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Application of Computed Tomography in Wound Ballistics

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Abstract:

The application of computed tomography (CT) in the field of wound ballistics has emerged as a critical tool for enhancing the understanding and assessment of ballistic injuries. This paper examines its function in forensic and clinical settings from a number of angles, including its limitations, ramifications, and capacities. Beginning with an overview of the basic concepts of wound ballistics, we next go over several case studies that show how effective CT is at explaining intricate projectile paths and injury patterns, especially in unusual situations like penetrating brain injuries and abdominal trauma. Because CT is non-invasive and can visualise wound tracks in great detail, it is superior to traditional modalities, according to a comprehensive assessment of the literature that highlights developments in imaging techniques. In the discussion section, the development of CT applications in forensic investigations is critically evaluated, with particular attention paid to its usage in virtual autopsy methods that make it easier to trace bullet pathways and identify bullets inside the human body. In order to improve the precision of ballistic evaluations and medical treatments in trauma care, we advocate for the use of CT in routine forensic practice. we highlight the importance of research in this field as well as the mechanics of bullet strikes on human tissues.

Keywords: *Computed tomography (CT), Wound ballistics, Ballistics, bullet, GSW, Virtual autopsy, Tomography, Imaging technique*

1. Introduction

Ballistics is the branch of mechanics that studies how projectiles, especially weapon munitions, launch, fly, and impact (Rhee et al., 2016). Ballein, which means "to throw" in Greek, is where the name "ballistics" comes from. Using a penetrating wave, the imaging method known as tomography produces images of sections or sectioning. X-rays and computer technology are combined in CT, a diagnostic imaging technique that creates fine-grained images of the interior of the body (Tassiopoulou et al., 2024a). Ballistics is the branch of mechanics that studies how projectiles, especially weapon munitions, launch, fly, and impact. Ballein, which means "to throw" in Greek, is where the name "ballistics" comes from (Moeng & Boffard, 2023). Using a penetrating wave, the imaging method known as tomography produces images of sections or sectioning. X-rays and computer technology are combined in CT, a diagnostic imaging technique that creates fine-grained images of the interior of the body (Tassiopoulou et al., 2024b).

"Ballistics was first researched in 1531 by Niccolò Tartaglia, an Italian mathematician. With the 1687 publication of Philosophiae Naturalis Principia Mathematica, Isaac Newton established ballistics on a mathematical and scientific basis. As the field of forensic imaging continues to evolve, ongoing research into the mechanics of bullet strikes on human tissues will further enhance CT's application in both forensic and clinical environments (Franchetti et al., 2022). A comprehensive understanding of these dynamics can lead to improved precision in ballistic evaluations, aiding law enforcement and medical professionals alike in delivering equitable trauma care Indeed, fostering research initiatives focused on refining CT methodologies will solidify its position as an essential tool in wound ballistics and trauma management.

2. Types Of Ballistics

Ballistics is often divided into three categories as discussed below, and also graphical representation has been shown in figure 1.

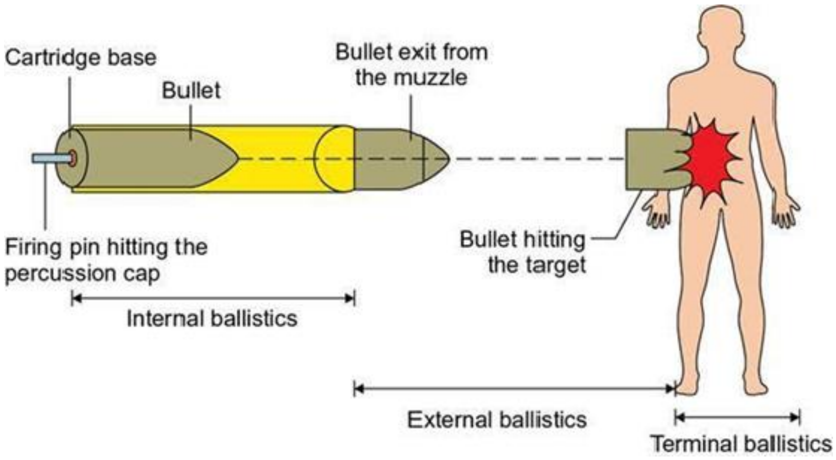

Figure 1. *Illustration of Types of Ballistics*

2.1. Internal ballistics

Internal ballistics refers to the investigation of projectile acceleration mechanisms. This encompasses the period from the moment the propellant ignites until the projectile exits the gun barrel or when thrust is generated by a rocket engine (Nasirov, 2024).

