela može pomoći u razumevanju načina smrti ljudi sahranjenih u analiziranim masovnim grobnicama. Veće fragmentacije tela na pojedinim sekundarnim masovnim grobnicama (vrednosti FI ispod 0,1) ukazuju da je disartikulacija tela verovatno izazvana peri-mortem eksplozivima, minama, minobacačima ili vatrom iz tenkova, što može da ukaže na ratne okolnosti.

Osim toga, ispitali smo kako FI utiče na tačnost procene minimalnog broja osoba (eng. minimum number of individuals – MNI). To je podrazumevalo upoređivanje procena MNI za različite masovnie grobnice sa rezultatima identifikacije DNK iz istih grobnica i koreliranje te MNI greške sa FI. Naši rezultati su pokazali snažnu negativnu korelaciju između FI i greške u proceni MNI.

Ključne reči: *masovne grobnice, tafonomija, fragmentacija, peri mortem okolnosti, MNI greška*

Naučna oblast: Medicina

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Author

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1. INTRODUCTION

Taphonomy deals with the study of the transition of various organic remains from the biosphere to the lithosphere (from the Greek "táphos" – grave and "nomos" – law) (1). Originally applied in palaeontology (paleotaphonomy), it deals with the processes influenced by natural factors that occur over geological intervals. On the other hand, forensic taphonomy, as defined by Haglund and Sorg in 1997, studies the changes that occur and develop over time on human post-mortem remains, including determining the cause of death, all for forensic purposes. (2). Forensic taphonomy explores factors that affect the decomposition or damage of post-mortem remains over time, making it important for forensic investigation. Dead bodies are considered evidence in a legal context, so any changes to them signify alterations and/or destruction of evidence. Therefore, forensic taphonomy also deals with identifying natural and human factors that have led to the disturbance of the original position of skeletal remains, determining the original body position in the grave, distinguishing post from perimortem pathologies and injuries, establishing the time elapsed since a person's death, and the time elapsed since burial (3).

Human (anthropogenic) factors refer to human activities that lead to changes in post-mortem remains. Such changes leave identifiable taphonomic traces in the archaeological record and can be recognized as a result of murder, execution, warfare, crime concealment, burial rituals, cannibalism, dismemberment of post-mortem remains, etc. (4) (5) (6). Since both natural (geological) and anthropogenic factors are considered taphonomic (7), there are two main branches of taphonomy: geo-taphonomy (wether, acidity, humidity…) and bio-taphonomy (animal, microbial and human activities). Garget suggests that three processes are most important in (taphonomy: tissue decomposition, disarticulation, and changes in the spatial position of human remains (8).

These processes follow a specific course in mass graves. There is no unified definition of a mass grave, but it is generally considered to be a grave in which a larger number of bodies are buried simultaneously. There are various classifications of mass graves, which will be discussed later. The most general division is between those resulting from natural (tsunamis, earthquakes) and human caused disasters (trafic i.e. train crashes and airplane crashes or blasts) and those resulting from criminal activities (murders, war crimes).

1.1 MASS GRAVES DEFINITION AND TYPOLOGY

Understanding the archaeological concept is essential for determining taphonomic status, i.e. to reconstruct all events from death of individuals to the moment of recovery of the remains, and it can be said that forensic archaeology is the application of archaeological theory to forensic circumstances (8). Application of archaeological methods to forensic circumstances is usualy related to mass graves investigations.

Mass graves are a common occurrence from prehistory to the present day, primarily before the use of crematoria (Ludovik Brunet devised the crematorium in 1873). Those who died during pandemics or perished in wartime conflicts before the advent of crematoria were typically buried in mass graves.

There is no precise and unified, or standardized, definition of mass graves (9) (10). The United Nations has defined a criminal mass grave as a burial site containing three or more victims of execution (11). Some authors define mass graves based on the number of individuals buried: Skinner states that a mass grave must contain the remains of at least six people (9), while Mant defines this term as sites where two or more bodies physically touch (12). A more comprehensive definition that includes an anthropological context is provided by Schmidt: according to him, a mass grave must contain the remains of at least two victims who share a common characteristic related to the cause of death and the manner of dying (13).

In addition to some mass graves being of criminal origin, the formation of mass graves can also have natural causes, such as weather disasters, earthquakes or epidemics.

Relocation of necropolises or cemeteries can produce ossuaries which are common burials of bodies decomposed elsewhere and at different times from different causes. A good example of this is the Parisian cemeteries and catacombs, from which the remains of around six million people were relocated to underground ossuaries at the end of the 18th century (14). Should be notted that ossuaries do not represent mass graves in strict sense.

Another way to categorize mass graves can be based on their construction or structure, which to a large extent reflects potential variations in taphonomic changes within them. Mass graves can be underground without structure, underground with structure (catacombs), on the surface without structure, on the surface with structure (ossuaries), etc.

If it involves the initial burial of human remains, the mass grave is considered primary. These are undisturbed burials where bodies are collectively buried for the first time. Secondary mass graves involve the opening of a primary grave, followed by the relocation and re-deposition of human remains to another location or locations (15).

1.2 THE PROCESS OF TISSUE DECOMPOSITION THROUGH (TAPHONOMICAL) TIME

Based on the degree of tissue decay or decomposition, forensic experts determine the time that has elapsed since death or the post-moretem interval (PMI). There is no simple and straightforward method for determining PMI based on the degree of decomposition because the decomposition process is influenced by external and internal factors. External or exogenous factors include the level of moisture, temperature, soil acidity, burial depth, the impact of plants, the influence of insects and/or other animals, and the effect of all these factors varies depending on the burial location (e.g., soil composition and climate differ geographically) and the position in which the body is disposed of (16). Additionally, a body on the surface of the soil undergoes changes and decomposition more rapidly than one buried in the ground (e.g., due to the effects of the sun, insects, and rodents) (17). On the other hand, in water, post-mortem processes occur more slowly than in the open air (e.g., due to the lower environmental temperature and reduced oxygen concentration around the body). Post-mortem processes are somewhat slower when the body is buried in the ground: the deeper the body is buried, the slower the post-mortem changes occur (18). Furthermore, the presence of clothing, caskets, and similar items can affect the rate of the formation and dynamics of post-mortem changes (17). Internal or endogenous factors also play a role in the occurrence and rate of development of post-mortem changes, including the cause of death, physical characteristics of the individual (such as musculoskeletal development, nutritional status, age, any existing medical conditions, and more) (19).

Shortly after death, early postmortem changes begin to appear and develop, including algor mortis (body cooling), livor mortis (lividity) and rigor mortis (stiffening of the body) (20). Simultaneously or shortly after these three post-mortem changes, primarily putrefaction start to occur (21). Putrefaction involves the breakdown of complex organic matter that constitutes the body into simpler organic compounds and eventually into inorganic substances. This process is driven by bacteria already present in the body during life, including those from the digestive, respiratory, and genitourinary tracts, as well as those on the skin. As putrefaction progresses, bodily fluids are lost to the external environment, and over time, the post-mortem remains go through complete skeletalization (21).

Around 48 to 72 hours after death, early postmortem changes, under ideal microclimatic conditions, typically start to fade away (20) (22). The initial signs of putrefaction become noticeable, primarily manifesting as a greenish discoloration of the skin on the abdomen, known as pseudomelanosis (23) (24). Subsequently, the appearance of the body changes due to putrefaction. In cases where the environment around the body has a reduced oxygen concentration (such as when the body is buried in moist or clayey soil or submerged in water), soft tissues rich in fats can undergo saponification. This process involves the post-mortem hydrolysis of triglycerides, releasing a higher amount of fatty acids. These fatty acids, in the presence of alkaline and alkaline earth metals, form soaps. Conversely, if the body is exposed to a low humidity environment with warm dry air, post-mortem desiccation occurs, leading to mummification of the body. The post-mortem transformation into soap (saponification) or mummification typically takes several months or longer to complete (23).

In comparison to unburied ones, buried bodies undergo the process of putrefaction about eight times more slowly (25) (3). However, under ideal microclimatic conditions, such as a warm and humid environment, a buried body can be skeletonized relatively quickly. In these conditions, complete skeletalization of a buried body may occur around eight years after death and burial, whereas an unburied body may take approximately one year to undergo complete skeletalization. (26) (27) (18). Once the soft tissue is completely lost post-mortem, only the disarticulated bones remain, and these skeletal remains are subjected to external environmental factors that can further alter them (28). Ligaments, tendons, and periosteal tags will initially remain connected to the bones during the early stages of skeletonization. However, over time, these connections break down (often facilitated by the activity of flora and fauna), causing the skeleton to disarticulate.

Bones are composed of an inorganic crystalline matrix made up of carbonated hydroxyapatite (HAP) with the addition of organic collagen (21). When buried in the ground, bones gradually lose their organic and carbonate content, while the so-called crystallinity index (CI) increases (29). The CI is a quantitative indicator of crystallization (30). The change in this ratio and the rate of bone degradation are primarily influenced by the acidic soil environment (low pH) and the type of soil (31). The soil's pH value affects the speed of bone degradation because HAP becomes soluble in an acidic environment (32).

Macromorphologically, bones buried in the ground become paler and more porous over time due to desiccation. Exfoliation (peeling of the cortex) occurs on the bone surfaces, and the bones themselves lose their elasticity and become brittle (17).

Depending on the environment and the characteristics of the skeleton, bone decomposition can take decades or even tens of thousands of years. In buried bones, the organic part of the bone, which accounts for about 25% of the bone mass, degrades first. The organic part, namely collagen, hydrolyzes into peptides and further into amino acids. The inorganic part consists mostly of calcium phosphate (in crystalline and amorphous forms) and is complexly structured in a crystalline lattice composed of HAP combined with calcium carbonate and tricalcium phosphate (33). The inorganic part makes up about 70% of the bone mass. The remaining 5% of bone mass consists of water and trace elements such as iron, magnesium, zinc, strontium, etc., which, since they are in ionic form, are gradually lost from the bone remains (17). However, a portion of the trace elements bound to minerals and collagen remains in the bones for a long time, allowing the determination of their concentration even in archaeological samples (19). Should be noted that trace elements are uncertain as they can be leached to or absorbed from the surrounding soil.

In the case of long-term burial in the ground, bones not only lose their inorganic component but also absorb minerals from the environment, soil, or the coffin (4). This often leads to the occurrence of hypermineralized zones in bone lamellae (17). In the case of teeth, the replacement of hydroxyl ions from hydroxyapatite with fluoride ions from the surrounding soil can occur over time (34) (35).

Just like the decomposition of soft tissues, postmortem changes in bones are influenced by various external and internal factors. Internal factors include the size and shape of bones, as well as age, and skeletal diseases of the individual. Smaller bones and those with more trabecular bone tissue generally undergo postmortem changes more rapidly. Skull bones are particularly sensitive to the pressure of the surrounding soil. The skeletons of the elderly, children, and individuals with, for example osteoporosis, degrade more quickly (19). External factors encompass local ecosystem diversity, geographical and geological terrain characteristics, as well as human, or anthropogenic factors.

All of this suggests that the degree of body decomposition at a given time varies depending on the existing environmental factors, including human activities. Therefore, precise determination of the time elapsed since death requires an understanding of these taphonomic factors and other methods like forensic entomology, botany etc. Of course, as more time elapses after death, the accuracy of estimating the time since death decreases.

The time of death, the time of burial or body deposition, and the time of investigation (exhumation and associated analyses) are three successive events that describe taphonomic time. Within these events, four temporal contexts are identified (6). These are the antemortem period (the time just before death and/or body deposition), the perimortem period (the time around the moment of death and/or body deposition), the postmortem period (the time from body deposition to the time of investigation), and the period after excavation (the time from the discovery of postmortem remains until the completion of the analysis).

From the perspective of forensic taphonomy, human influence is most significant during the perimortem and postmortem periods (13). Therefore, the primary goal of forensic and other investigations is to create a taphonomic profile that accurately describes the perimortem and postmortem changes on the body.

It is important to note that taphonomic time is not strictly defined as absolute chronological time because it is often impossible to determine it precisely. Taphonomic time is more commonly expressed as relative time, which reflects an archaeological concept of successive events defined by preceding and subsequent events. This means, for example, that we describe events as occurring before or after the relocation of the grave without specifying an exact chronological time (6).

1.3 TAPHONOMIC FACTORS IN THE CONTEXT OF MASS GRAVES

Taphonomic factors in the context of mass graves play a crucial role in shaping and transforming human remains over time. Mass graves are complex archaeological contexts that involve a large number of skeletal remains buried simultaneously or within a relatively short time frame. Various factors influence taphonomic processes in these graves, including (2):

1. **Perimortem Circumstances**: These are the circumstances at the time of death or immediately before or after it. The manner in which individuals died, whether they were executed, died in warfare, or by other means, significantly affects the condition of their remains in the grave.

2. **Geological (Natural) Factors**: Soil type, geological characteristics of the terrain, and other natural factors have a significant impact on taphonomic processes. For example, soil moisture, pH levels, and burial depth influence the rate of bone degradation.

3. **Animal Activities**: Animal activities, such as rodents, insects, and other organisms, can also have a substantial impact on the fragmentation and decomposition of bones.

4. **Anthropogenic Factors**: Human activities, including the use of heavy machinery for grave relocation or actions related to war crimes, also play a crucial role in shaping mass graves and transforming human remains. It's worth noting that human actions frequently influence the perimortem circumstances of individuals.

5. **Weather**: Weather factors, such as temperature fluctuations, rainfall, and seasonal changes, can also influence the processes of human remains degradation.

Given the complexity of these factors, understanding taphonomic processes in mass graves requires a multidisciplinary approach involving forensic archaeology, forensic anthropology, geology, and other scientific disciplines to accurately reconstruct the context and timing of events in these graves. This is essential for the research and interpretation of historical or forensic mass graves. In the context of mass graves, the most significant factors influencing taphonomy are geological and anthropogenic.

