Seminars in
ULTRASOUND
CT and MRI

Gunshot Wounds: Ballistics and Imaging Findings

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Ballistic traumas are defined by a projectile entering the body. Such projectiles include bullets, birdshot, and metal fragments from the covering or the contents of an explosive device. They frequently cause severe wounds characterized by a range of clinical pictures and a large spectrum of concomitant wounds.

The major aims of imaging are to define the path of the projectile or projectiles, to evaluate which tissues have been injured, to estimate the severity of injury, and to determine what additional studies are needed. A routine radiograph is performed in patients with gunshot wounds. The diagnostic approach has been changed by the use of multidetector row computed tomography (MDCT) due to its technical developments particularly faster data acquisition and advanced image reconstructions.

In the evaluation of patients with gunshot injuries, MDCT is considered the method of choice to identify hemorrhage, bullet, bone fragments, air, hemothorax, nerve lesions, musculoskeletal lesions, and vessel injuries. Moreover, MDCT technology and multiplanar reformation postprocessing allow meticulous trajectory analysis that potentially benefits the clinical outcomes of patients aiding time-saving triage and correct image-based diagnosis of organ and vessel damage.

Familiarity of ballistics and forensic sciences will therefore help the radiologist in assessment and localization of the damage caused by projectiles.

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Introduction

Peace-time gunshot wounds arise from a multiplicity of situations—terrorist and criminal incidents (including gunshots fired by law enforcement agents), attempted suicides, and unintentional firearm "accidents" (both civilian and those that occur in the armed forces).[1]

A recent edition of Uniform Crime Reports (2007) lists 16,919 murders, or 5.6/100,000 or 46/day in the United States, the maximum homicide rate in any Western industrialized country. Firearms account for approximately 60% of these homicides.[2] Gunshot homicides occur more frequently in young adults, while suicides are most likely in older age groups. Gunshot injuries are second only to vehicle accidents as a cause of adolescent injury-related deaths.

Wounds resulting from ballistic injuries are classified as penetrating, perforating, and avulsive.[3] They are commonly classified as low velocity (less than 609.6 m/s) or high velocity (more than 609.6 m/s). Those with higher velocity may be estimated to dissipate more energy into surrounding tissue as they slow and cause more tissue damage.[4] In fact, a high-velocity bullet is likely to lead to a quick and fatal injury to the victim, whereas a low-velocity bullet may cause a non-fatal injury.

Bullet injuries are most severe in friable solid organs such as the liver and brain, where damage may be caused by temporary cavitation remote from the actual bullet track. Dense tissues such as bone and loose tissues such as subcutaneous fat are more resistant to bullet injury.[3]

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The use of computed tomography (CT) within forensic practice is expanding rapidly, replacing plain radiography and fluoroscopy as more applications are recognized.

This article will provide an overview of the spectrum of imaging findings related to the evaluation of patients with gunshot wounds. Ballistics elements are also discussed.

Ballistics

The preponderance of ballistic injuries within the civilian population are caused by handguns, rifles, and shotguns. The resulting projectiles should be conceptualized as “low energy” or “high energy.” This refers to the kinetic energy (KE) of the projectile, which is equal to one-half the mass times velocity squared ($KE = {}^1/_2\ mv^2$). This KE establishes the upper bound of potential tissue destruction, which would occur if all the KE of the projectile was directly transferred producing tissue damage.[5]

There are 2 main mechanisms of tissue damage recognized, tissue crushing (or permanent cavitation) and tissue stretching (or temporary cavitation). The sonic pressure wave leading the projectile missile has been demonstrated to play no part in tissue injury mechanisms. The amount of tissue damage produced by weapons causing large temporary cavitation depends on the tissue characteristics. High-density tissue, such as bone and less elastic less dense tissue such as brain, incur more damage. The temporary conical cavity created pulsates several times before collapsing, creating negative pressure that may also suck debris, including clothing material, hair, and bone fragments, into the wound.[6]

The lethality of a projectile relates significantly and directly to its deformability and the degree of fragmentation it undergoes in the target.

The bullet itself may be a single or composite metal with or without a jacket. The jacket may cover the whole bullet, such as for military ammunition (full metal case or jacket), or be partial providing a soft bullet tip. The bullet (and jacket where existent) may be present within the body, but this is dependent upon the speed at which it is travelling and the distance of the body from the muzzle of the weapon.[7]

The calibre of a bullet is expressed as a decimal corresponding to the diameter in inches, or by the actual diameter in millimetres. Bullets of equal calibre may have different weights. Lead represents the most common base metal used for making bullets, and antimony or tin is generally added to increase the hardness. The barrels of rifles and handguns have grooves along their length to impart a rotational spin along the long axis of the bullet, which stabilizes the flight of the bullet.[8] Information about the type of bullet can be determined by its radiographic appearance. “Mushrooming,” which is the typical flattening of one end of the bullet when it strikes flesh, indicates a solid lead or partially metal-jacketed bullet.

Ballistics is a branch of science that deals with natural laws governing projectiles and their expected performance. Wound ballistics is a term used as a subset of terminal ballistics, referring to the different effects of projectiles on living tissues. Generally, bullet wounds (and, in fact, any projectile wound) are more severe when the projectile yaws through tissue, when the projectile fragments or deforms (eg, into a mushroom shape), when the projectile is large, or when the projectile is traveling at high velocity.

Figure 1 CT examination showing the presence of a bullet causing streak artifacts.