2.2. External ballistics

Ballistics is the branch of mechanics that studies how projectiles, especially weapon munitions, launch, fly, and impact (Nandi et al., 2022). Ballein, which means "to throw" in Greek, is where the name "ballistics" comes from. Using a penetrating wave, the imaging method known as tomography produces images of sections or sectioning (Withers et al., 2021a). X-rays and computer technology are combined in CT, a diagnostic imaging technique that creates fine-grained images of the interior of the body (Beddiar et al., 2023).

2.3. Terminal ballistics (Wound Ballistics)

The study of terminal ballistics examines how a projectile behaves and what happens when it strikes its target (Baum et al., 2022). This applies to projectiles of both small and big calibre (Veysset et al., 2021a).

Table 1. *Various Factors Affecting Ballistics*

Factor	Description
Material Composition	The internal composition of ballistic materials, such as fiber hybrid composites, significantly impacts performance (Bichanga'a et al., 2022). Variations in fiber types and configurations can alter effectiveness against impacts (Chen et al., 2023).
Projectile Characteristics	Specific parameters of the projectile, including shape, size, and mass, have a pronounced effect on its ballistic trajectory and energy transfer upon impact (Signetti & Heine, 2022). Yaw, caliber, and nose shape are critical dimensions to consider (Esaker et al., 2023).
Environmental Conditions	External factors such as temperature, humidity, and atmospheric pressure can significantly affect the performance of both the projectile and the target (Veysset et al., 2021b). Ballistic performance may diminish in extreme conditions (Pai et al., 2023).
Target Properties	Features such as the hardness, toughness, and yield strength of the target material contribute to the overall resistance to ballistic impacts (Pai et al., 2022). The geometry of the target also affects energy absorption (Siddique et al., 2022).
Aerodynamics	The design of the projectile impacts its aerodynamic efficiency, which is influenced by external conditions, including wind resistance, drag coefficient, and angle of attack during flight (Lubarda & Lubarda, 2022).
Launch Parameters	Factors such as muzzle velocity and the type of propellant can critically affect the initial energy and trajectory stability of the projectile when fired (Euteneuer & Courts, 2021).
Impact Dynamics	The interaction dynamics at the moment of impact involve complex mechanisms, including energy transfer efficiency, fragmentation, and deformation of the projectile and target materials (Zhou et al., 2023).

3. TOMOGRAPHY

A technique called **tomography** records the impact of energy waves travelling through an object to create three-dimensional representations of its inside structures (Withers et al., 2021b). Originating from the Ancient Greek terms "tomos," which means "slice, section," and "graphō," which means "to write" or "to describe," the word tomography was created. Tomograms are the images created by tomography, while tomographs are the devices used in tomography. The process of creating tomographic images, such as X-ray computed tomography, frequently depends on a mathematical process known as tomographic reconstruction that is produced from several projectional radiographs (Withers et al., 2021c). Filtered back projection (FBP) and iterative reconstruction (IR) are two of the many types of reconstruction techniques (Schofield et al., 2020). FBP requires less CPU power, but IR typically results in fewer artefacts at a higher cost (Halliburton et al., 2017).

4. Computed Tomography

CT scans combine X-rays to provide images of the inside of the body. A CT scan provides a detailed view of every part of the body, including the muscular system, bones, organs, and blood vessels (Schmidt et al., 2007). In CT scanners, an X-ray source is motorised and rotates around the circular aperture of a gantry, which is a donut-shaped frame (Kärnä, 2018). Small X-ray beams are delivered through the body while the X-ray tube rotates around the patient during a CT scan. A bed that slowly slides along the gantry holds the patient. The X-rays are picked up as they leave the patient and are sent to a computer by specialised digital detectors, which are situated directly across from the X-ray source (Yaffe & Rowlands, 1997). After that, the computer creates a slice of the patient's two-dimensional image. Compared to traditional X-rays, these slices—known as tomographic images—provide more detailed information (Maken & Gupta, 2023). To make a three-dimensional image, the computer can digitally "stack" subsequent slices. The figure 2 shows the systematic working of computed tomography.

