Chapter 5
Significant Medical Advances on the Battlefield and the Changing Roles of Imaging

Keywords Combat application tourniquet · Tactical combat casualty care · Casualty evacuation · Medical evacuation · Air evacuation · Extended focused abdominal sonography in trauma · Anatomic positioning system · Trajectory analysis · Decision support tools · Health vault · Universal trauma window

5.1 Record Survival Rates of Combat Casualties

American and coalition forces can claim one overwhelming victory in recent conflicts: the highest survival rate of combat casualties in history. Approximately 98% of all casualties brought to our facility survived, a higher percentage than ever before in prior wars. Some of the most obvious contributions to these record survival rates are due to advances such as the Combat Application Tourniquet (CAT) and its clear indications from TCCC (Tactical Combat Casualty Care). Other major contributors to heroic survival success is clearly due to improved helicopter casualty and medical evacuation from the front lines to the many combat hospitals. In addition, Air Force air evacuation out of war zone to the upper echelons of care is described earlier in this book. Myself and others believe advanced imaging techniques and applications, some discussed here, have also significantly contributed to these record survival rates.

An example of heroic performance of medical professionals in battle conditions is best exemplified by the helicopter combat medics that rescue the combat casualties from the point of injury. While often under fire, these medics and helicopter crews bring casualties on battlefield to advanced imaging and surgical capability in record time, often in minutes within initial injury. When active shooting and bombing stops (for the most part, anyway) in firefights of battle, the helicopter rescue efforts arrive to our medical center within minutes. In addition to getting shot at regularly, the heat, survival, protective gear, and logistical challenges are tremendous. The combat medics endure this daily and are physically and mentally fit, sharp, and experienced. The medics (essentially paramedics with flight environment and survival training) provide ACLS/ATLS, fluids and resuscitation like any medical response in the US, only within the fog of combat operations.

L. Folio (ed.), *Combat Radiology: Diagnostic Imaging of Blast and Ballistic Injuries*,
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Fig. 5.1 Photo of my preparing to transport a severely injured casualty from one combat hospital in Iraq to another. Radiologists with other medical specialties such as aerospace medicine may be called upon to transport patients on medical evacuation missions

As a flight surgeon, I can only empathize with the conditions that these true heros endure regularly. See Fig. 5.1 for a photo of me preparing to transport a casualty from one combat hospital to another for follow-up care. Note the survival vest to include weapon with rounds on top of the heavy body armor (Fig. 5.2).

5.2 Imaging Advances in Deployed Combat Hospitals

One of the first imaging advances a casualty experiences in Air Force Theater Hospitals is the ultrasound. After the trauma CBAs and continued urgent life support measures, comes the E-FAST (Extended Focused Abdominal Sonography in Trauma). In addition to the four abdominal quadrant FAST for abdominal fluid (e.g., Morrison’s pouch), pleural and pericardial fluid surveillance, a look for pneumothorax is obtained for instant information on these important parameters. This policy is AOR wide among all echelons for standardized care. Radiologists can play various roles in the E-FAST, however, are performed mostly by the ED docs and trauma surgeons.

Fig. 5.2 Photo taken within a UH-60 Blackhawk helicopter capable of transporting six litter patients at a time. Note again the survival gear to include M9 weapon all doctors are issued

Ultrasound is also commonly used in the ICU and wards for guided fluid drainage (for fluid collections in the chest, empyemas, abscesses, etc.) not significantly different than many medical centers. Since there is no role for MR in combat as of this writing, MSK US can be of tremendous value. Lastly, research is underway at USU to evaluate and train physicians to use US guidance for foreign body retrieval in blast casualties.

Although fixed fluoroscopy is not commonplace in deployed settings, direct digital C-Arms in the operating rooms have helped vascular/orthopedic surgeons and interventional radiologists perform procedures that rival many university medical centers and trauma hospitals. See Fig. 5.3, for example, C-Arm image capture of a coil placement into a pseudoaneurysm created by a GSW to the neck. See also Figs. 5.4–5.7 for CTA and coiling and postcoiling of pseudoaneurysm. More information on this casualty saved by our resourceful team of providers can be found in Military Medicine [1].