Projectile injury is classified by the location of the entrance and exit wounds and the course of the projectile path. The projectile path is typically described in 3 directions, defining the direction of projectile travel. The presence or absence of foreign material within the body (eg, bullet, metallic fragment, or other material) is always noted and characterized because retrieval of fragments is significant for ballistics documentation.[9,10]

Wounds resulting from ballistic injuries are classified as penetrating, perforating, and avulsive. Penetrating injuries involve a projectile striking soft tissue, but the projectile remains inside the body. Perforating projectiles enter and exit the body with light loss of tissue. Avulsive injuries include entrance and exit wounds, but unlike perforating injuries, result in extensive tissue loss.[5]

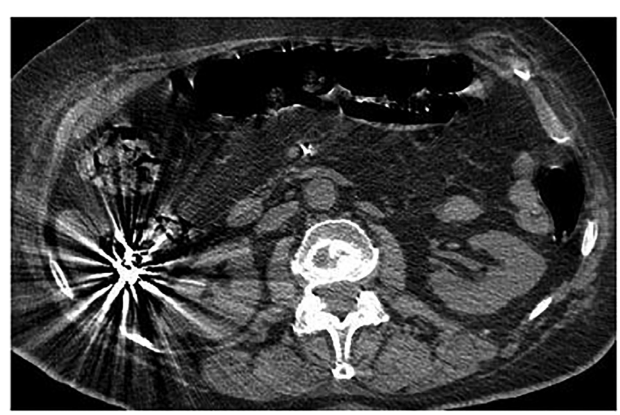

Figure 2 CT examination shows bullet causing streak artifacts.

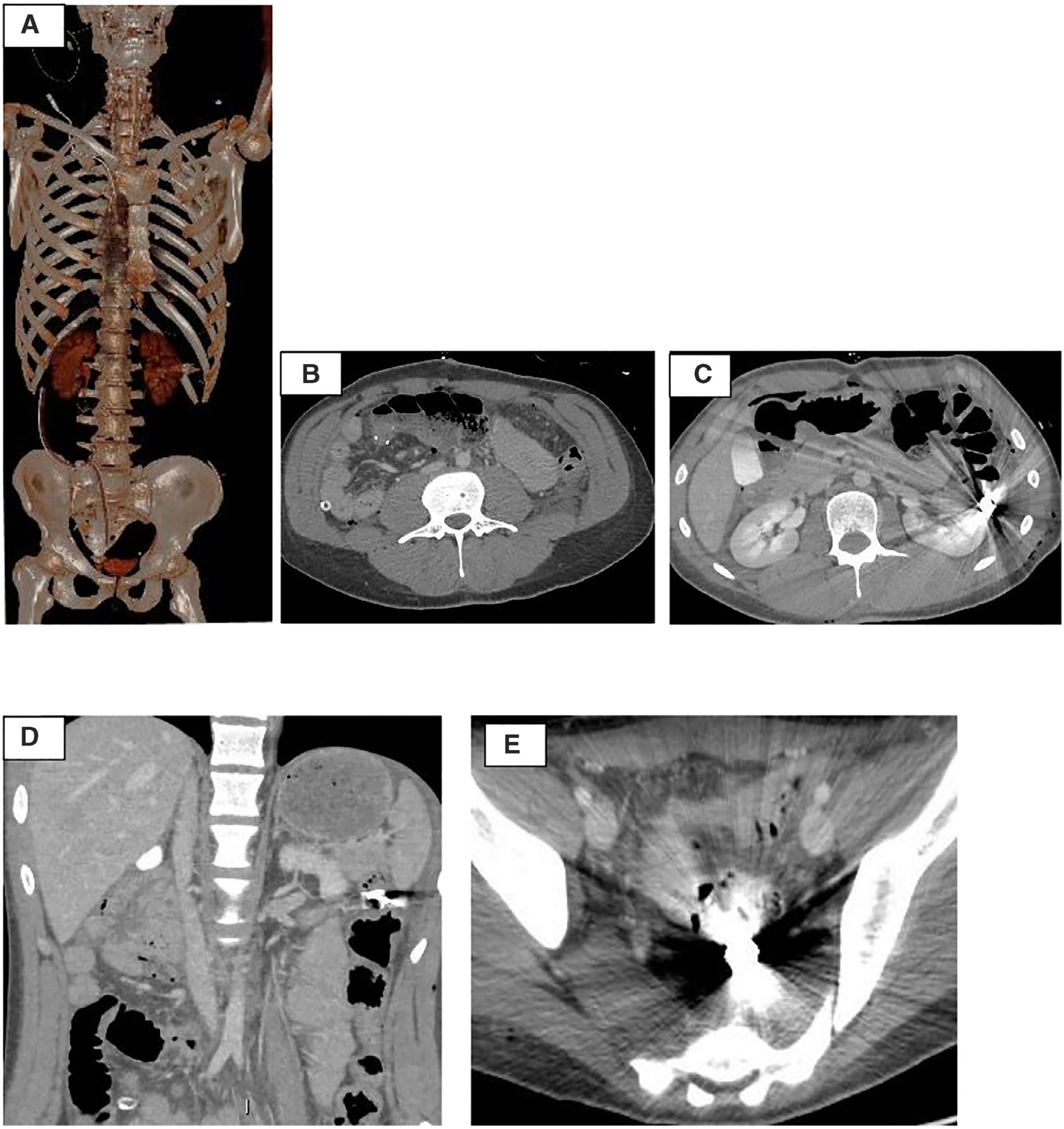

Figure 3 Volume rendering reconstruction (A), contrast-enhanced MDCT scan in axial (B, C) and coronal (D) planes. Patient with gunshot wounds underwent emergency right colectomy due to bowel perforation. After surgery, there is still a retained bullet in the lumen of the descending colon (C, D). It was found in the sigmoid colon at the second CT examination (E).

The type of weapon used can also be a factor in the potential for wound contamination. Shotguns have been shown to cause higher rates of infection than other low-velocity guns.[11]

Firearms are responsible for 2 types of wounds: tunnel of attrition where the tissue is directly damaged by the passage of the projectile and a peripheral zone where the tissue damage is produced by the transmission of the energy dissipated by the projectile.[12] This zone of temporary cavitation is more marked in case of tipping, fragmentation, or deformation of the projectile and may amount to 25 times the calibre of the bullet.[12]

Bullet fragmentation is the separation of the projectile either in part or whole, and bullets that tend to break apart upon impact, including semi-jacketed, hollow-point, non-jacketed, and soft-point bullets, create more injury than those bullets that do not fragment.[13]

A bullet entering the body usually will travel in a straight line until it comes to rest, strikes bone, or exits the body.