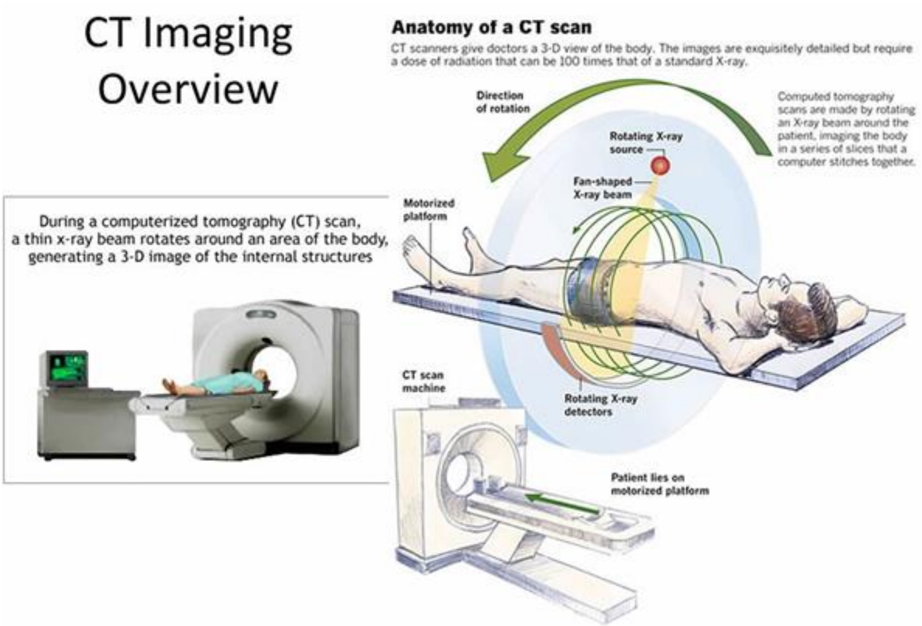

Figure 2. *Illustration of Computed Tomography Imaging*

We have reviewed more than 30 papers from databases such as PubMed, Scopus, Google Scholar, ScienceDirect, Web of Science, Microsoft Academic, etc., and therefore, constructed our following review study.

5. Utlization of Computed Tomography (CT) In Various Cases

Below is a synthesis of 10 case studies that illustrate the application of computed tomography (CT) in wound ballistic research and forensic investigations. Each of these studies demonstrates different aspects of CT imaging, ranging from quantitative analyses in simulants to clinical and postmortem evaluations in real-world cases.

CT was utilised to get sectional measurements of gelatine blocks in a study aimed at determining cavity volumes in ballistic simulants. Because of this, scientists were able to precisely assess the energy release along the bullet route, improving our comprehension of wound ballistics phenomena. The high resolution of CT imaging provided detailed quantification of temporary cavities, which is vital for correlating injury patterns with projectile kinetics (Stefanopoulos et al., 2017).

Investigations into cranial gunshot injuries where whole-body imaging yielded preliminary observations that linked radiological findings with traditional autopsy results demonstrated the value of CT in forensic postmortem examinations. In this context, CT imaging was pivotal not only for non-invasive examination but also for validating findings at autopsy in traumatic ballistic injuries (Makhlouf et al., 2013).

CT imaging has also been useful for terminal ballistic analysis. Using CT, researchers have examined ballistic blocks—gelatine phantoms that mimic tissue—non-invasively and tracked the development and spread of gunshot wounds in models of simulated heads. Such studies underscore the role of CT in replicating and understanding the terminal effects of high-velocity projectiles (Ditkofsky et al., 2018).

CT imaging was regarded as the gold standard in a clinical case involving a young kid who had been injured by an air pistol and had bihemispheric penetrating brain damage. It directly impacted surgical planning and care by precisely defining the projectile tract and the degree of visceral damage. This case study emphasizes CT's role in pediatric trauma and complex intracranial injuries (Wijaya et al., 2019).

CT can now be used in comprehensive wound ballistic studies, thanks to developments in radiologic imaging. In one method, CT was utilised in conjunction with other radiologic modalities, including fluoroscopy and traditional radiography, to locate and retrieve projectiles, increasing the accuracy of wound path documentation. This multimodal approach enhances forensic investigations, particularly when reconstructing crime scenes (Mazuchowski & Harcke, 2013).

A different case study explained how magnetic resonance imaging (MRI) and computed tomography (CT) work together in ballistic investigations. The cases in which bullets or pellets remained embedded in head injuries were the subject of this investigation. However, precautions about projectile heating and movement during MRI were also mentioned. CT was used to outline the trajectory, and its results were supplemented by MRI examinations. These findings highlight the complementary roles of CT and MRI in safely and effectively managing retained ballistic fragments (Gascho et al., 2020).