5.3 Anatomic Positioning System and Trajectory Analysis

Imaging advances on the battlefield include recent experience with MDCT and rapid MPR, and 3D volume rendered images to accurately guide trauma surgeons to involved regions and organs more effectively. For example, with CTA and MPR, a radiologist can quickly determine the wound path of a projectile (blast fragment or

Fig. 5.3 C-Arm interoperative selective ICA angiogram with isolated CTA 3-D correlation (3B).Reprinted with permission from Military Medicine: International Journal of AMSUS

GSW) and demonstrate to the ED doc and/or surgeon the path and potential organ, major vessel involvement [2]. Backus and Folio described these reconstructed MPR's that were off-axis from the cardinal planes as complex planes to include para-axial, para-sagittal, and para-coronal, depending on the closest parent cardinal plane (axial, sagittal, coronal) for consistent reporting and epidemiology.

Beyond the immediate patient care benefits or accurately assessing organ damage, extrapolation of the wound path to a trajectory outside the body can help investigators at the scene determine the location of a sniper based on extrapolated angles, for example. Knowing distance, body orientation or height of sniper, investigators can use the information from the trauma experienced radiologist to determine unknowns. Trajectory analysis has helped identify sniper locations, differentiate from terrorist from friendly fire, and helped catch sniper teams in warfare to help prevent this deadly activity.

The other relatively new concept includes APS or Anatomical Positioning System for accurately and consistently describing retained blast and ballistic fragment locations in a standard fashion. We are currently studying this concept along with the trajectory analysis to evaluate intra-observer accuracy with known fragment locations. We hope to determine trajectory angles to within 5° of azimuth and altitude and fragment location to within a centimeter from a single reference

Fig. 5.4 Isolated three-dimensional reformatted image of CT Angiogram showing the internal carotid pseudoaneurysm that correlates well with C-arm angiogram. Reprinted with permission from Military Medicine: International Journal of AMSUS

point. We are also looking into developing an overall fragment score based on size, number, and distribution of fragments for wounded warriors for long-term follow-up on them as individuals and for standard comparison with morbidity and mortality. Long-term research on war wounds, many in the complex planes described, may be easier to track if the terminology is consistent. In addition, for those individuals exposed to two, three, or even more blast injuries (not uncommon in war), retained fragments from past injuries can be differentiated from new blast fragments. In addition, identifying the migration of retained fragments will be enhanced by consistent tracking and documenting as projectiles migrate through vessels in the body.

Determining trajectory angles using standard terminology in complex planes and quantifiable angles can be consistently described with complex planes. The classic anatomic planes are shown in Fig. 5.8. Each of the classic planes is 90° offset from two other planes, similar to the cardinal directions of a compass. Cardinal navigational points include north, south, east, and west on a compass. Intermediate planes are introduced here as variations from the classic planes (see Fig. 5.9). Any plane from pure axial to 45° offset from axial is described here as para-axial. Then from that midway point between axial and the other two planes, a description of para-sagittal or para-coronal are appropriate. It should be kept in mind that all planar rotation refers to an infinite number of planes.

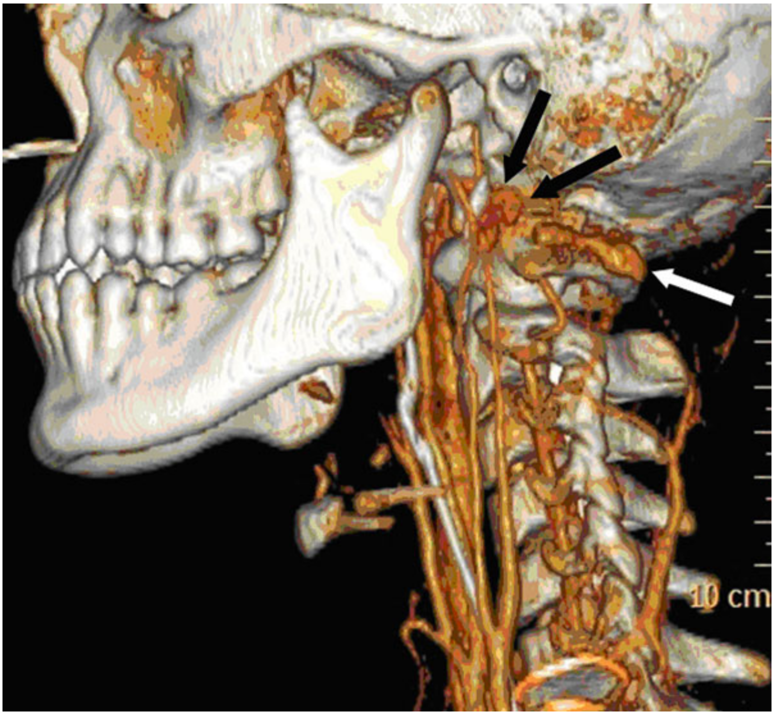


Fig. 5.5 Three-dimensional reformatted image of CT Angiogram showing the internal carotid pseudoaneurysm (*black arrows*) and small vertebral pseudoaneurysm (*white arrow*). Reprinted with permission from Military Medicine: International Journal of AMSUS