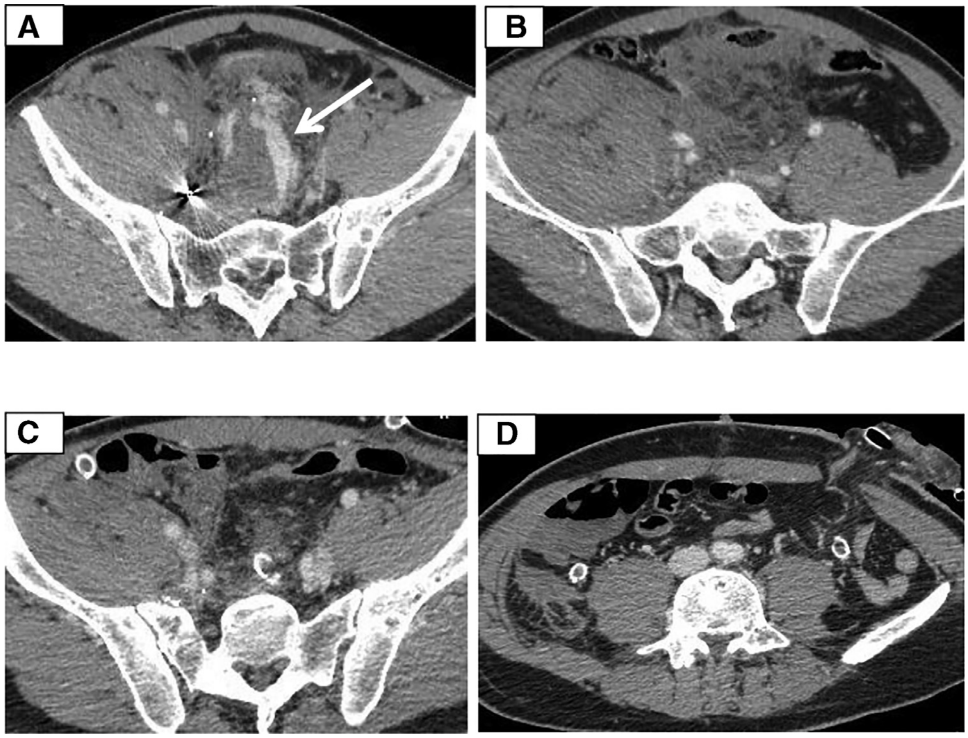

Figure 4 Contrast-enhanced MDCT examinations (A-D): Patient with gunshot wounds in the pelvis and active bleeding in the sigmoid mesocolon (arrow, A), underwent emergency surgical resection with left side colostomy (C, D).

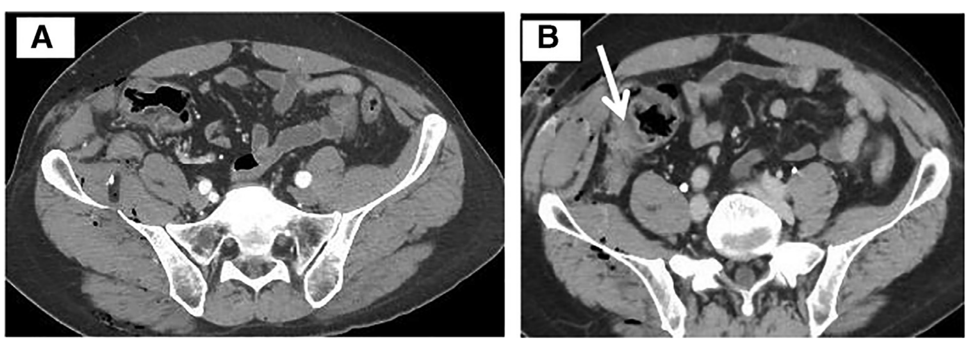

Figure 5 Contrast-enhanced CT examination (A and B) of a patient with gunshot wounds in the right iliac fossa. Evidence of iliac fracture, soft tissue emphysema along the bullet tracts, thickening of the cecum (B, arrow), and inhomogeneity of the adjacent mesentery due to previous bleeding.

Determination of the number of bullets expected or found within the body may be surprisingly difficult.[8] There may be misunderstanding between entrance and exit wounds. Movement of foreign objects within the body can occur in tubular structures such as the vascular system, the alimentary canal, the bronchial tree, the urinary tract, and the neural canal. They can also travel within less confined spaces such as the pleural space or the peritoneal cavity. Because they are of metallic density, bullets and pellets are readily visualized radiographically. Any missile not quickly located near its wound of entry or along an evident tract needs radiological localization.

The most significant factors in causing substantial injury, or death, are the projectile placement and projectile path. The head and torso represent the most vulnerable areas.[14,15] The extent of tissue and organ trauma depends on terminal ballistics, which is influenced by the type of bullet, its velocity and mass, and the physical characteristics of the penetrated tissue.