1.4 GEOLOGICAL (NATURAL) TAPHONOMIC FACTORS IN MASS GRAVES

Basic soil properties that influence the rate of corpse decomposition include (36):

1. **Physical Soil Texture**: The type of soil, whether sandy, silty, or clayey, affects the speed of post-mortem changes due to its impact on gas and water movement around the corpse.
2. **Chemical Soil Properties**: Soil acidity or alkalinity can influence the rate and nature of post-mortem changes.
3. **Biological Activity**: Soils with active fauna can decompose cadaveric tissue more rapidly.

Moreover, environmental factors such as temperature and moisture play a significant role in the post-mortem decay of bodies. Edaphic factors, which encompass the physical, chemical, and biological properties of soil and rocks, also affect the speed and character of post-mortem changes in buried bodies. These factors include soil pH, salinity, redox potential (the ability of a substance in solution to release or accept electrons), and the amount of nutrients (organic matter) in the soil (37).

The position of bodies within a mass grave or deposit also influences the rate of decomposition due to the varying exchange of materials between the environment (soil) and the buried bodies. Bodies in the center and toward the lower part of the deposit decompose more slowly and tend to undergo partial saponification. Bodies in the deeper central areas of the deposit are exposed to higher temperatures, the flow of post-mortem fluids and organic materials from the upper parts of the deposit, and anaerobic conditions. Essentially, a unique microclimate is created in the deeper central areas of the deposit compared to the rest, and this microclimate becomes more specific as the deposit size increases. The greater intensity of saponification in these cases is also influenced by increased humidity and reduced oxygen levels in the central part of the deposit. Therefore, these taphonomic outcomes and the occurrence of saponified remains in the deeper central part of the deposit should not be attributed to a longer time period elapsed since the death of the buried individuals but rather to different taphonomic processes in these parts of the deposit.

1.5 ANTHROPOGENIC TAPHONOMIC FACTORS IN MASS GRAVES

Prominent archaeologist Lewis Binford, followed by Liman, were the first to investigate the complex taphonomic factors that alter the contents of a grave (the collection of all bones within the grave) (38) (39). They observed that people play a crucial role in the process of mixing and dispersing bones, especially in cases involving the concealment of criminal activities, which can involve burning, fragmentation, or relocation of post-mortem remains.

The influence of the human factor as a taphonomic agent is most pronounced in the forensic context, especially in criminal mass graves. (2). Mass graves typically contain disarticulated and commingled skeletal material. In secondary mass graves, this commingling is even more pronounced and occurs during the process of creating the secondary grave, usually when post-mortem remains are moved from the primary location to the secondary one. For example fragmentation and commingling of the dead bodies can happen by using heavy machinery for relocation of the remains. In contrast to these post-mortem disarticulations, bodies can be dismembered perimortem, such as due to the effects of artillery or similar high-explosive weaponry on a group of individuals.

Although anthropogenic taphonomic factors are always present in mass graves with commingled human remains (40), the character of the grave doesn't necessarily have to be criminal (like mass burials of accident victims).

1.6 METHODS OF INVESTIGATING MASS GRAVES AND DATA ANALYSIS

The application of archaeological methods in forensics significantly enhances the investigative process. Archaeological excavation (or sometimes surface collection only) is the first step in the chain of collecting crime scene evidence. It has been shown that the use of the appropriate archaeological method yields the best results in terms of the quantity and quality of evidence collected (41). The stratigraphic method, which is routinely used in archaeological excavations, when applied in a forensic context, involves excavating while preserving the structure and features of the site. This preservation means that the structure of the site (walls, foundations, etc.) that determines the character (istics) of the site (e.g., a "ramp mass grave") is not physically destroyed to access the bodies laterally (the pedestal method) (41). It involves investigating, preserving, and documenting all material evidence (such as tire tracks from trucks and/or the bucket teeth of excavators) and not solely or exclusively the buried bodies.

The alternative to the stratigraphic method is the so-called pedestal method, where the focus of excavation is on the body pile (deposit). It involves the destruction of the burial features to gain access to the entire body deposit all at once. Some authors argue that in specific circumstances, the complexity of a mass grave inherently requires sacrificing the grave's walls to exhume the bodies (42).

However, maximizing the collection of evidence is crucial in investigations, and this is where the stratigraphic method significantly outperforms the pedestal method (41). Comparing these two excavation methodologies in two similarly formed mass graves from the same geographical area shows that the pedestal method results in disproportionately larger quantities of unconnected bones compared to the stratigraphic method (41). The stratigraphic method more faithfully reflects the original state of the archaeological record created during the formation of the grave. This method allows for determining the origin of unconnected fragmented findings, i.e., which individual the scattered skeletal elements and artifacts belong to (41). Additionally, stratigraphic excavation yields a higher representation of exhumed small bones. Scattered, fragmented, and unconnected skeletal elements, which are common in mass graves, significantly complicate the excavation process, quantification, and analysis of human remains.

Therefore, forensic archaeology involves the application of scientific excavation, observation, and analysis methods to discover, document, and interpret material evidence. Through ongoing critical evaluation, methods are adapted and modified to fit specific conditions and situations. New methods are developed for highly specific contexts, such as hybrid graves where bodies from different events are buried. The application of forensic archaeological methods and routine collection of information related to the context of skeletal findings have given rise to a new field called forensic taphonomy.

1.7 QUANTIFICATION OF COMMINGLED OSTEOLOGICAL MATERIAL

The most commonly applied method for quantifying any type of commingled osteological material is the estimation of the *minimum number of individuals* (MNI). The principles of this technique were defined by White (43). The MNI calculation relies on the most numerous identical bone segments or complete bones found in a mass grave taking into account distinctions in age (immature vs. adult, e.g. only the distal parts of the right femur or only the left tibia). The essence of the method is to determine that the analyzed fragments originate from different individuals. The fundamental principle of MNI estimation is to avoid counting the same person twice (44). MNI is calculated by first anatomically lateralizing the bones (grouping them by the side of the body – left or right), and then taking the largest number of the same complete bones or their parts as an estimate of the minimum number of buried individuals. This technique is precise if all bodies are buried intact, with all skeletal elements, but it provides a less accurate estimate if skeletal elements are only partially represented. The MNI method is particularly problematic in burials where the skeletons are extremely fragmented. A study has shown that the error in estimating MNI in secondary mass graves containing highly fragmented skeletal material is so significant that it does not actually provide any indication of the number of buried individuals (45).

The MNI technique can be somewhat improved statistically when using bones that are morphologically and metrically paired. In other words, when anthropological examination and analysis confirm that left and right skeletal elements belong to the same individual. This pairing (pair matching) is used in Lincoln's Index (LI) and in the estimation of the *most likely number of individuals* (MLNI). LI is designed to represent the original, primary number of individuals and is calculated using the formula LI = L*R/P, where L is the number of skeletal elements on the left side of the body, R is the number of skeletal elements on the right side of the body, and P is the number of paired elements (from both sides) from the same individual.

To assess possible sampling bias, Seber modified this formula in 1973. Adams and Konigsberg introduced it in 2004 as the estimated *most likely number of individuals* (MLNI)(46)(47). It is calculated using the formula: MLNI = [(L+1)(R+1)/(P+1)-1]. MLNI is more suitable for use in fragmented skeletal assemblages because the estimates become more precise when at least 50% of skeletal fragments are present, whereas MNI estimates remain low in such cases (48).

The most precise technique for determining the total number of individuals in a mass grave is DNA identification. This is an exact method and, unlike MNI/MLNI, represents the actual situation. Therefore, in forensic cases with mixed and fragmented remains, DNA identification is of special importance and is increasingly used (49)(50)(51). The application of human molecular genetics has influenced many fields, not only forensics but also medical science (52)(53), evolutionary biology (54), archaeology and anthropology (55) (56). In a mass grave the goal of DNA analysis is to identify unknown individuals and determine the total number of individuals. It is most commonly performed as an autosomal method, such as HLA typing (57)(58) or repeat loci (59), but can also be conducted as non-autosomal methods, including mitochondrial genome sequencing (60) and Y-chromosomal analysis (61). The current obstacle to the standard use of DNA identification in mass graves is the high cost associated with analyzing each sample. However, as technology continues to advance, it is expected that costs will decrease over time, making DNA identification more accessible for such applications.

1.8 FRAGMENTATION

The first attempts to measure the degree of fragmentation were made within the field of zooarchaeology. To characterize the degree of fragmentation, archaeologist Curtis Marean introduced the *completeness index* (CI), which is calculated based on the number of carpal and tarsal bones (62). The CI is obtained by adding up the numbers of all present accountable bones for each specimen of a particular species, and then this number is divided by the number of specimens. A lower CI indicates greater fragmentation that occurred after bone deposition (burial) (62). Calculating this index allows for distinguishing changes in bones due to diagenesis from those resulting from biostratigraphic factors.

Marean's Completeness Index is essentially an improvement over the earlier Klippel and Cruz-Uribe measures of fragmentation based on the NISP:MNI or NISP:MNE ratios (43). NISP stands for the *number of identified specimens*, MNI represents the *minimum number of individuals*, and MNE is the *minimum number of skeletal elements* needed for a sample. Lyman describes the NISP:MNI ratio as a measure of the "intensity of fragmentation" (63). This ratio helps assess the degree of fragmentation and can provide insights into the taphonomic processes that affected the assemblage of remains. The limitation of this method is that both MNI and MNE are derived values and never truly represent the actual condition of the sample (64) (45).

These values are estimations and are subject to some degree of uncertainty, as they are based on the available skeletal elements and the assumptions made during their calculation. Therefore, while they provide useful information, they should be interpreted with an awareness of their potential limitations.

Marean's Completeness Index and Klippel and Cruz-Uribe measures of fragmentation helps researchers assess the level of fragmentation and the taphonomic history of the remains in archaeological and paleontological contexts.

The quantification of human remains' fragmentation in a forensic context, such as a mass grave, can be achieved using the so-called *fragmentation index* (FI) (65). It is designed to quantify the degree of fragmentation of human remains primarily found in the context of secondary mass graves. This index assesses the level of fragmentation in human remains discovered in mass graves. It uses the following formula: $FI = B / (BP + GBP + B)$ (64), where B (body) represents the number of mostly (75%+) complete bodies, BP (body part) is the number of body parts (bones physically connected by non-decayed soft tissue but separated from the body), and GBP (general body part) stands for the number of individual bones completely detached from the body. FI is expressed on a scale from 0 to 1, where lower values indicate greater fragmentation.

The examination of mass graves arising from war conflicts revealed varying degrees of body fragmentation among secondary mass graves, despite sharing similar formative processes. The premise is that graves of the same age and formative context have the same level of fragmentation in human remains, assuming that perimortem circumstances are the same. Therefore, differences in the level of body fragmentation among mass graves with similar origins and taphonomic processes can suggest varying perimortem circumstances. Calculating the fragmentation index proves highly beneficial in these scenarios, as it quantifies the disparities among the graves. This helps identify additional factors in some graves that contribute to a higher level of fragmentation. Additionally, this index can also indicate whether mass graves have a primary or secondary origin.

Forensic experts, as well as legal authorities, raise numerous questions regarding excavated remains in mass graves. These questions include why some bones are missing, why they are damaged, fragmented, or modified in some way. Additionally, they seek to determine whether humans influenced any of these changes to the bones at the time of death or later. They also inquire about the duration the remains were at the site where they were found and whether there is evidence that might suggest the cause and manner of death. Therefore, the analysis of taphonomic processes is crucial because obtaining reliable answers to these and many other questions is not possible solely through a detailed analysis of the exhumed bones but also by examining the context of the findings and the nature of the environment from which the human remains were exhumed.

2. RESEARCH AIMS

Given that the fragmentation of human remains in mass graves is highly variable, there is a need to quantify it. Furthermore, a difference in fragmentation has been observed between primary and secondary mass graves, as expected, but the variability in fragmentation among secondary graves formed in the same manner is striking. Therefore, the specific objectives of this thesis are:

1. Calculating the fragmentation index (FI) for each analyzed mass grave and conducting an in-depth analysis of the distribution of varying fragmentation levels within the entire group of examined graves.
2. Investigating disparities in the degree of FI between primary and secondary graves.
3. Conducting a comparative analysis of the FI degree among secondary mass graves with similar chronologies and formation histories.
4. Determining and calculating the correlation between fragmentation index (FI) and the error in minimum number of individuals (MNI) estimation.

3. MATERIAL AND METHOD

3.1 MATERIAL

The study is based on data gathered from 13 mass graves, all stemming from the ex-Yugoslavia war. 12 mass graves were established in mid-1995 within the present-day territory of Republika Srpska in Bosnia and one from Srbija (Rudnica, 1999). The dissolution of the former Yugoslavia began in 1991 with the secession of the Republic of Slovenia, reaching its peak in Bosnia and Herzegovina from 1992 to 1995 (66).

Following the armed conflict in Bosnia, the International Criminal Tribunal for the former Yugoslavia (ICTY) initiated the excavation of mass grave sites, focusing predominantly on primary sites. Post-2000, the responsibility for the forensic process and DNA identifications transitioned to the Missing Persons Institute of Bosnia and Herzegovina (MPI) and the International Commission on Missing Persons (ICMP).

In the Srebrenica region of eastern Bosnia, numerous mass graves containing male Bosnian Muslim victims were discovered. The data extracted from these excavations were meticulously organized in databases at the Centre for Research of War, War Crimes, and Tracing of Missing Persons in Banja Luka, Republic of Srpska. These databases hold a wealth of information, including original forensic fieldwork reports detailing the number of bodies and body parts excavated from each specific grave, and these sites were included in our analysis.