An important element to understand complex planes requires an understanding of anatomic axes [3]. Pilots have defined and named rotation around each of the three axes of their aircraft in order to clarify communication as seen in Fig. 5.10. Pivoting around the *X*-axis is "roll," around the *Y*-axis is "pitch," and around the *Z*-axis is "yaw." Pilots use degrees to describe how much they have pivoted around the appropriate axis, such as "Pitch up 10° to climb." That direction is easily translated to rotate 10° around the *Y*-axis. It is concise, clear, and easy to convert and describe.

See Fig. 5.11 to show how anatomic axes relate to established axes in aviation. Degree deviations from the classic planes could be used similarly to precisely describe complex planes intermediate between the classic planes of section (Fig. 5.12). When referring to CT however, the *x*- and *y*-axes are switched to accommodate for pixel locations on image space. This has recently been applied to tumor navigation and identification [4].

The following is an example how to qualitatively describe these starting with the *para-sagittal plane*. In this example, the difference is between a para-sagittal plane and the classic sagittal plane. See Fig. 5.13 showing an example para-sagittal plane.

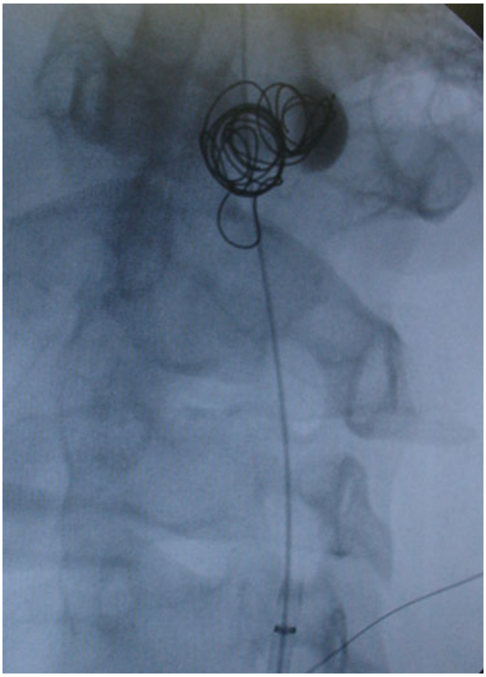


Fig. 5.6 Selective coiling of pseudoaneurysm performed by our deployed interventional radiologist and vascular surgeon in an isoshelter operating room in the tent facility. Reprinted with permission from Military Medicine: International Journal of AMSUS

The para-sagittal plane drawn in this example is rotated around the anatomic *Z*-axis 25° left. One can describe any para-sagittal plane intermediate between the sagittal and coronal plane by defining the rotation around the *Z*-axis relative to the "pure" sagittal. These planes would all be between 0 and 45° (for purposes of description) total arc. A para-sagittal plane intermediate between sagittal and coronal could be described by yaw left or right (from the patient's viewpoint). For example, a radiologist could specify a para-sagittal plane yawed (or rotated around the Z-axis) 30° right. Once past the 45° point, I call this the para-coronal plane.

A *para-axial plane* is intermediate between the axial and coronal plane by defining the pitch up or pitch down from "pure" axial. These planes would all be between up/down 45° or a 90° (for purposes of description) total arc. Para-axial planes intermediate between axial and sagittal can be described by their roll (or rotation around the *X*-axis). For example, a radiologist could specify a para-axial plane rolled (or rotated around the *X*-axis) 30° right.

A *para-coronal plane* intermediate between coronal and sagittal could be described by the yaw (or rotation around the *Z*-axis) while a para-coronal plane intermediate between coronal and axial could be described by pitch (or rotation around the *Y*-axis) forward or backward. The intersection of two skewed (off-axis) planes results in a line that represents the trajectory of the missile, inside and outside of the body.

Fig. 5.7 Selective ICA showing adequate intracerebral patency. Note the coils inhibiting flow into pseudoaneurysm. Reprinted with permission from Military Medicine: International Journal of AMSUS

5.4 Compass Analogy

The classic planes are not unlike the cardinal directions on a compass (Fig. 5.14a) or the geometric x, y, z coordinate system. The degree headings of a compass (Fig. 5.14b) will relate to the anatomic quantifiable trajectories. Using this same analogy, intermediate or complex planes introduced here are like intermediate headings on a compass such as NW (NorthWest, or the midpoint between North and West). The direction between North and NorthWest can be further defined as NNW (North-NorthWest). Similarly, a plane intermediate between axial and coronal, but closer to axial could be described as axial-axialcoronal (AAC) (Fig. 5.15). This can also be true about each of the anatomic axes, see Fig. 5.16 for an example.