Direct gunshot injuries to the face and relatively localized soft tissue emphysema can occur as a typical appearance in penetrating neck wounds not breaching the upper aerodigestive tract.[16-18] Sometimes, the site of laryngo-tracheal soft tissue breach or cartilaginous disruption may be easily identified on the CT assessment,[19,20] but in cases of laryngeal injury, extensive extralaryngeal and endolaryngeal soft tissues swelling and hematoma may conceal the site of direct injury. This can be mostly evident in projectile penetrating trauma due to gunshot injury where radiological interpretation may be further hindered by streak artifacts (Figs. 1 and 2). Injury of the pharynx and proximal (cervical) esophagus is uncommon,[21] but should be considered when the trajectory of

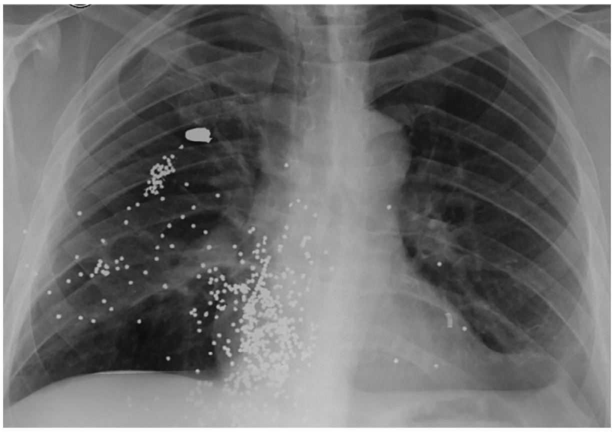

Figure 6 Chest radiograph. A high-velocity gunshot wound to the right chest showing a typical "lead snowstorm" of fragments.

the penetrating injury comes into close proximity with either of these structures.[22,23]

The abdomino-pelvic region (Figs. 3-5) has been considered as one of the most vulnerable regions of the body, and injuries involving this area of the body are very serious.[24-26] Moreover, injuries to the abdomen and pelvis are not always isolated but are often associated with injuries to other parts such as the head, chest, spine, and extremities. CT has emerged as a useful adjunct in the nonoperative management of patients with abdominal gunshot wounds.[27-31]

Bone is form of dense connective tissue composed of calcium salts embedded in a matrix of collagenous fibers, which is infrequently damaged without concomitant muscle injury. Bone may be injured without direct impact due to the dispersion of KE. A minimum velocity of 59.4-61.0 m/s is necessary for a bullet to breach its cortex. The clinical and radiographic appearance of the entrance hole is usually a punched out round-to-oval shape. In contrast, the exit site typically has an excavated, cone-like appearance with a variable amount of combinations.[32]

Lower-velocity projectiles can produce many different fracture patterns, either incomplete or complete. There are 3 types of incomplete fractures: (1) the "drill-hole" fracture, which generally occurs through the soft metaphyseal region of long tubular bones and is characterized by entrance and exit holes with diameters close to the diameter of the bullet; (2) the unicortical ("divot") fracture, which involves a portion of bone removed from the main structure and occasionally a nondisplaced fracture line extending from the divot; and (3) the chip fracture, more common in stab wounds and rarely seen after bullet injuries. Complete fractures are more frequent in diaphyseal bone and include patterns such as the single and double "butterfly" fractures.

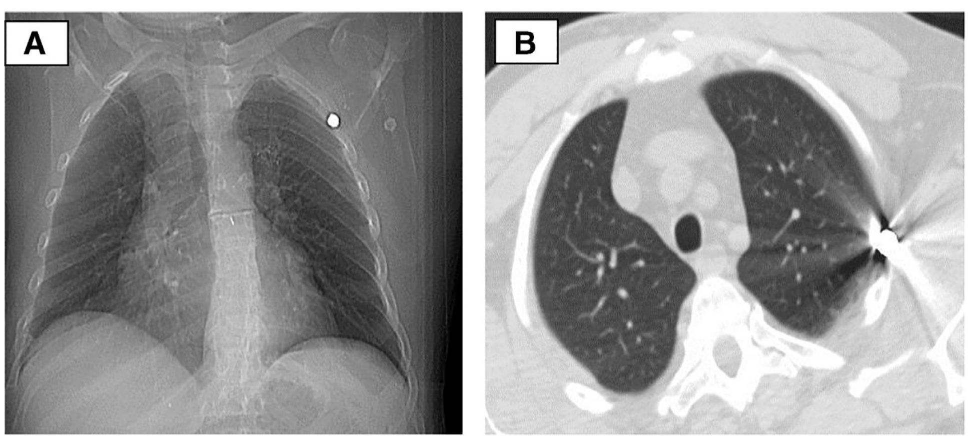

Figure 7 Chest CT examination. Presence of bullet in the left lung (A, scout view; B, axial scan).

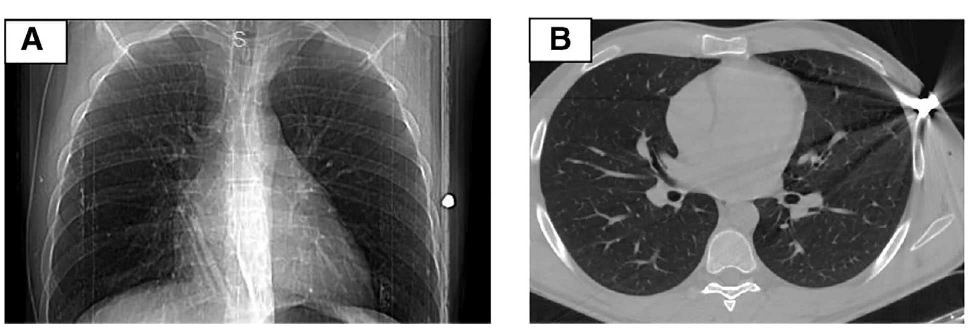

Figure 8 Chest CT examination. Left thoracic bullet wound. Chest CT examination: scout view (A) and axial section (B). Evidence of the entry wound of the bullet in the subcutaneous tissue of the chest wall at the level of the fifth left intercostal space.