In an experimental investigation, the "triple contrast" method for wound ballistic analysis was introduced. In this instance, CT imaging was crucial for analysing intricate ballistic head models that featured layers that resembled the tissue of the skin, skull, and brain. Barium sulphate was added to contrast media to improve CT visualisation of projectile trajectory and backspatter, demonstrating a nondestructive method of preserving ballistic data (Schyma et al., 2015).

Another creative application was precisely documenting the quantity, position, and directionality of gunshot wounds using makeshift bullet marks in combination with 3D CT reconstruction. This case study showed how CT-based marker tracking may permanently record the locations of wounds, which greatly facilitates medicolegal investigations by offering reliable, long-term spatial data on the projectile routes (Ramasamy et al., 2008).

Additionally, CT imaging has been helpful in the forensic evaluation of gunshot residues. According to a study, three-dimensional CT made it possible to find radiologically detectable gunshot remnants in soft tissue, which may be utilised to determine the ammunition type and range of firing. When early clinical management or cleaning techniques have changed the wounds, this method is beneficial (Steín et al., 2000).

In a case study, a thorough assessment of an abdominal gunshot wound was obtained by combining postmortem CT and MRI. The intracorporeal bullet trajectory was depicted using CT imaging, and the results were subsequently verified by autopsy. The study confirmed that CT is a useful, non-invasive technique that may be used in conjunction with traditional autopsy, especially when it comes to determining the nature of complex abdominal injuries, even though it can't always detect all injuries (Gascho et al., 2020). This case study presents a complex forensic investigation concerning a 76-year-old man who died by suicide using a Walther Manurhin PPK 7.65 mm pistol. His suicide followed a recent diagnosis of advanced pancreatic cancer, which is associated with significantly elevated suicide risks. Studies have consistently shown that suicide rates spike in the wake of cancer diagnoses, particularly in cases of pancreatic cancer, which has one of the highest incidences of suicidal behaviour compared to other types of cancer (Viel et al., 2009).

The investigation revealed that the deceased was found supine with the firearm in his left hand, indicative of a self-inflicted injury. A detailed examination of the crime scene, followed by a whole-body Multi-Slice Computed Tomography

(MSCT), uncovered severe cranial injuries consistent with a gunshot. Notably, the imaging revealed a cranial vault defect with outward beveling, indicative of an entrance wound, along with signs of pneumoencephalus—air pockets in the cranial cavity, a common occurrence following penetrating head injuries(Villa et al., 2023).

The autopsy findings confirmed the trajectory of the bullet, which had entered through the hard palate, traveled through the brain, and exited through a round wound on the skull. This detailed forensic anatomical analysis is essential as bullet trajectories can provide critical insights into the circumstances surrounding the death, helping to clarify whether it was indeed a suicide or if other scenarios, such as foul play, could be plausible.The absence of gunshot residues (GSR) near the wound suggested either a close-range shot or peculiarities in the handling of the weapon, highlighting the need for careful forensic analysis (Minzière et al., 2023).

With respect to the deceased's medical condition, the presence of pancreatic cancer significantly correlates with depression and suicidal ideation, as highlighted in relevant literature.Research indicates that the period following a cancer diagnosis is particularly perilous, as patients often struggle with mental health issues stemming from their prognosis and treatment. It is widely recognized that psychological support systems are crucial in mitigating the risk of suicide for cancer patients, especially during the challenging first year post-diagnosis (Wang et al., 2024).

Applications of computed tomography (CT) in wound ballistics research range from the detection of ballistic wound routes to the accurate characterisation of gunshot wound patterns. When combined with advances in radiologic imaging, CT technology makes it easier to investigate wound ballistics by evaluating virtual "slices" of certain regions (Pinto et al., 2019a).

The biophysical elements of wound ballistics are studied with CT, which is also frequently utilised for diagnostic purposes. It can also be used to mark the routes taken by projectiles through tissues in forensic and clinical contexts. The best method for accurately analysing GSW patterns in a cadaveric animal limb model has been demonstrated to be CT with contrast, which enables flexible damage quantification (Pinto et al., 2019b).

CT for ballistic wound patterns in phantoms can be precisely identified. For additional analysis, multi-planar reconstruction (MPR) and 3D reconstructed pictures are made possible by the use of contrast inside wound tracks. The position, quantity, and direction of projectiles in fatal ballistic injuries are described by postmortem CT (PMCT) and autopsy results with extremely good agreement (Rajiah & Schoenhagen,2013).