The available ICTY reports on the few secondary mass graves excavated before 2001 did not align with the methodological standards introduced later in the ICMP forensic protocol for labeling human remains, so they are not included in this analysis. As a result, the present study focuses its analysis on 12 mass graves, consisting of two primary graves and ten secondary ones (refer to Figure 1). Additionally, we analyzed one secondary mass grave from Serbia, related also to the war preseeding the disintegration of Yugoslavia, with disposal of the bodies made in the similar manner as some of the secondary sites from Srebrenica event.

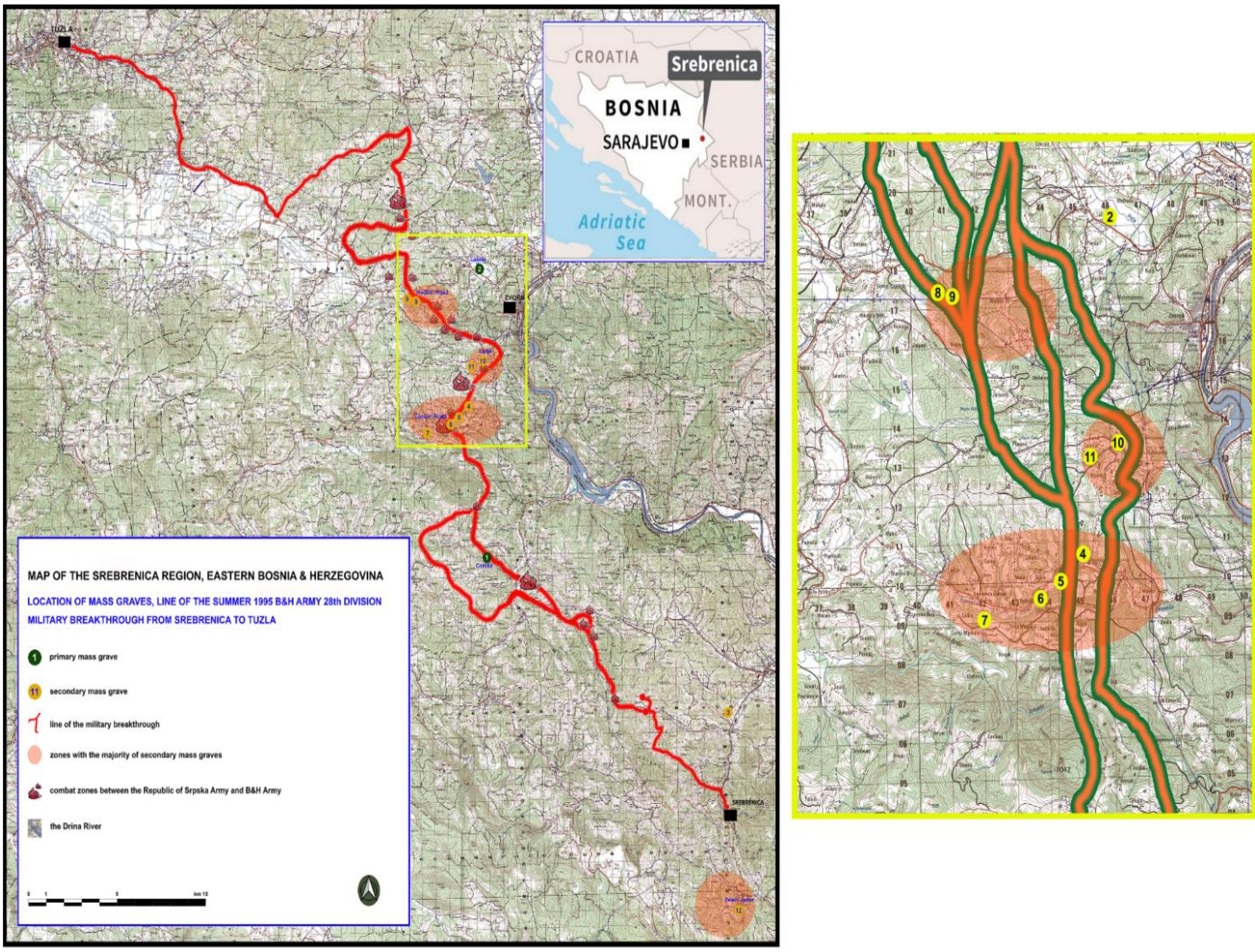

Figure 1: Hybrid map of the east Bosnian Drina River Region, showing the distribution of 12 analysed mass grave sites (detail: Cancari Road, Liplje and Hodzici Road mass graves – drawn and digitally processed by A. Starovic)

The detailed descriptions of the mass grave sites included in the study are provided in the following list and the Table 1:

1. **Cerska (CSK)** (67): Located in the village of Cerska, Vlasenica municipality, eastern Bosnia, this site contained 168 cases of human remains, with 154 "B" (Body), 14 "BP" (Body Part), and 0 "GBP" (General Body Part) cases. Forensic analysis by W. Haglund concluded that this mass grave was primary and undisturbed.

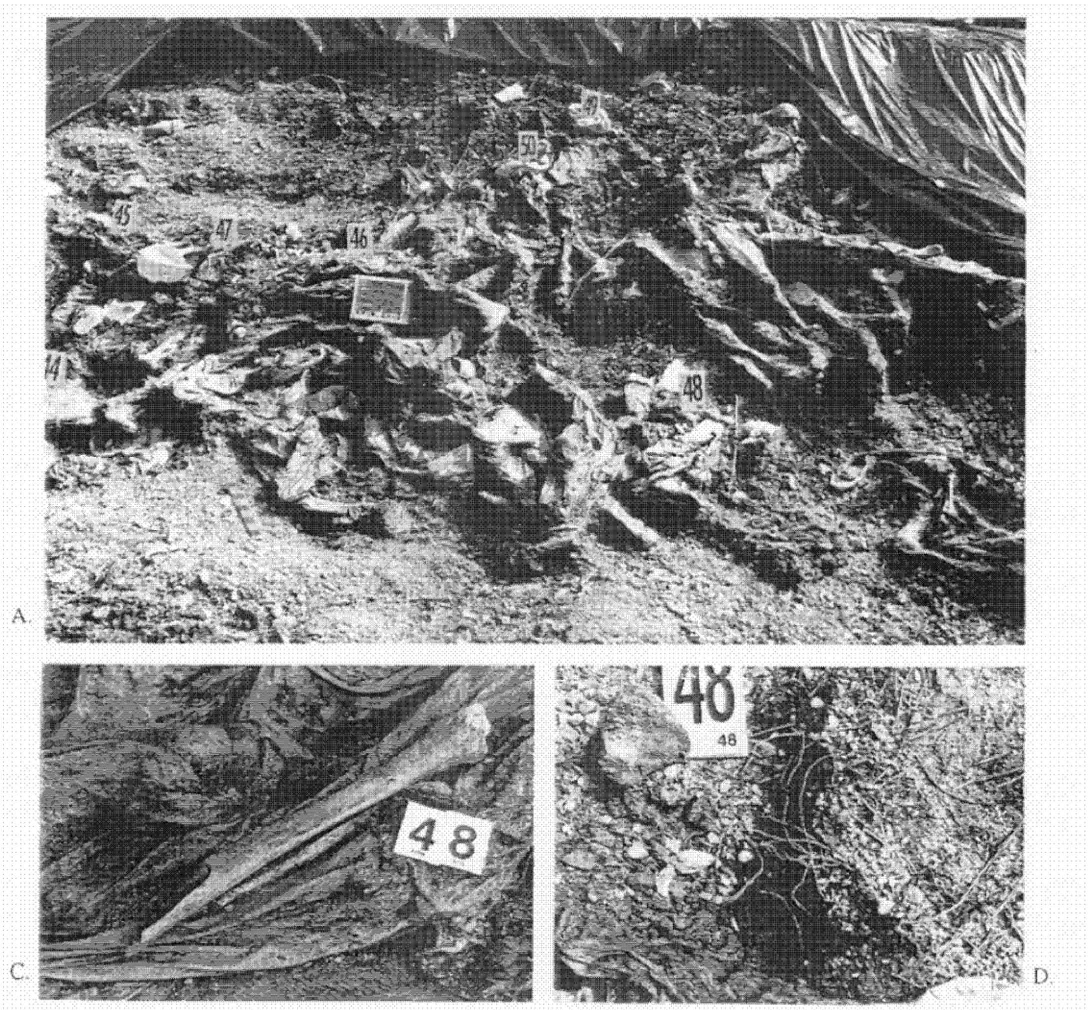

Figure 2. Primary mass grave Cerska , overview of deposit, from the forensic investigation of the Cerska grave site report by Haglund W. (67).

2. **Lazete 01 (LZ01)** (68): Situated in the village of Gušteri, Zvornik municipality, eastern Bosnia, this grave held 143 cases of human remains, including 129 "B", 14 "BP", and 0 "GBP". Like CSK, this mass grave was primarily undisturbed but had some signs of disturbance, such as robbing.

Figure 3. Primary mass grave Lazete 01, overview of deposit, from the excavation and exhumation report Lazete 1 by Peccerelli F. (68).

3. **Budak 01 (SR-BUD-01)** (69): Located in the village of Dugo Polje, Srebrenica municipality, eastern Bosnia, this grave contained 269 cases of human remains, including 21 "B", 157 "BP", and 91 "GBP". According to the ICMP report, this was a secondary mass grave.

Figure 4. Secondary mass grave Budak 01, overview of the deposits, from the ICMP summary report on the archaeological findings relating to the excavation of Budak 01 (69).

4. **Cancari Road 04 (KAM04ZVO)** (70): Situated in the village of Gornja Kamenica, Zvornik municipality, eastern Bosnia, this mass grave contained 393 cases of human remains, with 145 "B", 218 "BP", and 30 "GBP". According to the related ICMP report, this was a secondary mass grave.

Figure 5. Secondary mass grave Cancari Road 04, overview of layer of human remains, from the ICMP summary report on Cancari Road 04 (70)

5. **Cancari Road 06 (KAM06ZVO)** (71): Also located in Gornja Kamenica, Zvornik municipality, this grave contained 1133 cases of human remains, including 29 "B", 854 "BP", and 250 "GBP". According to the relevant report, this was a secondary mass grave.

Figure 6: Secondary mass grave Cancari Road 06, overview of layer of human remains, from the ICMP summary report on Cancari Road 06 (71).

6. **Cancari Road 08 (KAM08ZVO)** (72): In the same village, this mass grave contained 340 cases of human remains, with 22 "B", 318 "BP", and 0 "GBP". According to the related report, this was a secondary mass grave.

Figure 7: Secondary mass grave Cancari Road 08, overview of layer of human remains, from the ICMP summary report on Cancari Road 08 (72).

7. **Cancari Road 10 (KAM10ZVO)** (73): Also situated in Gornja Kamenica, this grave contained 1344 cases of human remains, with 146 "B", 1012 "BP", and 186 "GBP". According to the related report, this was a secondary mass grave.

Figure 8: Secondary mass grave Cancari Road 10, overview of layer of human remains, from the ICMP summary report on Cancari Road 10 (73).

8. **Hodzici Road 01 (SNA04ZVO)** (74): Located in the village of Snagovo, Zvornik municipality, this mass grave was represented by 156 cases of human remains, including 92 "B", 64 "BP", and 0 "GBP". According to ICMP field team experts, this was a secondary mass grave.

Figure 9: Secondary mass grave Hodzici Road 01, overview of almost emptied grave, from the ICMP summary report on Snagovo 04 (74).

9. **Hodzici Road 02 (SNA03ZVO)** (75): Also in Snagovo, this grave contained 160 cases of human remains, including 95 "B", and 65 "BP", and 0 "GBP". It was classified by investigators as a secondary mass grave.

Figure 10: Secondary mass grave Hodzici Road 02, overview of grave outline, from the ICMP summary report on Hodzici Road 02 (75).

10. **Liplje 02 (ZV.LIP-02)** (76): Located in Snagovo, this mass grave contained 192 cases of human remains, with 4 "B", and 188 "BP", and 0 "GBP". Forensic pathologist C.H. Lawrence characterized this grave as secondary, and R. Wright confirmed this assessment (77).

Figure 11: Liplje 02 secondary mass grave deposit, from the report on exhumations in Eastern Bosnia in 1998 by Wright, R. (77).

11. **Liplje 07 (ZV.LIP-07)** (78): Situated in Snagovo, this grave contained 681 cases of human remains, including 7 "B", 472 "BP", and 202 "GBP". According to ICMP experts, this was a secondary mass grave.

Figure 12: Close up on Liplje 07 secondary mass grave deposit, from the ICMP summary report on Liplje 07 (74).

12. **Zeleni Jadar 04 (ZJA08)** (79): Located in the village of Zeleni Jadar, Srebrenica municipality, this grave contained 226 cases of human remains, with 33 "B", 193 "BP", and 0 "GBP". According to the relevant report, this was a secondary mass grave.

Figure 13: Beginning of the excavation on Zeleni Jadar 04 secondary mass grave site, from the ICMP summary report on Zeleni Jadar 04 (79).

13. **Rudnica (RUDN I)** (80)**:** Located near town of Raška in soutern Serbia. This grave contained 158 cases of human remains, with 45 "B", 88 "BP, and 25 "GBP". According to the relevant report, this was a secondary mass grave.

Figure 14: First layer of human remains on Rudnica secondary mass grave site, from the unpablished report to the higher court in Belgrade (80).