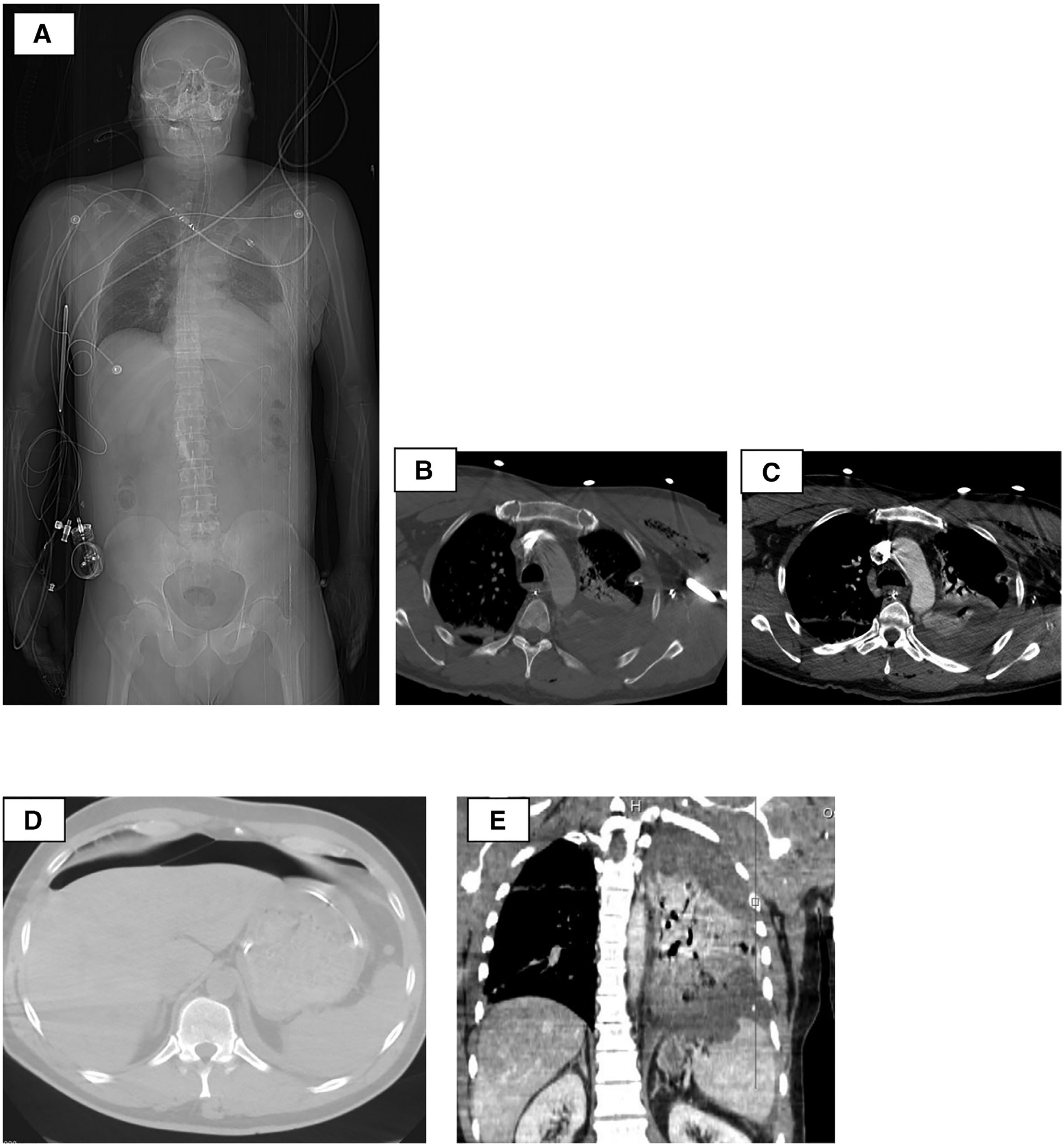

Figure 9 MDCT examination: scout-view (A), axial sections (B-D) and coronal reconstruction (E). Left complex thoracic-abdominal bullet wounds: thoracic subcutaneous emphysema, left haemothorax, multiple ipsilateral rib fractures, pulmonary contusions, left diaphragmatic injury, hemoperitoneum, splenic contusion, and pneumoperitoneum.

Role of Plain Radiographs and CT in the Evaluation of Gunshot Wounds

The use of radiology in the analysis of a firearm injury is standard practice.[33,34] The main objectives, both clinically and forensically, are to establish the precise position of any projectile, the path the projectile has taken and the degree of the damage caused along its course.[7,35,36]

Bullet injuries are different from other trauma-related injuries. Traumatic injuries are usually isolated to the area of impact, whereas a bullet, as it enters the body, forms