Taking that one step further, one could apply the radial degrees around each of several axes like the degrees on a compass (Fig. 5.17) to precisely describe intermediate planes, but a more intuitive system using fewer than 360° can be devised.

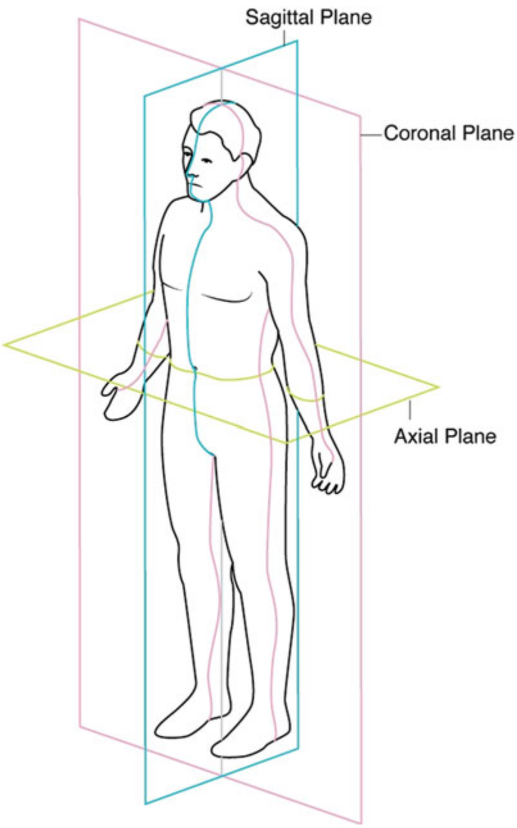


Fig. 5.8 The basic anatomic planes, axial, coronal, and sagittal. Drawing by Sofia Echelmeyer

5.5 Construction of the Trajectory Plane(s) from the CT Dataset

Radiologists typically interpret CT datasets by scrolling through axial CT scan slices on a daily basis. With the introduction of MDCT in recent years, it has become more common to complement the traditional interpretive process with a more complex viewing of volumetrically acquired datasets [5]. Trajectories have been analyzed in the past, both by administration of contrast and by CT [6]. Recent work from Walter Reed Medical Center has demonstrated identification of trajectories using Anatomic Positioning System Cartesian coordinates and image space/table position on CT [7]. This was further validated on analysis of combat casualty data from Iraq where investigators were able to identify wound paths consistently and qualitatively described them in 90% of trajectories. We further demonstrated that radiologist's measurements using image space and table position were able to

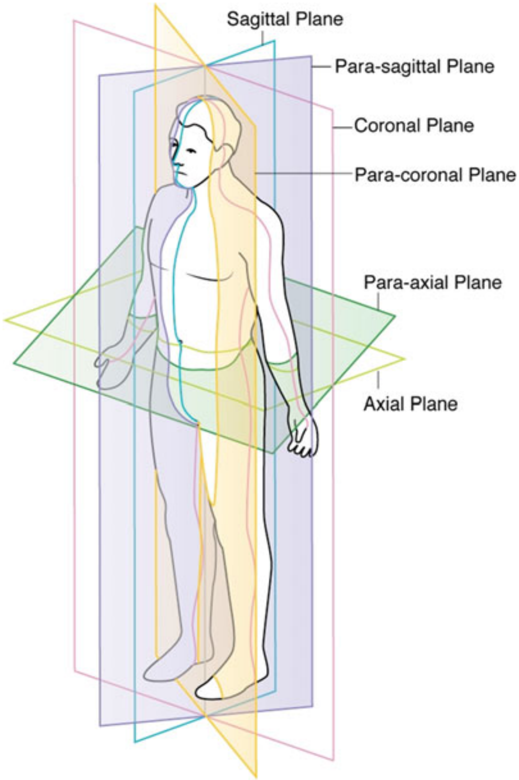


Fig. 5.9 Artist's representation of complex planes is now possible with modern imaging. The complex planes and nomenclature are defined here as intermediaries of the simple planes described above. Each of the planes here are 30° off their parent planes as an example. Reprinted with permission from Military Medicine: International Journal of AMSUS

be mapped consistently enough to calculate the qualitative descriptions of trajectories at the same rate [8]. We created a Cartesian coordinate calculator that could also calculate qualitative trajectories from radiologist measurements using Excel.