Table 1. Information regarding the structural details of human remains within the studied mass grave sites.

site no.	SITE NAME	SITE CODE	TOTAL CASES	B	BP	GBP	GRAVE TYPE
1	Cerska	CSK	168	154	14	0	Primary
2	Lazete 01	LZ01	143	129	14	0	Primary
3	Budak 01	SR-BUD-01	269	21	157	91	Secondary
4	Cancari Road 04	KAM04ZVO	393	145	218	30	Secondary
5	Cancari Road 06	KAM06ZVO	1133	29	854	250	Secondary
6	Cancari Road 08	KAM08ZVO	340	22	318	0	Secondary
7	Cancari Road 10	KAM10ZVO	1344	146	1012	186	Secondary
8	Hodzici Road 01	SNA04ZVO	156	92	64	0	Secondary
9	Hodzici Road 02	SNA03ZVO	160	95	65	0	Secondary
10	Liplje 02	LP-02	192	4	188	0	Secondary
11	Liplje 07	LP-07	681	7	472	202	Secondary
12	Zeleni Jadar 04	ZJA08	226	33	193	0	Secondary
13	Rudnica	RUDN I	158	45	88	25	Secondary

In all surveyed cities, comprehensive data concerning the number of bodies (B), body parts (BP), and general body parts (GBP) were meticulously recorded. Author of this thesis, as forensic archaeologist, participated in excavation of all secondary sites used in this study.

However, data about MNI were available only for five specific sites (SNA04ZVO, KAM04ZVO, KAM06ZV, KAM08ZVO, KAM10ZVO) and these sites were used for calculating MNI error and correlation between FI and MNI estimation error, which is specified in the fourth goal of this study.

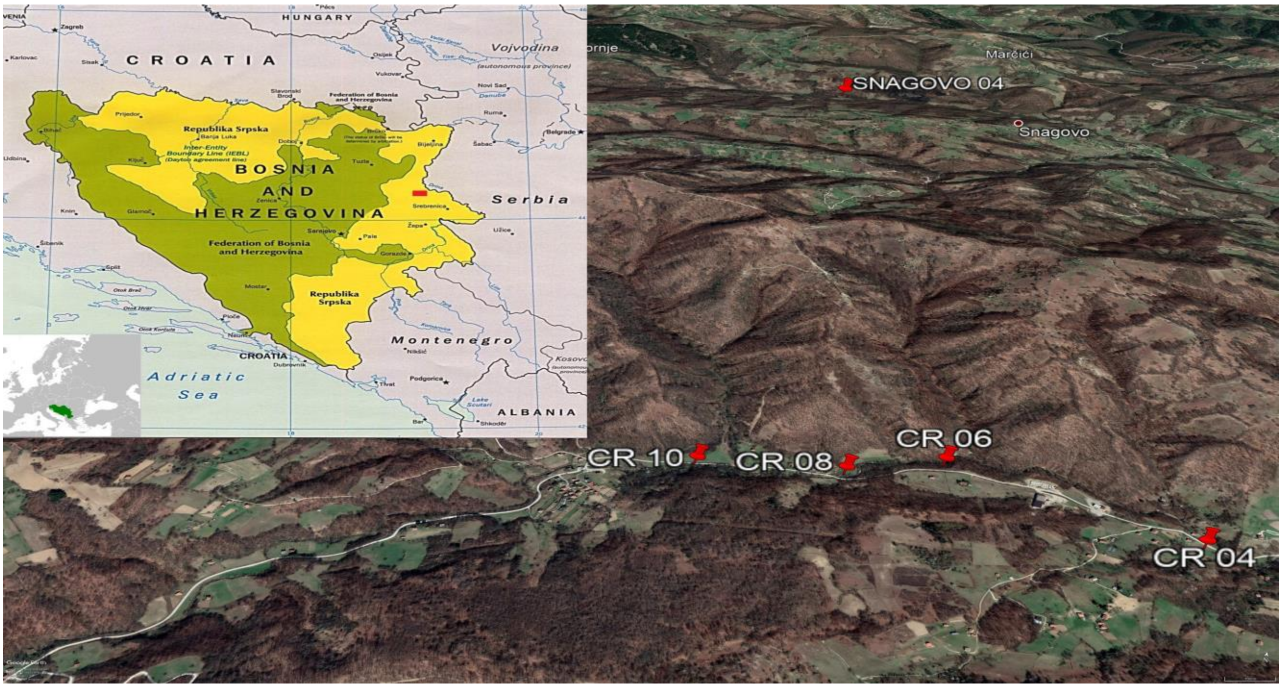

Figure 15. Small portion of south-east part of Bosnia and Hercegovina (BiH) with marked mass grave sites. Embedded map represent position of BiH within former Yugoslavia (mass graves marked with red rectangle) and position of former Yugoslavia within Europe.

The DNA data needed for calculating MNI error is sourced from the International Commission on Missing Persons (ICMP) public database (81), while the MNI data were gathered during the mass graves excavation process conducted by the ICMP, which also included the author of this study. These excavation reports are available at the Republic of Srpska Center for the Research of War, War Crimes, and the Search for Missing Persons.

Summary of the data related to sites involved in the study:

1. **Hodzici Road 01 (SNA04ZVO)** (74)
    - Total cases of human remains: 156
    - Breakdown: 92 complete bodies (B), 64 body parts (BP), 0 general body parts (GBP)
    - MNI: 104 (based on the presence of the distal third of the right tibia)
    - DNA profiling results: 88 new identities, 72 re-associations
    - Total different individuals represented in the grave: 160

2. **Cancari Road 08 (KAM08ZVO)** (72)
    - Total cases of human remains: 340
    - Breakdown: 22 complete bodies (B), 318 body parts (BP), 0 general body parts (GBP)
    - MNI: 84 (based on the left tibia)
    - DNA profiling results: 50 new identities, 273 re-associations
    - Total different individuals represented in the grave: 323

3. **Cancari Road 04 (KAM04ZVO)** (70)
    - Total cases of human remains: 393
    - Breakdown: 145 complete bodies (B), 218 body parts (BP), 30 general body parts (GBP)
    - MNI: 189 (based on complete right femora)
    - DNA profiling results: 183 new identities, 236 re-associations
    - Total different individuals represented in the grave: 419

4. **Cancari Road 06 (KAM06ZVO)** (71)
    - Total cases of human remains: 1133
    - Breakdown: 29 complete bodies (B), 854 body parts (BP), 250 general body parts (GBP)
    - MNI: 203 (based on the presence of the right tibia)
    - DNA profiling results: 182 new identities, 1063 re-associations
    - Total different individuals represented in the grave: 1245

5. **Cancari Road 10 (KAM10ZVO)** (73)
    - Total cases of human remains: 1344
    - Breakdown: 146 complete bodies (B), 1012 body parts (BP), 186 general body parts (GBP)
    - MNI: 368 (based on two-thirds or more of the right femur)
    - Total different individuals represented in the grave: 1152 (378 new identities + 774 re-associations)

DNA identifications of "new identities" pertain to cases of missing individuals who were identified for the first time in a specific mass grave. DNA "reassociation" refers to cases involving individuals whose other body parts, typically designated as BP or GBP, had previously been discovered in other graves.

The distinction between new DNA identities and DNA reassociations is important. New DNA identities typically pertain to largely complete bodies excavated from a specific grave, while DNA reassociations are often related to smaller body parts, such as lower arms or feet, found in different graves than the majority of the skeleton. Therefore, the sum of reassociations from all the mentioned graves does not equate to the sum of people buried because a single individual may be represented by multiple reassociated body parts from different mass graves.

Total DNA-based identifications encompass the combined total of new identities and reassociations. This figure provides insight into the number of different individuals represented in a given grave.

Table 2. The overview of the sites, the types of remains found, MNI calculations, and the results of DNA profiling in terms of new identities and re-associations.

Site	Hodzici Road 01 (SNA04ZVO)	C.ancari Road 08 (KAM08ZVO)	Cancari Road 04 (KAM04ZVO)	Cancari Road 06 (KAM06ZVO)	Cancari Road 10 (KAM10ZVO)
Total cases of human remains	156	340	393	1133	1344
B (Bodies)	92	22	145	29	146
BP (Body Parts)	64	318	218	854	1012
GBP (General BP)	0	0	30	250	186
DNA new identities	88	50	183	182	378
DNA reassociations	72	273	236	1063	774
TotalDNA-new ident.+reassociations	**160**	**323**	**419**	**1245**	**1152**
MNI	**104**	**84**	**189**	**203**	**368**

3.2 METHOD

Fragmentation index (FI) measures the proportion between mostly complete bodies (comprising trunk with attached heads and limbs) and dismembered body parts (including isolated heads, limbs, hands, feet, and partial trunks). This index illustrates the ratio of almost intact bodies identified at a specific mass burial site to the sum of individual body parts. The FI utilized in this study is a slight adaptation of the bodies-to-body-parts index developed by Vaduveskovic and Djuric (45).

In the context of forensic archaeology protocols (82) (83) (84), human remains are categorized in the fieldwork using specific case numbers. "B" is used to denote a complete corpse, which typically constitutes at least 75% of the body. "BP" is employed for all recovered parts of human corpses representing upper body parts, lower body parts, and other articulated remains of a single individual. "GBP" is the term assigned to isolated smaller body parts, such as individual bones, that are not found in situ with any other remains in their immediate vicinity. It's important to note that all the examined sites contained small amounts of very small bone fragments or isolated bones that were discovered disarticulated and out of depositional context. These small fragments were collected separately and are not categorized as GBP in this study.

The fragmentation index (FI) is computed by dividing the number of complete bodies by the sum of disarticulated and isolated elements from the same context plus complete bodies:

$$Frag.Index\ (FI) = \frac{B}{BP + GBP + B}$$

A smaller FI value indicates a higher degree of fragmentation and disarticulation among body elements. Mass graves that exclusively contain either complete bodies or only body parts are self-explanatory, so there's no need to calculate a FI for them.

These calculations were carried out for two primary burial sites where bodies were largely intact and for 10 secondary burial sites where fragmentation was more prevalent. The results were organized into tables, and the characteristics of the analyzed sites were examined.

Since fragmentation of the bodies could also occur perimortem we reviewed the existing databases and examined the official death certificates for all the individuals identified in these 12 mass graves, in order to obtain information related to injuries caused by explosive and heavy weapons as potential causes of death. This examination aimed to investigate whether blast injuries could have contributed to the fragmentation of bodies before they were buried.

The methodology for Objective 4 involves a comparison between MNI estimations derived from the initial excavations and the verified number of individuals interred in specific graves, determined through DNA identification of exhumed remains. The aim of this objective is to investigate how the complexity of a mass grave influences the precision of MNI estimation. The complexity of mass graves is quantified by the Fragmentation Index (FI) value for the respective sites.

The DNA identification was conducted by the ICMP, and general information regarding reassociations and identification numbers, organized by excavation location names, is publicly accessible on the ICMP website (81). This identification process relies on comparing blood samples from the family members of missing persons with DNA profiles extracted from bone samples recovered from the mass graves (85).

To investigate how mass grave complexity impacts the estimation of the MNI, we need to calculate MNI error first. This involves comparing the MNI estimation for a particular site made at the time of excavation with the total DNA profiles for the same site obtained at a later date. DNA profiles serve as a reference representing the actual number of individuals buried. The error in the MNI estimation will be calculated according to the following formula: MNI error = (MNI – DNA number) / DNA number (%).

We examine the correlation of the obtained MNI error with the FI values for the given sites, in order to examine the relationship between the MNI error and the degree of fragmentation of the skeletal remains. FI values and MNI error are displayed descriptively as mean ± standard deviation or median (min–max) depending on the normality of data distribution (Kolmogorov-Smirnov test). The difference in FI between primary and secondary graves is examined with statistical test to assess the significance of two independent samples: correlation between MNI error and FI is examined using Pearson's correlation. A P value of less than 0.05 will be considered statistically significant. The EZR (Easy R) and Origin 8.5 program are used for statistical analysis

4. RESULTS

To analyze the ratio of almost intact bodies identified at a specific mass burial site to the sum of individual body parts we computed body fragmentation indexes (FI) for the investigated sites. The results are presented in Table 3.

Table 3. Summary data of investigated mass grave sites: number of collected bodies, body parts, general body parts, and calculated FI values.

SITE NO.	SITE NAME	SITE CODE	TOTAL CASES	B	BP	GBP	FRAGMENTATION INDEX (FI)	GRAVE TYPE
1	**Cerska**	**CSK**	**168**	**154**	**14**	**0**	**0.92**	**Primary**
2	**Lazete 01**	**LZ01**	**143**	**129**	**14**	**0**	**0.90**	**Primary**
3	Budak 01	SR-BUD-01	269	21	157	91	0.08	Secondary
4	Cancari Road 04	KAM04ZVO	393	145	218	30	0.37	Secondary
5	Cancari Road 06	KAM06ZVO	1133	29	854	250	0.03	Secondary
6	Cancari Road 08	KAM08ZVO	340	22	318	0	0.06	Secondary
7	Cancari Road 10	KAM10ZVO	1344	146	1012	186	0.11	Secondary
8	Hodzici Road 01	SNA04ZVO	156	92	64	0	0.59	Secondary
9	Hodzici Road 02	SNA03ZVO	160	95	65	0	0.59	Secondary
10	Liplje 02	LP-02	192	4	188	0	0.02	Secondary
11	Liplje 07	LP-07	681	7	472	202	0.01	Secondary
12	Zeleni Jadar 04	ZJA08	226	33	193	0	0.15	Secondary
13	Rudnica	RUDN I	158	45	88	25	0,29	Secondary

The body fragmentation index (FI) values across both primary and secondary sites varied between 0.01 and 0.92. Notably, the most extensive fragmentation was observed at the Liplje 7 secondary site, whereas the least fragmentation occurred at the Cerska primary grave. Rudnica, the only site from Serbia, scored 0.29 FI, close to Cancari Road 04.