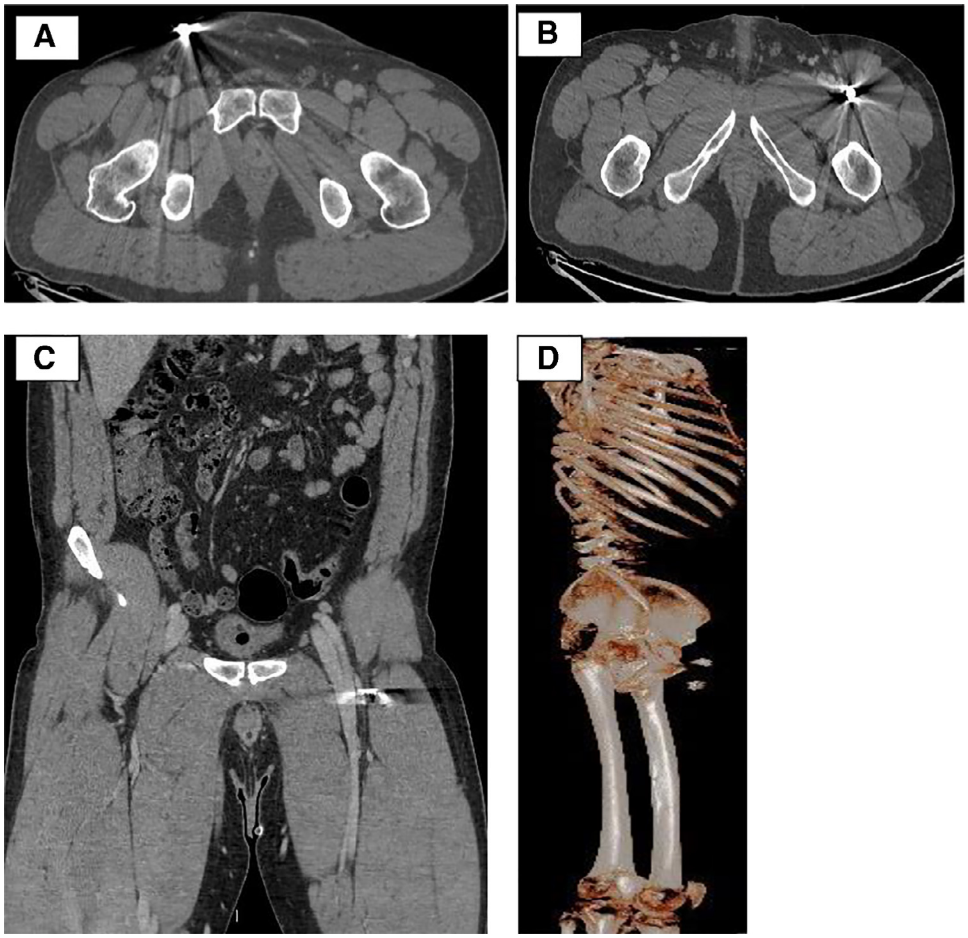

Figure 10 Contrast-enhanced CT scan: axial images (A, B) coronal reconstruction (C) and volume rendering reconstruction (D). Patient with multiple gunshot wounds and retained bullets in the lower limbs. The bullet on the right side is retained in the subcutaneous tissue (A) whereas on the left side (B) it is located near the femoral vessels, without signs of active bleeding.

fragments that magnify the damage in the direction of the bullet. The injury that a bullet creates is therefore unpredictable. To evaluate this damage, the basics of ballistics need to be well understood.[17]

Hemodynamically stable patients and patients who stabilized after immediate resuscitation are assessed with a careful evaluation of history and physical examination. Imaging is critical for the assessment of ballistic injuries, especially when management does not include immediate exploratory surgery. A routine radiograph (Fig. 6) is performed in patients with gunshot wounds. Conventional radiography can detect ballistic material within the body, providing information related to the projectile tract, identify ballistic fractures, as well as detail the amount and location of bullet deformation or fragmentation.

Evaluation of bone injuries and the dissemination of bone and bullet fragments on radiographs can be helpful in determining the direction of travel, which is important not only for clinical assessment but also for forensic evaluation of the incident. Although radiography can frequently demonstrate the direction of travel accurately, it has been shown that trauma physicians are unable to reliably distinguish exit wounds from entry wounds.[37] Bone and bullet fragments are generally disseminated along the bullet track within the soft tissues, beyond the defect in the bone. Careful analysis of the images should reveal bevelling of the bone toward the direction of travel. The degree of bullet fragmentation is also affected by bullet construction.

With the further evolution of CT technology (Figs. 7 and 8), multidetector row computed tomography (MDCT) angiography has become a fundamental part of the initial assessment of injured patients (Figs. 9-11).[38-40] It is widely available, easily accessible, and is a screening modality for the evaluation of all the soft-tissue structures in the body regardless of the location of the external wound.[41,42] In many centers, MDCT angiography is available 24 hours a day and allows close monitoring of the patient by the clinical team.[43]

MDCT angiography can promptly reveal common vascular injuries, such as vessel occlusion, pseudoaneurysm, extravasation, intimal flap, and dissection. Moreover, it can aid in