CT is frequently utilized for diagnostic purposes and for studying the biophysical elements of wound ballistics. In both forensic and clinical contexts, it is employed to mark the routes of projectiles through tissues. The knowledge of wound ballistics and wounding mechanisms is essential for radiologists to interpret CT findings in gunshot wounds, as the severity of a bullet wound depends on factors like tissue elasticity, bullet velocity, and yaw (Pinto et al., 2019c).

CT for examining GSW patterns in cadaveric animal limb models, CT with contrast is the most efficient technique, allowing for flexible damage measurement. Contrast improves the examination of wound tracks by enabling multiplanar reconstruction (MPR) and 3D reconstructed pictures in CT imaging. Complete GSW tracks can be precisely measured in terms of dimensions using this method, which also offers detailed visualisation in different viewing planes (Franchetti et al., 2022b).

6. Discussion

The application of computed tomography (CT) in wound ballistics represents a significant advancement in forensic science, particularly in the analysis of gunshot wounds (GSWs) and the dynamics of ballistic trauma. This synthesis aims to elucidate the multifaceted role of CT in investigating wound ballistics through the examination of its capabilities, benefits, and limitations as reflected in contemporary literature.

One of the primary advantages of CT lies in its non-invasive nature, enabling detailed visualization of ballistic injuries without the need for invasive postmortem procedures. This capability is especially beneficial in assessing GSWs, where understanding the trajectory and impact of the projectile is crucial. CT scans are capable of accurately determining the wound tract, identifying retained bullet fragments, and elucidating the extent of visceral injuries, which is paramount in forensic investigations. Notably, the ability of CT to produce three-dimensional reconstructions from the imaging data allows for enhanced analysis of the relationship between the projectile and the injured tissues. Such analyses can lead to important insights regarding both the immediate and remote effects of the bullet on bodily structures, which is a significant aspect of wound ballistics

The integration of CT within wound ballistics extends beyond merely capturing images. It facilitates a comprehensive understanding of terminal ballistics—the effects that bullets inflict upon striking tissues. CT has been utilized effectively to analyze the temporary cavity and permanent cavities created by ballistic impacts Studies have demonstrated that CT can visualize the dynamics of both permanent and temporary cavities in ballistic substances, providing a clearer picture of energy transfer and tissue disruption caused by projectiles This aspect is critical not only for clinical diagnosis but also for the judicial presentation of evidence in court.

Forensic institutes have increasingly adopted CT as an auxiliary technique to augment traditional ballistic analysis. Particularly in cases where projectiles are retained in the body, CT's capacity to traverse different tissue densities provides valuable information about the type of ammunition used and its potential trajectory The ability to visualize and assess damage caused by different types of bullets—including full metal jacketed and expanding bullets—via CT has been explored in forensic studies, affirming its relevance for comparative analyses in ballistics This versatility is essential for forensic pathologists who require comprehensive data to reconstruct shooting incidents.

However, despite its numerous advantages, the application of CT in wound ballistics is not without limitations. One notable challenge includes the presence of beam hardening artifacts, which can obscure critical details in images Additionally, while CT scans offer excellent spatial resolution, the evaluation of complex ballistic injuries often requires corroboration with other modalities, such as magnetic resonance imaging (MRI), which can depict soft tissue injuries more effectively Thus, while CT serves as a powerful tool in forensic ballistics, it operates best when used in conjunction with other technologies to provide a more holistic assessment of the injuries.

7. Conclusion

In wound ballistics, CT is helpful for biophysical study and is frequently utilised for both therapeutic and diagnostic purposes. Analysis of wounds from explosives and bullets can be done effectively and efficiently with multidetector computed tomography. CT can be used in forensic and clinical contexts to trace the trajectory of projectiles via tissues. Additionally, the anatomy of the human body can be replicated by CT imaging by simulating the trajectory of a bullet using ballistic gel**.** In a cadaveric animal limb model, CT with contrast is the most successful technique for accurate GSW pattern interpretation. The accurate delineation of the GSW track in various planes of view is made possible by the existence of contrast. The full GSW tracks from each scanned limb can be measured in three dimensions, thanks to this and the measurement facilities in the software program that views the pictures. By enabling a ballistic phantom to be practically sliced into slices of the same thickness in cross-section throughout the bullet trajectory, the CT data contributes to increased measurement accuracy.

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