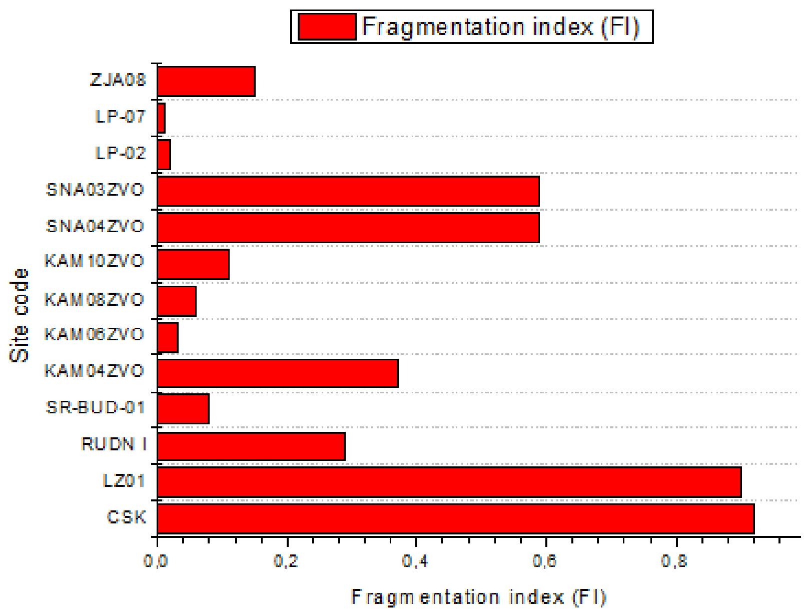

Figure 16: Fragmentation index (FI) values indicate the degree of fragmentation for both primary and secondary sites in the series.

Notably, primary sites exhibit the highest FI values, reflecting their lower level of fragmentation compared to secondary sites.

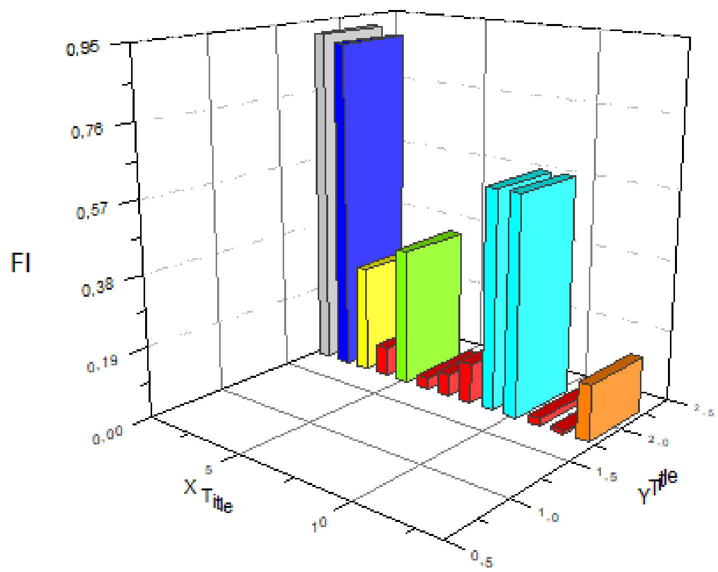

Figure 17: 3D color chart illustrating the grouping of both primary and secondary sites based on the level of fragmentation.

Each site on Figure 17 is depicted as a data point on the chart, with its color indicating its level of fragmentation. Sites with similar levels of fragmentation are grouped together and represented by similar colors, allowing for easy visual identification of clusters or patterns within the data. The red color represents sites with highest fragmentation (FI below

0.12: Liplje 07, Liplje 02, Cancari Road 06, Cancari Road 08, Cancari Road 10 and Budak 01). Zeleni Jadar 04 (brown color), with 0.15 FI is closer to this group than to the mid range secondary sites.

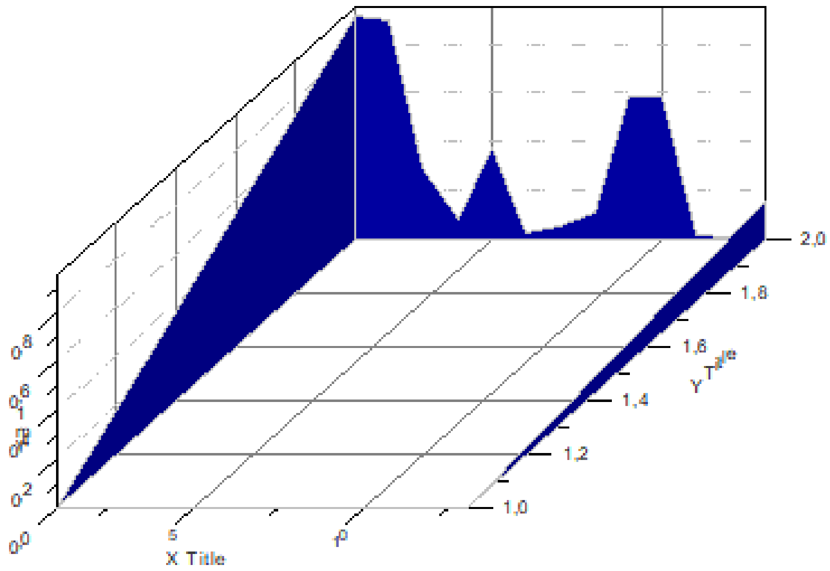

Figure 18: The distribution of fragmentation index (FI) values for both primary and secondary sites.

Three distinct groups can be identified in Figure 18. Sites exhibiting the highest levels of fragmentation (below 0.15) are predominantly clustered on the right side of the figure. In contrast, primary sites are concentrated on the left side, representing the opposite extreme in terms of fragmentation index (FI) values (0.90 and 0.92 for Lazete and Cerska). Positioned along the x-axis, the third group falls between the previous two, depicting secondary sites with significantly higher FI values compared to the first group of secondary sites on the right. Thise sites are Rudnica, Cancari Road 04, Hodzici Road 01 and Hodzici Road 02.

When focusing on secondary sites, the variation was slightly narrower, ranging from 0.01 to 0.59 (illustrated in Figure 19). A statistical summary of the FI values for secondary sites, as computed by Easy R software, provides the following results: Minimum: 0.01, 1st Quartile: 0.045, Median: 0.11, Mean: 0.2090909, 3rd Quartile: 0.33, Maximum: 0.59 with standard deviation of 0.2196112.

The data clearly shows that the secondary mass graves in this study can be grouped into two distinct categories (as depicted in Figure 20). Five sites exhibit FI values between 0.01 and 0.08, while the remaining sites have FI values scattered between 0.10 and 0.59. A secondary mass grave with a higher FI value indicates a greater presence of preserved (complete) bodies. The threshold value for FI in secondary graves with a more complete body profile is determined by the dataset's mean value, which is 0.21 (FI values exceeding 0.21 represent graves with more preserved bodies). In contrast, clusters of graves where most remains were highly fragmented exhibit FI index values lower than 0.11 (0.11 serves as the threshold value for highly fragmented bodies and is determined by the median value of the dataset).

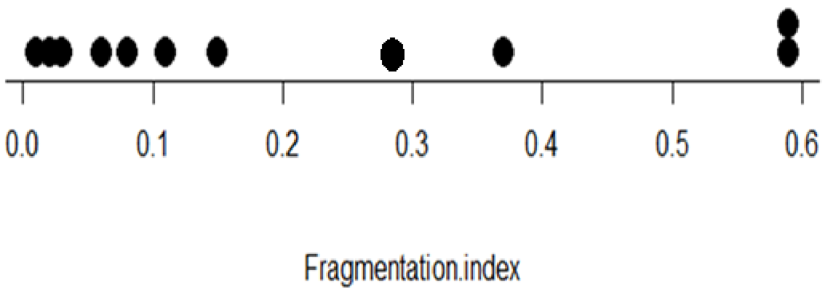

Figure 19: The dot plot illustrates the distribution of fragmentation index (FI) values for secondary mass grave sites.

Each dot on the plot of Figure 19 represents an individual secondary site, positioned along the y-axis based on its FI value. By visually inspecting the dot plot, patterns and trends in the distribution of FI values among secondary sites can be easily identified.

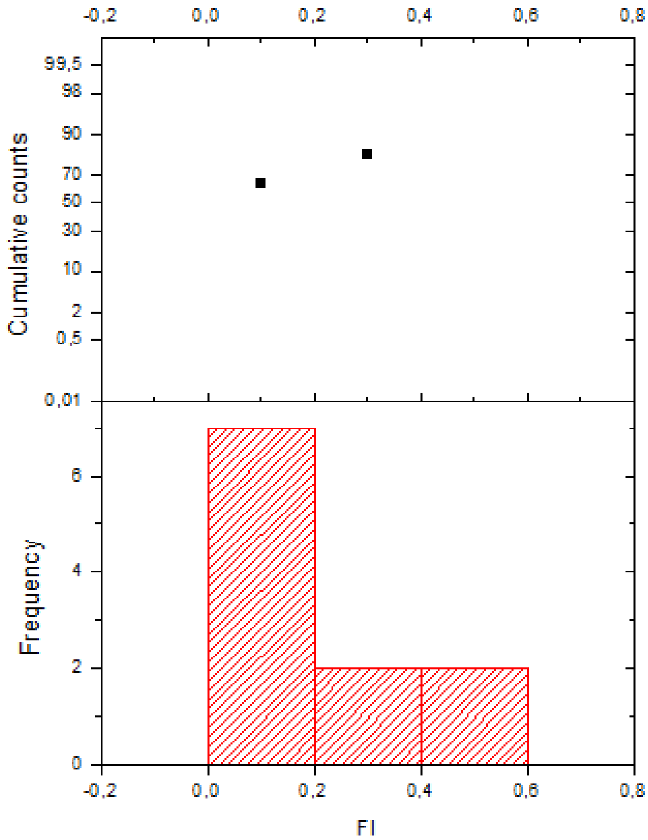

Figure 20: The histogram illustrates the grouping of fragmentation index (FI) frequencies of secondary sites into two distinct groups, represented by cumulative counts.

In the lower section of the histogram (Figure 20), secondary sites are categorized based on their FI values, with each bar representing the cumulative count of sites falling within a specific FI range. The histogram reveals a clear separation between two distinct groups of secondary sites, characterized by different average FI values. This distinct grouping aids in identifying and distinguishing between subsets of secondary sites with varying levels of fragmentation which imposes questions about the circumstances that lead to such a difference among the sites created in a similar manner.

Calculated MNI error and the FI values for the investigated sites (results for objective 4) are provided in Table 4.

Table 4. Summary table of MNI error and Fragmentation index in investigaed sites

Site (SITE CODE)	Hodzici Road 01 (SNA04ZVO)	C.ancari Road 08 (KAM08ZVO)	Cancari Road 04 (KAM04ZVO)	Cancari Road 06 (KAM06ZVO)	Cancari Road 10 (KAM10ZVO)
MNI error	**-0.35**	**-0.74**	**-0.55**	**-0.84**	**-0.68**
Fragmentation Index (FI)	**0.59**	**0.06**	**0.37**	**0.03**	**0.11**

To illustrate discrepancy between estimated minimum number of individuals (MNI) and the real number of individuals (identified by DNA) we calculated MNI error. The MNI error values range from -0.35 to -0.84. The negative sign indicates that the MNI underestimates the real number of individuals represented in the grave. Multiplying these values by 100 allows us to express the percentage deviation.

To assess the possible cause of this inaccuracy in MNI estimation, a correlation analysis was conducted. The MNI error for each site were correlated with the FI for each site respectively. Normality of the distribution is tested using the Shapiro-Wilk test, revealing normal distribution for MNI error ($p = 0.82222$) and FI ($p = 0.22661$). The Pearson's correlation coefficient was calculated as -0.979 with a 95% confidence interval ranging from -0.999--0.705, and a p-value of 0.00376. This indicates a significant negative correlation, where MNI error increases as FI decreases.

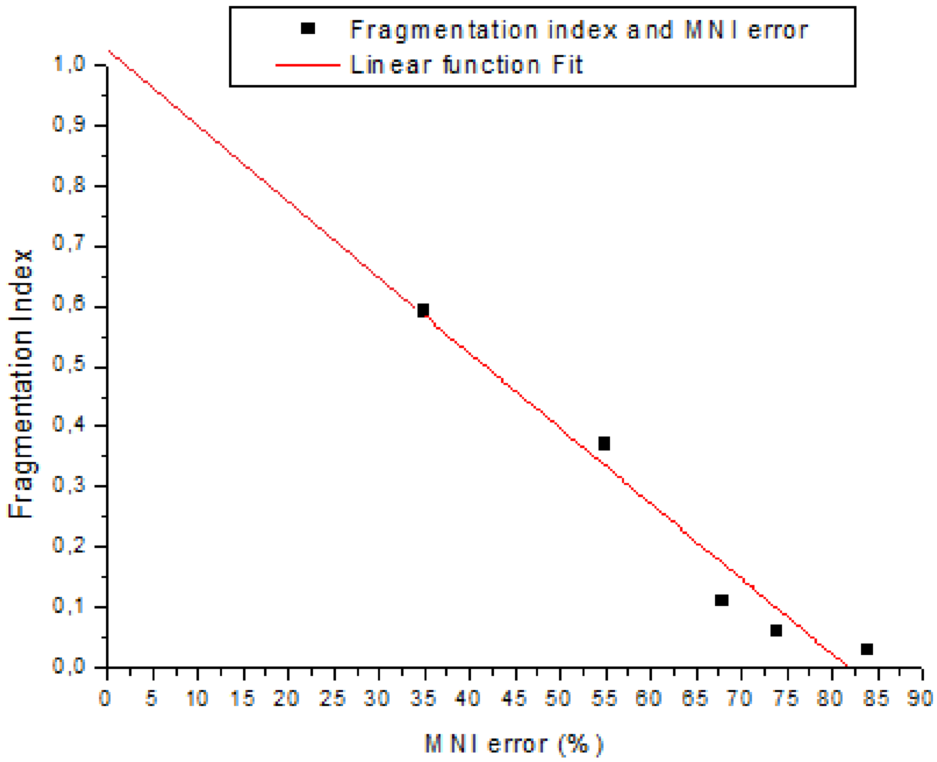

Figure 21: Linear function of FI and MNI error

In Figure 21, the extrapolated line of linear correlation intersects the FI axis little above maximal theorethical value for FI which is 1, simultaneously suggesting a 0% MNI error on the other axis. The slight deviation in the function on the high end of the fragmentation index (FI) distribution, approximately 1.05 compared to the expected value of 1, suggests a minor offset in prediction accuracy. Highest point on the graph (SNA04ZVO site with FI=0.59), reveals the lowest fragmentation of this data set associated with a -35% MNI error. Furthermore, at the other end of the line of correlation, where it intersects the MNI error axis at around -82%, the prediction falls just a little away from the actual data (-84% for KAM06ZVO site), indicating somewhat good predictive accuracy.