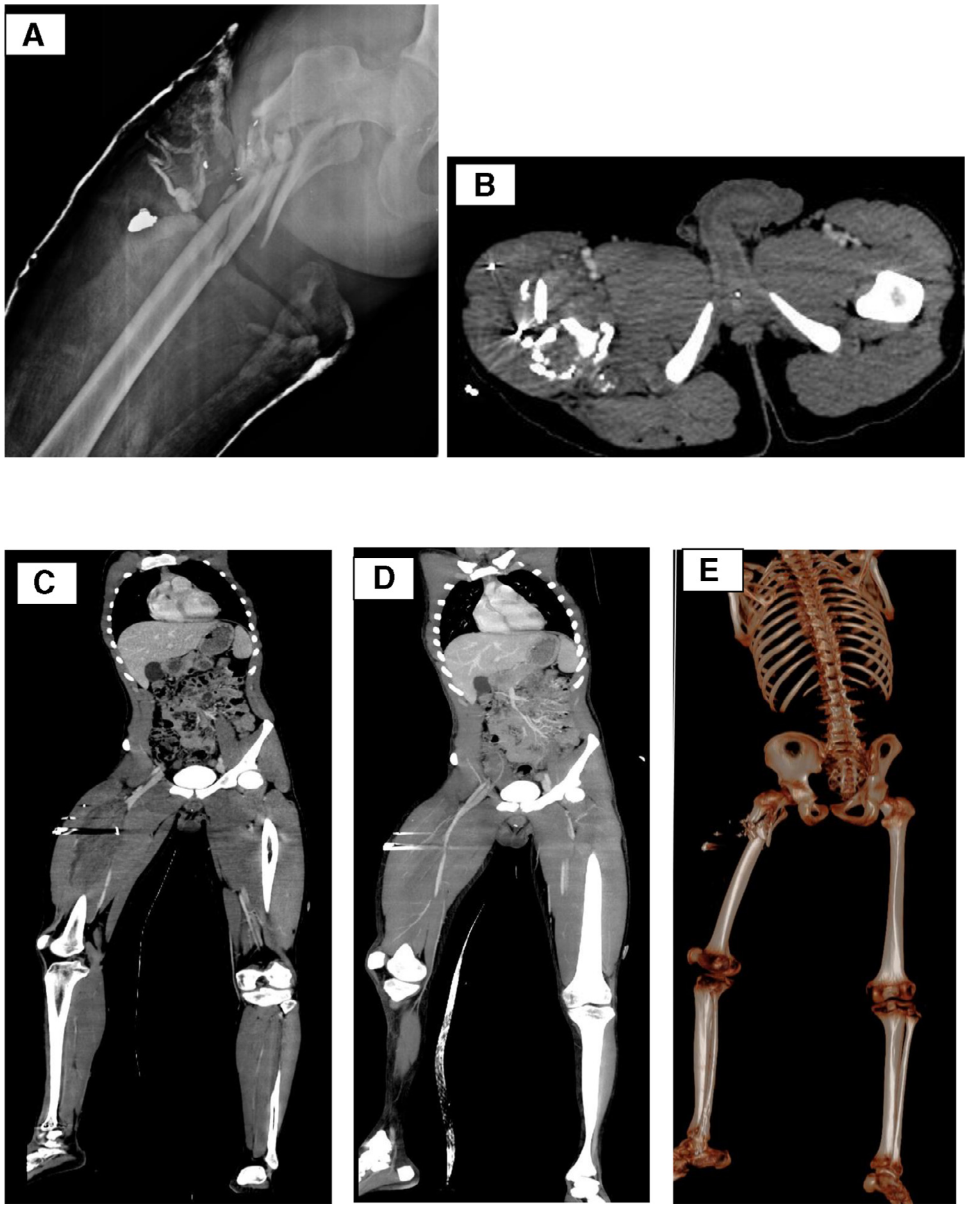

Figure 11 Radiograph (A), contrast-enhanced MDCT scan in axial (A) coronal planes (C, D) and volume rendering reconstruction (E). Patient with gunshot wound and retained bullets in the right lower limb. The gunshot wounds caused a complex fracture of the proximal femur (A, B, E) and an extensive injury of the adjacent muscles (C), without signs of active bleeding.

estimating the proximity to vascular structures by depicting the trajectory of bullets and the location of missiles or bone fragments (Figs.12 and 13) in cases of gunshot injuries.[44,45]

The 3D capability of MDCT is of crucial importance in the assessment of foreign bodies as it allows more accurate location than plain radiography and allows more detailed assessment of damage to the internal structures.[46] This information is used in the clinical setting to direct further investigations and management, and in the forensic arena to investigate the circumstances surrounding the patient's death which may also be useful as evidence in court. The absence of foreign material is equally as important as it suggests the projectile may have crossed the body and exited.

Axial images detect subtle changes in vessel calibre and small contrast extravasations.[47] Multiplanar reformations and 3D reconstructions aid interpretation of challenging cases and most surgeons prefer reconstructions that closely resemble angiography. Maximum intensity projection images display only the highest attenuation voxels within a given thickness. The image combining multiple slices easily displays vascular course, irregularities, and extravasated contrast.

Occasionally, beam hardening artifacts can simulate an intimal tear in any of the arteries, increasing risk of a false-positive read.[48,49] Vascular abnormalities and variants can also simulate vascular injury.[50]