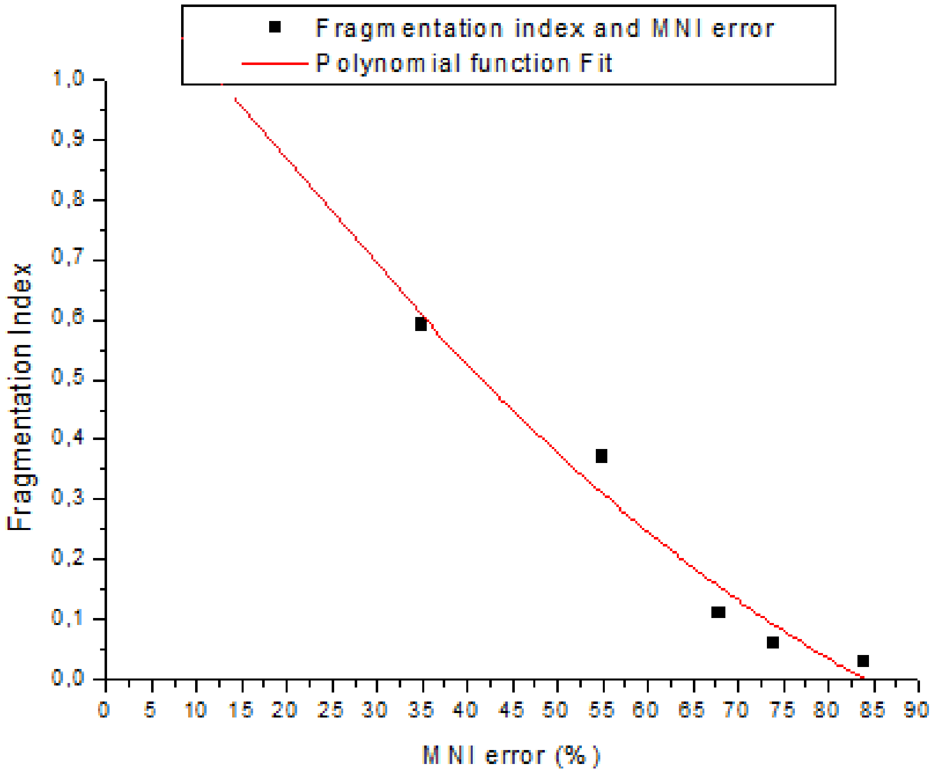

Figure 22: Polynomial function of FI and MNI error.

In Figure 22, the extrapolated line of polynomial function intersects the FI axis way above 1, simultaneously suggesting a 0% MNI error on the other axis. This huge over the top value for fitted function suggest no prediction value for the top end of FI values. At the other end of the line of correlation, where it intersects the MNI error axis at around -84%, matches the actual data (-84% for KAM06ZVO), indicating excellent predictive accuracy.

For the purpose of calibrating MNI estimation for prediction accuracy, the Polynomial function demonstrates greater suitability for lower values of FI. Conversely, the Linear function performs well with higher values of FI and maintains decent accuracy even in the lower end of the FI distribution. Despite the Polynomial function's precision in the lower end of the FI distribution, the Linear function emerges as the superior overall predictor due to its effective performance across the entire spectrum of FI values.

5. DISCUSSION

The extensive fragmentation of an excavated group of skeletons often results from human activities, including the manipulation of human remains postmortem (86) (e.g., moving graves with heavy machinery) or perimortem activities (e.g., the use of explosives, or other heavy weapons/tools can lead to dismemberment) (87) (88) (65).

Different circumstances of postmortem bone damage lead to varying degrees of fragmentation, particularly the manner in which bodies are deposited (40). Therefore, quantifying fragmentation is essential for drawing conclusions about the taphonomic processes that have led to the current state of the archaeological and anthropological record. Additionally, animal activity can contribute to increased fragmentation (89).

High fragmentation of bodies makes excavation of secondary mass graves a complex process as disarticulated and commingled body parts make it difficult to recognize separated body parts. The application of a stratigraphic, unit-based method is needed during the recovery process in order to significantly reduce the level of additional disarticulation of bodies during the exhumation (90).

Nonetheless, despite the meticulous application of archaeological methods, some secondary graves exhibit an unusually high degree of body disarticulation and the dispersion of body parts. In order to investigate this phenomenon, we examined a group of secondary mass graves from Bosnia to determine whether the taphonomic processes exclusively influenced the graves that share similar characteristics and histories. These characteristics include:

- Geographic proximity
- Nearly simultaneous creation
- Similar sizes and shapes (access-ramp-mass graves)
- The utilization of heavy machinery for the excavation and looting of primary graves shortly after the initial burials
- Swift excavation and backfilling with bodies and soil
- Employment of consistent archaeological methods (stratigraphic approach) and protocols during excavation and exhumation.

Based on these similarities, one might anticipate a consistent level of body fragmentation in the examined sites. Surprisingly, the results of this study have revealed notable distinctions among the graves. Firstly, the FI values clearly distinguish between the primary mass burial sites and the secondary graves. As indicated in Table 3, primary sites like Cerska and Lazete 01, with FI of 0.92 and 0.90, exhibit considerably lower fragmentation than the nearest secondary sites with a value of 0.59 (Hodzici Road 01 and 02). This distinction is anticipated since undisturbed primary burial sites should not demonstrate the same level of body disruption as secondary mass graves. The varied formation processes and manipulation of bodies account for this difference. Secondary graves, especially those from the Bosnian war, were predominantly created by extracting bodies from primary sites using heavy machinery and subsequently relocating them to other locations. This process resulted in body fragmentation, indicating a higher degree of disarticulation compared to bodies from primary sites.

Nonetheless, the secondary graves in the study exhibit two distinct groups (as seen in Figure 20), and one of them (comprising Liplje 07 and 02, Cancari Road 06 and 08, along with Budak 01) displays an exceedingly high degree of disarticulation, fragmentation, and scattering of body parts. Cancari Road 06, with its 1,133 cases, represents one of the largest unique assemblages in the region. The other group (encompassing Cancari Road 10 and Zeleni Jadar 04, followed by Cancari Road 04 – all with "middle range" values, up to Hodzici Road 01 and 02, with notably high FI values, shows considerably less overall disarticulation of bodies, despite their similar history.

Considering that similar taphonomic processes occurred during the formation of secondary sites in eastern Bosnia, significant differences in body fragmentation among certain graves should be attributed to additional circumstances and factors. These differences could arise from peri-mortem or post-mortem injuries that occurred before the final inhumation. Explosive weapons, like grenades, mortars, tank fire, and minefields, have the potential to cause blast injuries leading to the dismemberment of bodies. In such cases, bodies would initially be fragmented, and subsequent fragmentation could result from taphonomic processes. The disruption and fragmentation of bodies during explosions stem from a variety of mechanisms, including the primary effects of the blast wave, damage from shrapnel, secondary debris impacting the body, the body being propelled into fixed objects, as well as crush injuries and burns (91) (92).

A thorough analysis of pathological reports from these sites and reviewed certificates of death for the individuals identified and buried in these mass graves reviled that in most cases, the cause of death was not definitively determined. While some were believed to have died from gunshot injuries, many others, particularly from the Cancari Road, Hodzici Road, Zeleni Jadar, and Liplje sites, were listed as having died due to injuries from "explosive or likely explosive weapons."

The analysis of the cause of death cited in the Excel database produced by the Podrinje Identification Project (PIP) in 2015 revealed that in 301 cases, wounds from explosive weapons were mentioned as a possible cause of death. The highest concentration of individuals with explosive wounds was found in secondary grave sites along Cancari Road, totaling 122, followed by Liplje with 29 individuals. These graves, along with the 57 individuals found as surface remains, follow the spatial pattern of the breakthrough line and combat areas, suggesting that these individuals likely died in a combat situation.

The analysis of ICTY trial transcripts revealed significant discrepancies regarding the manner of death in the Srebrenica massacre (87). Review of the autopsy reports presented on the trials (88) highlighted that approximately 150 cases had the presence of burst-out bone injuries indicating injuries consistent with those caused by heavy weapon, rather than conventional execution methods. The extent of bone damage and fragmentation suggested a projectile impact more like that of the Praga or similar weapons, rather than an ordinary bullet (87). Shrapnel fragments were discovered in the remains of 477 victims, further indicating that the cause of death may have been related to combat situations rather than deliberate executions (87).

These findings strongly suggest that not all victims of the Srebrenica massacre were executed in a manner commonly perceived. Instead, there is evidence to suggest that some may have been casualties of legitimate combat, particularly those associated with the retreating 28th Division column of the Bosnian Muslim army. This underscores the complexity of the events surrounding the Srebrenica massacre and the need for careful analysis of forensic evidence in understanding the true nature of the casualties.

Based on this information, it can be inferred that at least some of the individuals interred in these secondary sites may have been killed in combat. Determining the exact cause of death was challenging due to the advanced state of decomposition and the absence of soft tissues, which presents a significant limitation in the forensic pathology evidence for such cases (93). Assessing whether bone damage occurred peri-mortem or post-primary burial was also a difficult task. Consequently, the common scenario that all these individuals were victims of mass execution cannot be definitively supported by forensic evidence given the condition of the remains.

A spatial analysis of the distribution of secondary mass graves revealed four major clusters: 1) alongside the local asphalt road near the area known as Zeleni Jadar to the south of Srebrenica, 2) between the villages of Snagovo and Hodzici to the west of Zvornik, 3) in Liplje, south of Zvornik, and 4) near the local road leading to the village of Cancari in the Kamenica valley. The total number of graves in these four areas exceeded 30, with an estimated minimum number of individuals (MNI) surpassing 3,800. The generally accepted interpretation (94), supported by DNA connections between body parts found in different graves, is that all these graves held the remains of victims who were executed by gunfire at five primary execution sites: Kravica, Branjevo, Kozluk, Orahovac, and Petkovci.

Upon closer examination (refer to Figure 1), it becomes evident that a significant portion of the graves, especially those located at Cancari Road, Hodzici Road, and Liplje, are situated near the path of the 28th Division military breakthrough in July 1995. They are in very close proximity to combat zones (95) (96) (97), which raises a critical question. The presence of highly fragmented remains, explosive injuries, and their proximity to combat zones suggests that at least some "secondary" graves may actually be "hybrid" graves, containing the remains of individuals both executed and killed in combat.

The high fragmentation index (FI) values for secondary sites Hodzici Road 01 and 02 (both with FI values of 0.59) likely represent typical taphonomic changes resulting from the relocation of bodies with heavy machinery. Cancari Road 04 with 0.37 FI is closest to the group, thus, these three sites are probably not hybrid graves but rather secondary depositions originating from systematic executions. Rudnica, with an FI of 0.29, had a different formation history compared to the sites in Bosnia. The matrix in which the bodies were relocated consists of bedrock with sharp rocks and boulders of various sizes (80) which likely contributes to a slightly higher fragmentation in Rudnica compared to counterparts from Bosnia.

In summary, the development of a quantitative method for classifying the degree of body fragmentation in mass graves within this region can provide valuable insights into understanding the manner of death and the subsequent handling of the deceased. Unusually high levels of body fragmentation (FI value below 0.1) in some secondary sites suggest that body disarticulation was likely caused peri-mortem by explosives, landmines, mortars, or tank fire, indicating a combat-related situation. Alternatively, it could imply execution by grenades or explosives. There's also a theoretical possibility that a high level of body fragmentation was intentionally inflicted post-mortem in an attempt to destroy human remains.

The results within objective 4 indicate that the complexity of a mass grave significantly affects the accuracy of the minimum number of individuals estimation. In primary burials, ideally, one case number represents one individual. However, in secondary burial sites, one case number may represent just a small body part, such as a right foot or left ulna and radius. Secondary sites also generate numerous unassociated single bones, often recorded as general body parts due to their lack of articulation with other bones. Complexity further increases with tertiary mass graves or multiple deposit interment sites.

In the secondary mass graves considered in objective 4, the majority of individuals are represented by a single body part or even a single bone, while the remaining body parts are scattered across different mass grave locations. These disarticulated cases, often the only evidence of a person in a specific grave, pose challenges for MNI estimation because they typically lack complete long bones, which are commonly used in MNI estimation.

While MNI has been a common practice in routine work for many years, to the best of our knowledge, there is only one published papers addressing the inaccuracy of MNI estimation in secondary mass graves (45). Even in commingled contexts, which may not necessarily involve secondary deposits, there are no assemblages for which the initial number of individuals is known before commingling occurs (98). This situation makes it impossible to assess the inaccuracy of MNI estimation prior to the implementation of DNA identification techniques, which have been utilized in this study to ascertain the actual number of individuals interred.

Establishing accurate MNI in commingled mass graves presents several challenges due to high bone disarticulation, fragmentation and absence of bones that might be used in MNI calculation (corresponding bone elements are frequently located in different burial locations). Problems with high bone disarticulation and high fragmentation can be somewhat mitigated by using well-defined archaeological methodology during the excavation of mass graves. The application of a strict stratigraphic, unit-based methodology, among other techniques, can significantly reduce the degree of body disarticulation during the recovery process (90). For example, it has been demonstrated that the stratigraphic excavation method, as opposed to the so-called pedestal method, yields superior results, as observed in two Batajnica mass grave sites (41). The best outcomes are achieved through a combination of spatial analysis based on mass grave mapping data and the implementation of a stratigraphic approach in the excavation process. This comprehensive approach enhances the accuracy of MNI estimation and aids in addressing the complexities associated with commingled mass graves (99).

The variation in calculating the number of individuals through osteological assessment methods can be significant (98). Anthropological methods for matching skeletal elements is based on lateralization of paired bones, morphological and size similarity between the bones of different sides, congruence of articular surfaces and other features, but taking into account the age of individuals (adults vs. non-adults). Additionally, the utilization of different techniques may result in disparities in estimation (100). However, at its core, the validity of MNI estimation relies on the percentage of individuals represented by the excavated body elements. This percentage is a crucial factor in determining the accuracy of MNI estimation (101) (102) (103).

The results of this study have shown a significant correlation between the FI and MNI inaccuracy. In other words, the smallest FI value correlates with the largest MNI error, indicating that a higher proportion of disarticulated bones in relation to complete bodies leads to a greater inaccuracy in MNI estimation. While this relationship is intuitively logical, the aim of this quantification was to numerically determine the specific level of inaccuracy associated with different proportions of disarticulated elements compared to complete bodies. This information can be applied to correct MNI estimates in future complex sites and reduce imprecision in MNI estimation.

All the sites analyzed in MNI error study are of the same type (secondary ramp mass graves) and were excavated and analyzed by the same forensic teams under similar conditions. This uniformity helps eliminate potential impacting factors on the research. However, the study could be expanded by including more commingled sites from different contexts to improve the statistical accuracy of the method presented. With a larger sample, including data from less commingled sites and primary sites, it would be possible to create a single function that accurately interpolates both ends of the graph.

6. CONCLUSION

The disintegration of Yugoslavia and the subsequent military conflicts that raged across the region from 1991 to 1999 led to the loss of over 140,000 lives (104). These tragic events also gave rise to the establishment of numerous mass graves. One of the long-lasting mass graves investigations in Bosnia and Herzegovina known as the Srebrenica Project resulted in the detection and excavation of more than 100 grave sites. A majority of the mass graves, uncovered by excavations that began in the late 1990s and continue to this day, have been identified as secondary in nature. The problem of interpreting the fragmentation of bodily remains, primarily skeletons, in secondary mass grave sites is insufficiently explored concerning the level of information that can be obtained based on variations in the degree of skeletal fragmentation between different grave sites and within individual graves.

Through empirical observation during the excavation of mass graves, we noted that graves reportedly of the same origin exhibit significantly different levels of skeletal fragmentation. This should not be the case if all bodies had the same treatment, i.e., if they were initially buried in primary graves and later, after some time, excavated with loaders and transported by trucks to secondary graves. Due to a similar context, fragmentation should be uniform across the skeletal series; however, significant variations exist, as highlighted in the results.

To potentially answer why this is the case, we devised a mathematical method to "measure" fragmentation of bodies in mass graves. Quantified results indicate three groups. As expected, the primary graves have the least fragmentation. The other two groups consisting of secondary graves clearly show variations in fragmentation. The group with moderate fragmentation corresponds to taphonomic changes occurring during the transfer of bodies from primary to secondary burials. This process involves the breaking of bodies by heavy machinery, typically by loaders or excavators, resulting in some bodies being halved, sometimes even longitudinally, while extremities are often disarticulated.

The group with the highest skeletal fragmentation suggests different circumstances, as the fragmentation is so severe that it corresponds to the dismemberment of bodies perimortem by heavy weaponry such as mines, tank fire, or close-range artillery in a group setting. This possibility is suggested in many documents related to the events before creation of the mass graves. If this is a case, these secondary graves are actually hybrid graves containing individuals from different events and contexts. This term is relatively new in forensic archaeology and emerged to precisely define the formation process of a specific graves. In legal cases, every level of information is potentially crucial for elucidating the events leading to the observed state of crime scene.

In this thesis, newly established index of fragmentation demonstrated that the minimum number of individuals (MNI) method in secondary graves is entirely useless and carries no weight in indicating the victim group or estimating the number of individuals represented. This is logical since parts of individuals were scattered across multiple graves, and an individual could potentially be represented in a grave with a body part not considered in the MNI assessment. It is undoubtedly the DNA method that is the most appropriate for determining the number of individuals in complex secondary mass graves.

Application of quantitative methods in forensic investigation of mass graves is a significant contribution to objectivity and standardization of the procedures. This makes comparison between the sites possible and gives additional source of evidence. Nevertheless, because the context of each mass grave is unique, there is no universal guideline for investigation, so investigators need to adapt to the circumstances and contextualize each finding.

7. BIBLIOGRAPHY

1. Efremov IA. Taphonomy: a new branch of paleontology. Pan-American Geol. 1940;74:81–93.
2. Haglund, W.D. and Sorg MH. Forensic Taphonomy: The Postmortem Faith of Human Remains. Haglund WD and SMH, editor. CRC Press, Boca Raton, FL.; 1997.
3. Tibbett M, Carter DO. Research in forensic taphonomy: A soil-based perspective. In: Criminal and Environmental Soil Forensics. Springer, Dordrecht; 2009. p. 317–31.
4. Boddington, A., Garland, A.N. and Janaway RC (Eds. . Death, Decay and Reconstruction. Approaches to Archaeology and Forensic Science. Manchester: Manchester University Press; 1987.
5. Duday H; Masset C. Anthropologie Physique et Archaeologie. Paris: C.N.R.S.; 1987.
6. Haglund, W.D. and Sorg MH. Advancing Forensic Taphonomy: Method, Theory, and Archaeological Perspectives. Haglund, W.D. and Sorg MH, editor. Advances in Forensic Taphonomy. Washington, D.C.: CRC Press, Boca Raton, FL.; 2002.
7. Bonnichsen R, Sorg MH. Bone Modification. Center for the Study of the First Americans, Orono, ME.; 1987.
8. Hunter JR. A pilgrim in Forensic Archaeology. In: Sorg ed. WDH and MH, editor. Advances in Forensic Taphonomy. 2002.
9. Skinner M. Planning the archaeological recovery of evidence from recent mass graves. Forensic Sci Int. 1987 Aug;34(4):267–87.
10. Ubelaker DH. Review of: The Scientific Investigation of Mass Graves: Towards Protocols and Standard Operating Procedures. J Forensic Sci. 2008;53(4):1014–1014.
11. Élisabeth Anstett J-MD. Human remains and identification: Mass violence, genocide and the "forensic turn." Oxford University Press; 2015. 169–171 p.
12. Mant AK. Knowledge acquired from post-war exumations. In: A. Boddington, A.N. Garland and RCJ, editor. Death, Decay and Reconstruction: Aproaches to Archeology and Forensic Science. London: Manchester University Press; 1987.
13. Schmitt S. Mass Graves and the Collection of Forensic Evidence. In: Sorg, M.H. and Haglund WD, editor. Advances in Forensic Taphonomy. 2001.
14. Beyern B. Guide des tombes d'hommes célèbres. Le Cherch Midi. 2008;
15. Jessee E, Skinner M. A typology of mass grave and mass grave-related sites. Forensic Sci Int. 2005 Aug 11;152(1):55–9.
16. Vaduveskovic IĐM. Forenzička tafonomija masovnih grobnica. Med Podml. 2023;
17. Djuric M. Forenzička Antropologija. In: D.J.Dunjić, editor. Ekspertizna Medicina. Evropski centar za mir i razvoj (ECPD); p. 349–400.
18. Mann RW, Bass WM, Meadows L. Time Since Death and Decomposition of the Human Body: Variables and Observations in Case and Experimental Field Studies. J Forensic Sci. 1990 Jan 1;35(1):12806J.
19. Djuric-Srejic M. Uvod u fizicku antropologiju drevnih populacija. Beograd: Zavod za udžbenike i nastavna sredstva; 1995.
20. Dušan J. Dunjić. Ekspertiza Smrti i Agonije. In: D. J. Dunjić, editor. Ekspertizna medicina. Beograd: Evropski centar za mir i razvoj (ECPD); 2008.
21. Rattenbury AE. Forensic taphonomy. In: Forensic Ecogenomics: The Application of Microbial Ecology Analyses in Forensic Contexts. Elsevier; 2018. p. 37–59.
22. Varetto L, Curto O. Long persistence of rigor mortis at constant low temperature. Forensic Sci Int. 2005 Jan 6;147(1):31–4.
23. Saukko P, Knight B. Knight's forensic pathology. 4th ed. Boca Raton: CRC Press;

2016.
24. DiMaio V, Dana S. Time of Death—Decomposition. Handb Forensic Pathol Second Ed. 2006 Oct 31;23–8.
25. Rodriguez W C BWM. Decomposition of Buried and Submerged Bodies. In: Forensic Taphonomy. CRC Press; 1996.
26. Vass A, Barshick S, Sega G, Caton J, Skeen J, Love J, et al. Decomposition Chemistry of Human Remains: A New Methodology for Determining the Postmortem Interval. J Forensic Sci. 2002 May 1;47(3):542–53.
27. Christensen AM, Passalacqua N V., Bartelink EJ. Forensic Taphonomy. Forensic Anthropol. 2014;119–47.
28. Dupras TL, Schultz JJ, Wheeler SM, Williams LJ. Forensic Recovery of Human Remains. Forensic Recovery of Human Remains. Taylor & Francis; 2011. 364 p.
29. Howes JM, Stuart BH, Thomas PS, Raja S, O'Brien C. An Investigation of Model Forensic Bone in Soil Environments Studied Using Infrared Spectroscopy. J Forensic Sci. 2012 Sep;57(5):1161–7.
30. Sa Y, Guo Y, Feng X, Wang M, Li P, Gao Y, et al. Are different crystallinity-index-calculating methods of hydroxyapatite efficient and consistent? New J Chem. 2017;41(13):5723–31.
31. Kyle B. Extrinsic Factors That Effect the Preservation of Bone. Nebraska Anthropol. 2004;19:38–45.
32. Boaks A, Siwek D, Mortazavi F. The temporal degradation of bone collagen: A histochemical approach. Forensic Sci Int. 2014;240:104–10.
33. Cox M, Mays S. Human Osteology in Archaeology and Forensic Science. 2000 [cited 2024 Mar 29];550. Available from: https://search.worldcat.org/title/44780031
34. Tihaček-Šojić L, Đurić-Srejić M. Analysis of the Optical Properties of Medieval Enamel. Dent Anthropol J. 2018 Sep 7;13(1):14–20.
35. Tihaček-Šojić L, Milićević V, Đurić-Srejić M. Crystallographic and Colorimetric Analysis of Dental Enamel. Dent Anthropol J. 2018 Sep 7;11(2):5–11.
36. Fiedler S, Graw M. Decomposition of buried corpses, with special reference to the formation of adipocere. Naturwissenschaften. 2003 Jul 1;90(7):291–300.
37. Surabian D. Preservation of buried human remains in soil. U.S Department of Agriculture: Natural Resources Conservation Service. 2012. p. 1–54.
38. Binford L. Antient Men and Modern Myts. New York: Academic Press; 1981.
39. Lyman RL. Vertebrate Taphonomy. Cambrige: Cambrige University Press; 1994.
40. Ubelaker DH. Approaches to the Study of Commingling in Human Skeletal Biology. In: Sorg, M.H. and Haglund WD, editor. Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives. Washington, D.C.: CRC Press, Boca Raton, FL.; 2001.
41. Tuller H, Durić' M. Keeping the pieces together: Comparison of mass grave excavation methodology. Forensic Sci Int. 2006 Jan 27;156(2–3):192–200.
42. Haglund WD, Connor M, Scott DD. The archaeology of contemporary mass graves. Hist Archaeol. 2001 Mar 18;35(1):57–69.
43. Klein RG, Cruz-Uribe K. The Analysis of Animal Bones from Archeological Sites. Chicago: University of Chicago Press; 1984.
44. Konigsberg LW, Adams BJ. Estimating the Number of Individuals Represented by Commingled Human Remains: A Critical Evaluation of Methods. Commingled Hum Remain Methods Recover Anal Identif. 2014 Jun 17;193–220.
45. Vaduvesković I, Djuric M. Mass grave complexity effects on the minimum number