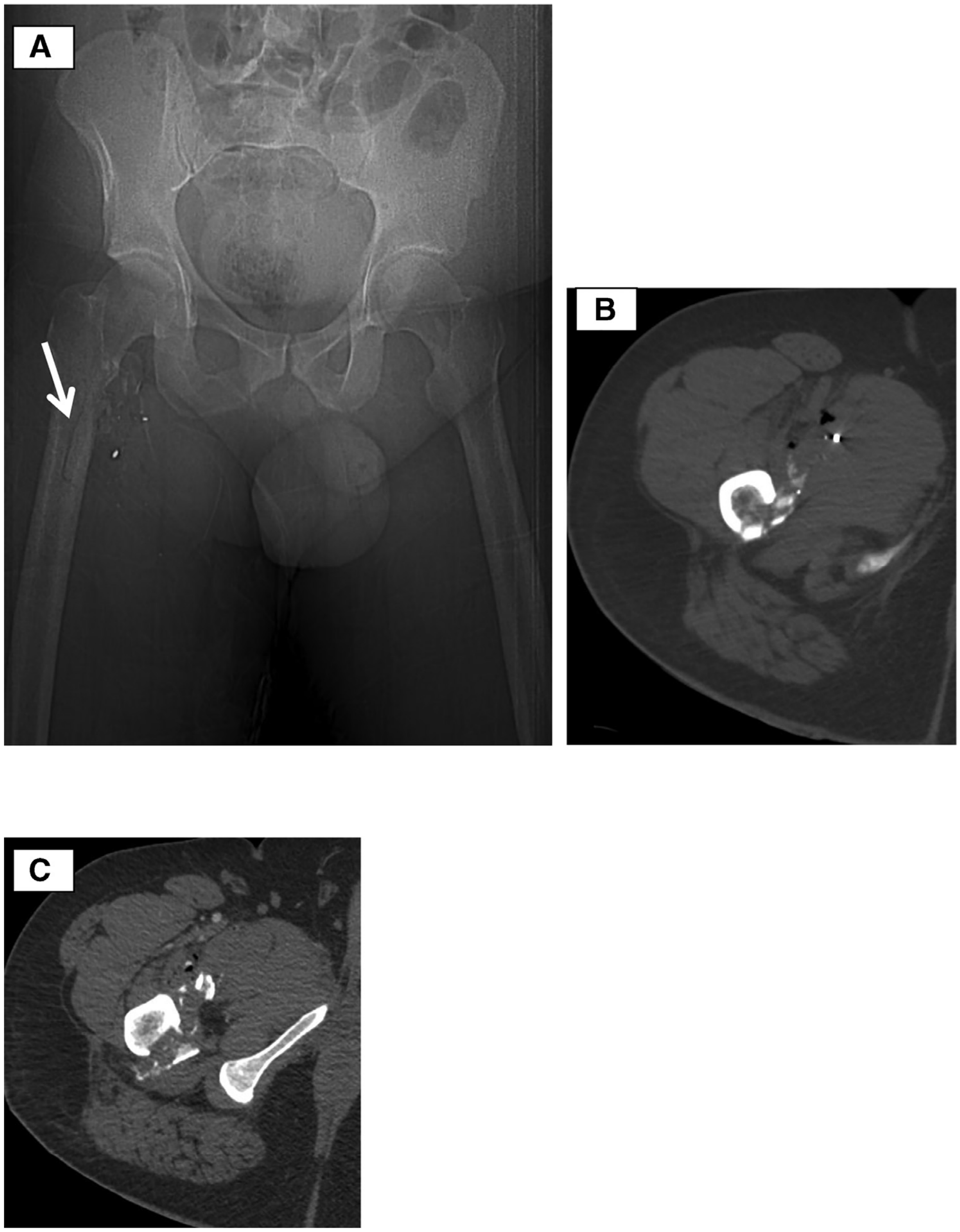

Figure 12 MDCT examination: scout-view (A), axial sections (B, C). Gunshot wounds to the right thigh region. Fracture of right femur (arrow, A) and lesser trochanter avulsion. CT shows the bony fragments and bullet remnant (A-C).

Conclusions

Gunshot wound injuries, most often caused by low-velocity civilian bullets, carry a certain mystique and are feared because of the "blast effect" and the damage it can cause to nearby tissues.

The pathological effects of the gunshot wound will depend not only on the calibre of weapons but also on the quantity of energy transferred, the rate of transfer and energy flux, which is influenced by the range of shot, the type of shot (size and weight of pellets), the impact velocity, and the body tissue resistance.

The use of MDCT within forensic practice is expanding rapidly, replacing the use of plain radiography and fluoroscopy as more applications are identified. MDCT can provide us with valuable information in victims of projectile injuries in both clinical and forensic cases. In living victims the information provided can be used to direct further investigations and management. This is important for all forensic work, and in particular for the detection of projectile injuries.

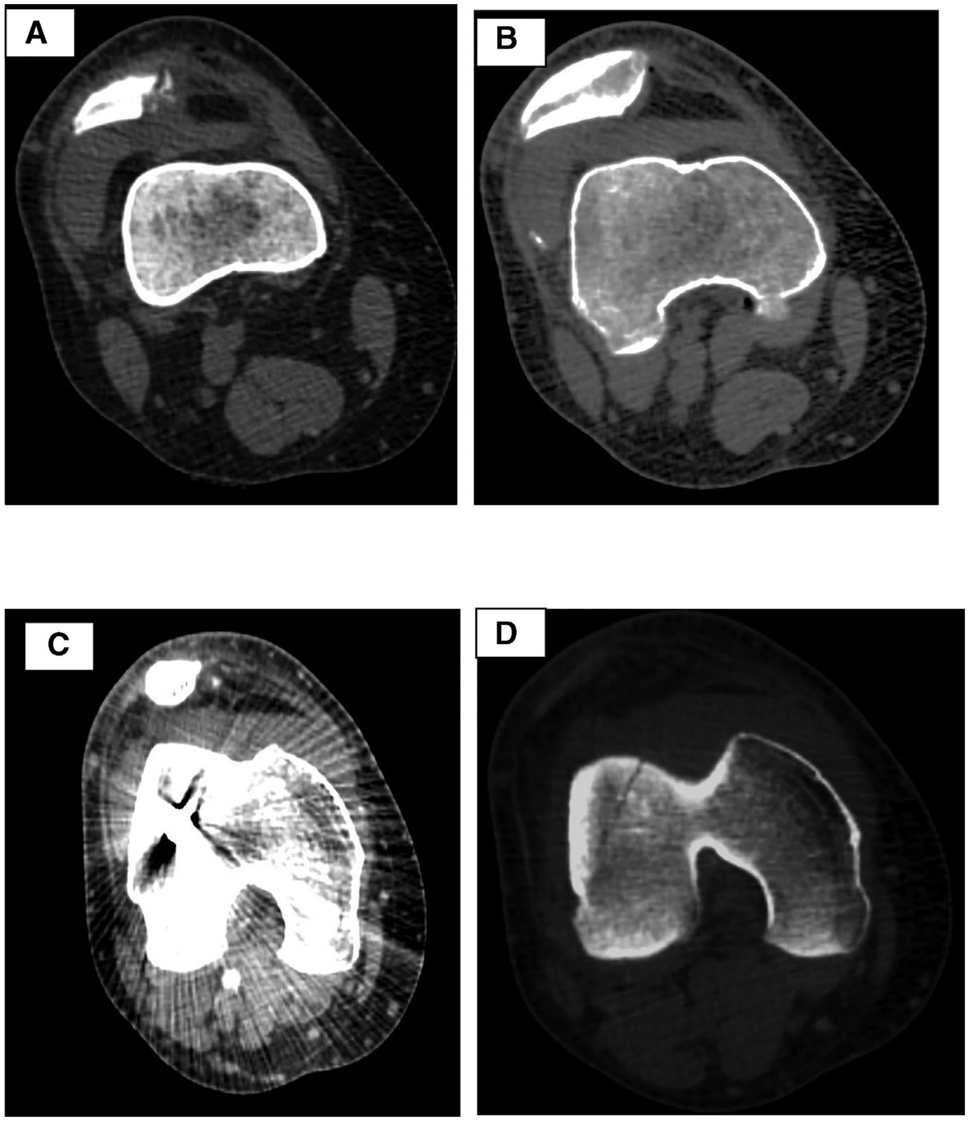

Figure 13 CT examination. Gunshot wounds to the knee. Fracture of the patella (A) and joint effusion (A-D). The bullet is located within the bone (C). There is evidence of fracture extending to the femoral condyle (D).

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