of individuals estimation. Forensic Sci Med Pathol. 2020 Mar 1;16(1):57–64.
46. Jolly GM, Seber GAF. The Estimation of Animal Abundance and Related Parameters. J Anim Ecol. 1974;43(2):603.
47. Adams BJ, Königsberg LW. Estimation of the most likely number of individuals from commingled human skeletal remains. Am J Phys Anthropol. 2004 Oct;125(2):138–51.
48. Robson DS, Regier HA. Sample Size in Petersen Mark–Recapture Experiments. Trans Am Fish Soc. 1964;93(3):215–26.
49. Just RS, Leney MD, Barritt SM, Los CW, Smith BC, Holland TD, et al. The Use of Mitochondrial DNA Single Nucleotide Polymorphisms to Assist in the Resolution of Three Challenging Forensic Cases. J Forensic Sci. 2009 Jul;54(4):887–91.
50. Mundorff AZ, Shaler R, Bieschke E, Mar-Cash E. Marrying anthropology and DNA: Essential for solving complex commingling problems in cases of extreme fragmentation. Recover Anal Identif Commingled Hum Remain. 2008;285–99.
51. Verdugo C, Kassadjikova K, Washburn E, Harkins KM, Fehren-Schmitz L. Ancient DNA Clarifies Osteological Analyses of Commingled Remains from Midnight Terror Cave, Belize. Int J Osteoarchaeol. 2017 May 1;27(3):495–9.
52. White TJ. The future of PCR technology: diversification of technologies and applications. Trends Biotechnol. 1996;14:478–83.
53. Bucket P. Toward a new natural medicine. Naturwissenschaften. 1998;85:155–63.
54. Krings M et al. Neanderthal DNA sequences and the origin of modern humans. Cell. 1997;90:19–30.
55. Brown TA, Brown KA. Ancient DNA: Using molecular biology to explore the past. BioEssays. 1994 Oct 1;16(10):719–26.
56. Hagelberg E and JBC. Isolation and characterisation of DNA from archaeological bone. Proccedings R Soc London Biol Sci 244. 1991;244:45–50.
57. Lee HC. Identification and grouping of bloodstains. Forensic Sci Rev. 1982;267–337.
58. Lee HC, Ladd C, Bourke MT, Pagliaro E, Tirnady F. DNA typing in forensic science: I. Theory and background. Am J Forensic Med Pathol. 1994 Dec;15(4):269–82.
59. Parsons TJ, Muniec DS, Sullivan K, Woodyatt N, Alliston-Greiner R, Wilson MR, et al. A high observed substitution rate in the human mitochondrial DNA control region. Nat Genet. 1997 Apr;15(4):363–8.
60. Michele Harvey and Mary-Claire King. The Use of DNA in the Identification of Postmortem Remains. In: William D. Haglund MHS, editor. Advances in Forensic Taphonomy Method, Theory, and Archaeological Perspectives. CRC Press, Boca Raton, FL.; 2002. p. 474–83.
61. Underhill PA, Shen P, Lin AA, Jin L, Passarino G, Yang WH, et al. Y chromosome sequence variation and the history of human populations. Nat Genet. 2000;26(3):358–61.
62. Marean CW. Measuring the post-depositional destruction of bone in archaeological assemblages. J Archaeol Sci. 1991 Nov;18(6):677–94.
63. Lyman RL. Relative abundances of skeletal specimens and taphonomic analysis of vertebrate remains. Palaios. 1994 Jun;9(3):288–98.
64. Lyman RL. Quantitative Units and Terminology in Zooarchaeology. Am Antiq. 1994 Jan 20;59(1):36–71.
65. Vaduveskovic I, Starovic A, Byard RW, Djuric M. Could a “body fragmentation index” be useful in reconstructing events prior to burial: Case studies of selected primary and secondary mass graves from eastern Bosnia. Leg Med. 2020 Nov

1;47:101766.
66. Djurić M. Dealing with human remains from recent conflict: Mass grave excavation and human identification in a sensitive political context. Handb Forensic Anthropol Archaeol. 2016 Jan 1;532–44.
67. Haglund W. Forensic investigation of the Cerska grave site, Bosnia and Herzegovina, made on June 1998 (expert report to ICTY), pp. 01493690–01493759. Source: Republic Center for Research of War, War Crimes and Tracing of Missing Persons, Banja Luka. 1998.
68. Peccerelli F. Excavation and exhumation report Lazete 1, Bosnia and Herzegovina, made on October 2000 (expert report to ICTY), pp.X006 4000–X006 4032.Source: Republic Center for Research of War, War Crimes and Tracing of Missing Persons, Banja Luka. 2000.
69. ICMP Summary Report. Report on the archaeological findings relating to the excavation of Budak 01, Bosnia and Herzegovina, made on July 2005 (technical expert report to ICMP). Source: Republic Center for Research of War, War Crimes and Tracing of M. 2005.
70. ICMP Summary Report. Cancari Road 04, Bosnia and Hercegovina, made on October 2008 (technical expert report to ICMP). Source: Republic Center for Research of War, War Crimes and Tracing of Missing Persons, Banja Luka. 2008.
71. ICMP Summary Report. 2008. Cancari Road 06, Bosnia and Hercegovina, made on December 2008 (technical expert report to ICMP). Source: Republic Center for Research of War, War Crimes and Tracing of Missing Persons, Banja Luka. 2008.
72. ICMP Summary Report. Cancari Road 08, Bosnia and Hercegovina, made on November 2008 (technical expert report to ICMP). Source: Republic Center for Research of War, War Crimes and Tracing of Missing Persons, Banja Luka. 2008.
73. ICMP Summary Report. Cancari Road 10, Bosnia and Hercegovina, made on April 2008 (technical expert report to ICMP). Source: Republic Center for Research of War, War Crimes and Tracing of Missing Persons, Banja Luka. 2008.
74. ICMP Summary Report. Report to ICMP – Snagovo 04 Excavations, made on November 2006 (technical expert report to ICMP). Source: Republic Center for Research of War, War Crimes and Tracing of Missing Persons, Banja Luka. 2006.
75. ICMP Summary Report. Hodzici Road 02, Bosnia and Hercegovina, made on April 2008 (technical expert report to ICMP). Source: Republic Center for Research of War, War Crimes and Tracing of Missing Persons, Banja Luka. 2008.
76. Lawrence CH. Report on human mortal remains autopsy from the site Liplje 2, made on June 1998 (formal expert report to OTP), pp. 00921322–00921361. Source: Republic Center for Research of War, War Crimes and Tracing of Missing Persons, Banja Luka. 1998.
77. Wright, R. Exhumations in Eastern Bosnia in 1998, made on May 1999 (expert report to ICTY), pp. 00848214–00848395. Source: Republic Center for Research of War, War Crimes and Tracing of Missing Persons, Banja Luka. 1999.
78. ICMP Summary Report. Report on the Archaeological Findings related to the excavation of Liplje 07, made on September 2005 (technical expert report to ICMP). Source: Republic Center for Research of War, War Crimes and Tracing of Missing Persons, Banja Luka. 2005.
79. ICMP Summary Report. Report to ICMP – Zeleni Jadar 04 Excavations, made on April 2008 (technical expert report to ICMP). Source: Republic Center for Research of War, War Crimes and Tracing of Missing Persons, Banja Luka. 2008.

80. Commission on expert witnesses. Unpablished report to the higher court in Belgrade, department for war crimes. Beograd; 2014.
81. ICMP - International Commission on Missing Persons [Internet]. [cited 2023 Oct 28]. Available from: https://oic.icmp.int/index.php?w=site_summary&l=en&x=search&xw=siteSummaryFilterLoadSitesSitecode&x_region_id_sel=&x_municipality_id_sel=&x_municipality_place_id_sel=&x_site_id_sel=&x_sites_sitecode_id_sel=&quick_find_pp=15&quick_find_q=&country_id=33&region_id=6&municipality_id=3342&municipality_place_id=228&site_id=3214&sites_sitecode_id=1614
82. CIFA. Standard and guidance for forensic archaeologists. Reading: The Chartered Institute for Archaeologists. 2014 [cited 2023 Nov 1]; Available from: https://www.archaeologists.net/sites/default/files/CIfAS&GForensics_2.pdf
83. Haglund WD, Connor M, Scott DD. The archaeology of contemporary mass graves. Hist Archaeol. 2001;35(1):57–69.
84. Skinner M, Lazenby RA. Found! Human Remains: a field manual for the recovery of the recent human skeleton. Burnaby: Archaeology Press, Simon Fraser Univesity,; 1983.
85. Yazedjian L, Kešetović R. The application of traditional anthropological methods in a DNA-led identification process. Recover Anal Identif Commingled Hum Remain. 2008;271–84.
86. Gerdau-Radonic K, Herrera A. Pourquoi fouiller des dépôts funéraires pillés? Deux exemples et quelques réponses de Keushu (Ancash, Pérou). Bull Mem Soc Anthropol Paris. 2010;22(3–4):145–56.
87. De La Grandmaison GL, Durigon M, Moutel G, Herve C. The international criminal tribunal for the former Yugoslavia (ICTY) and the forensic pathologist: ethical considerations. Med Sci Law [Internet]. 2006 [cited 2024 Feb 3];46(3):208. Available from: /pmc/articles/PMC3348121/
88. Karganović, S., Simić, L., Herman, E., Pumphrey, G., Maher, J.P., Wilcoxon A. Deconstruction of a virtual genocide: an intelligent person's guide to Srebrenica. Den Haag – Belgrade: NGO Srebrenica Historical Project.; 2011.
89. Roksandic M. Position of Skeletal Remains as a Key to Understanding Mortuary Behavior. Adv Forensic Taphon. 2001 Jul 30;
90. Tuller HH. Mass Graves and Human Rights: Latest Developments, Methods, and Lessons Learned. A Companion to Forensic Anthropol [Internet]. 2012 Mar 23 [cited 2023 Oct 28];157–74. Available from: https://www.researchgate.net/publication/222089891_Mass_Graves_and_Human_Rights_Latest_Developments_Methods_and_Lessons_Learned
91. Prahlow JA, Byard RW. Miscellaneous. Atlas of Forensic Pathology. Totowa, NJ: Humana Press; 2012. 847–893 p.
92. Edirisinghe A, Samarasekera A. Injury, fatal and nonfatal: explosive injuries. Elsevier Ltd; 2016.
93. Clark J. ICTY operations in Bosnia – Herzegovina 2001 season. Report of the chief pathologist, pp. 2–5. Source: Republic Center for Research of War, War Crimes and Tracing of Missing Persons, Banja Luka. 2001.
94. Parsons TJ, Huel RML, Bajunović Z, Rizvić A. Large scale DNA identification: The ICMP experience. Forensic Sci Int Genet. 2019 Jan 1;38:236–44.
95. D. R. Endgame. The betrayal and fall of Srebrenica, Europe's worst massacre since World War II. New York: Penguin Books; 2012.

96. Honig JW BN. Srebrenica. Record of a War Crime. New York: Penguin Books; 1996.
97. Srebrenica Report. The Netherlands Institute for War Documentation. [Internet]. Available from: https://www.niod.nl/en/srebrenica-report/report
98. Lambacher N, Gerdau-Radonic K, Bonthorne E, Valle de Tarazaga Montero FJ. Evaluating three methods to estimate the number of individuals from a commingled context. J Archaeol Sci Reports. 2016 Dec 1;10:674–83.
99. Tuller H, Hofmeister U. Spatial Analysis of Mass Grave Mapping Data to Assist in the Reassociation of Disarticulated and Commingled Human Remains. In: Commingled Human Remains: Methods in Recovery, Analysis, and Identification. Elsevier Inc.; 2014. p. 7–32.
100. Herrmann NP, Devlin JB. Assessment of commingled human remains using a GIS-based approach. Recover Anal Identif Commingled Hum Remain. 2008;257–69.
101. Casteel RW. Characterization of faunal assemblages and the minimum number of individuals determined from paired elements: Continuing problem in archaeology. J Archaeol Sci. 1977;4(2):125–34.
102. Grayson DK. Minimum Numbers and Sample Size in Vertebrate Faunal Analysis. Am Antiq. 1978 Jan;43(1):53–65.
103. Horton DR. Minimum numbers: a consideration. J Archaeol Sci. 1984 May 1;11(3):255–71.
104. ICTJ 2009. Transitional Justice in the Former Yugoslavia. New York: International Center for Transitional Justice. [Internet]. [cited 2023 Nov 1]. Available from: https://www.ictj.org/sites/default/files/ICTJ-FormerYugoslavia-Justice-Facts-2009-English.pdf

The list of candidate's published papers from the thesis:

1. Vaduvesković I, Djuric M. Mass grave complexity effects on the minimum number of individuals estimation. Forensic Sci Med Pathol. 2020 Mar 1;16(1):57–64. DOI: **10.1007/s12024-019-00186-3**

2. Vaduveskovic I, Starovic A, Byard RW, Djuric M. Could a "body fragmentation index" be useful in reconstructing events prior to burial: Case studies of selected primary and secondary mass graves from eastern Bosnia. Leg Med. 2020 Nov 1;47:101766. DOI: **10.1016/j.legalmed.2020.101766**

3. Vaduvesković I, Djuric M. Forenzička tafonomija masovnih grobnica. Medicinski Podmladak 2024. DOI: 10.5937/mp76-41657

PROFESSIONAL BIOGRAPHY

Igor Vaduvesković was born in Zaječar in 1980, where he completed his primary and secondary education. He earned a degree in archaeology from the Faculty of Philosophy at the University of Belgrade, specializing in the Department of Archaeology. As an archaeologist, he has been involved in various projects with numerous local and foreign institutions, including the Petnica Science Center, National Museum, Republic Institute for the Protection of Cultural Monuments, Institute for Balkan Studies, Institute of Archaeology, Faculty of Philosophy (Department of Archaeology), University College London (UCL), Sapienza Università di Roma - Dipartimento di Biologia Ambientale, and New York University - Department of Anthropology.

Moreover, a significant portion of Igor's professional career is dedicated to forensic archaeology, particularly in mass grave investigations. As a forensic expert, he collaborates with the District Court in Belgrade, the Higher Court in Belgrade, the Department for War Crimes, the European Union Police Mission (EUPM), the International Commission on Missing Persons (ICMP), the University of Belgrade - Faculty of Medicine, and the Republic Center for Research on War, War Crimes, and the Search for Missing Persons.

Presently, Igor is pursuing a PhD in Skeletal Biology at the Medical Faculty of the University of Belgrade. His research interests encompass a wide array of topics, including forensic science, forensic archaeology, statistics in forensic science, Bayesian statistics, quantitative techniques, site recording methodology, archaeogenetics, biomolecular archaeology, and ancient DNA.

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