Basically this means that radiologists can tilt the plane on any level which is called Multi-Planar Reformation (MPR) [9]. This capability is especially helpful in determining trajectories of blast and ballistic fragments, or resultant pathways when able. This further assists trauma radiologists in providing detailed descriptions to trauma surgeons on an immediate basis as to what anatomical structures are potentially involved, or not involved. This is key in radiologic diagnosis, triage of multiple casualties say from a blast, and guiding trauma surgeons to operating with greater precision. An example of an application of this methodology is described here using a case of a GSW to the chest. Additional cases are reviewed to show how this can apply to other types of projectiles in various anatomic regions.

The first case is a 31-year-old active duty male deployed troop that suffered a gunshot wound (GSW) to the left chest. More detail about the clinical information is available in the author's prior work in Military Medicine [10]. This combat casualty was immediately medevaced from field conditions to a combat hospital in Iraq. The patient was hemodynamically stable in the ER, with the following AP

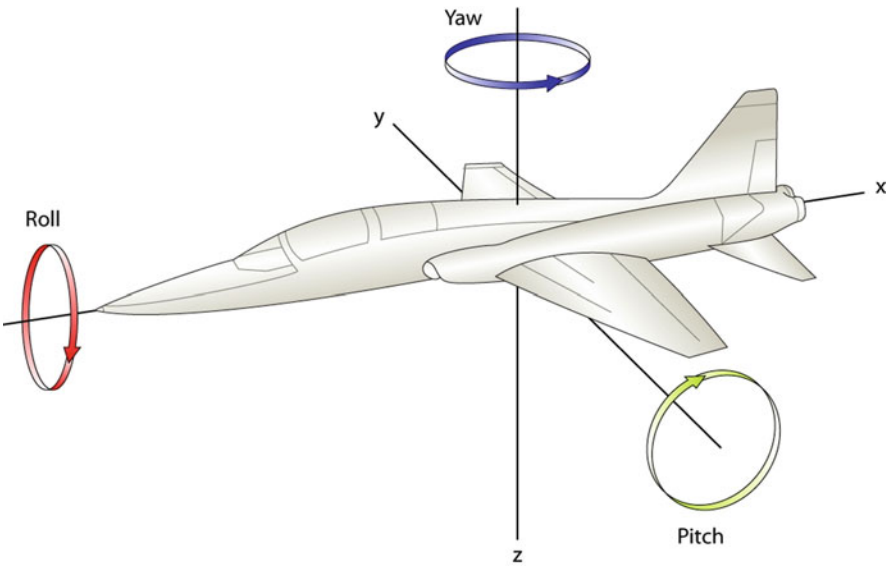


Fig. 5.10 In the aviation sciences, axes are assigned to each possible movement of aircraft for descriptive purposes. Reprinted with permission from Military Medicine: International Journal of AMSUS

chest image obtained to evaluate involvement and rough missile trajectory estimate. This, combined with the clinical observation of single entrance wound to upper left chest anteriorly, demonstrated the bullet overlying the mediastinum, likely posterior. Figure 5.17 demonstrates the bullet overlying the mediastinum, likely posterior, based on isolated anterior entrance noted clinically. Figure 5.18 is reformatted para-axial slice showing the obvious pathway of the missile. The longitudinal homogenous pathway from anterior to posterior aligns with the bullet and entrance. This is the permanent cavity left from the missile. Figure 5.19 shows the para-sagittal plane along the tilted trajectory and can serve as a scout for the para-axial plane determined by pivoting around the known path points.

The first step in trajectory analysis is for the radiologist to walk to the Emergency Department (ED), trauma unit, or less optimally CT and see the patient and wound locations. Ideally, face to face interaction with the ED physician and trauma surgeon will optimize the scan protocol based on the injuries, help determine the wound path, and optimally guide the trauma surgeons based on involved vasculature and organ damage. Based on the most expeditious protocols for that casualty, image acquisition is next. Institution CT protocols often include volumetric data acquisition. Volumetric acquisition is ideal to recreate the data in any plane about any axis. Then postprocessing or image dataset manipulation is done at a diagnostic radiologist workstation or networked PC with dedicated DICOM software. At that point, one identifies the classic plane that the complex plane (described earlier) most closely resembles. However, more precision is available by defining the deviation from the classic plane using the terminology already established in aviation.

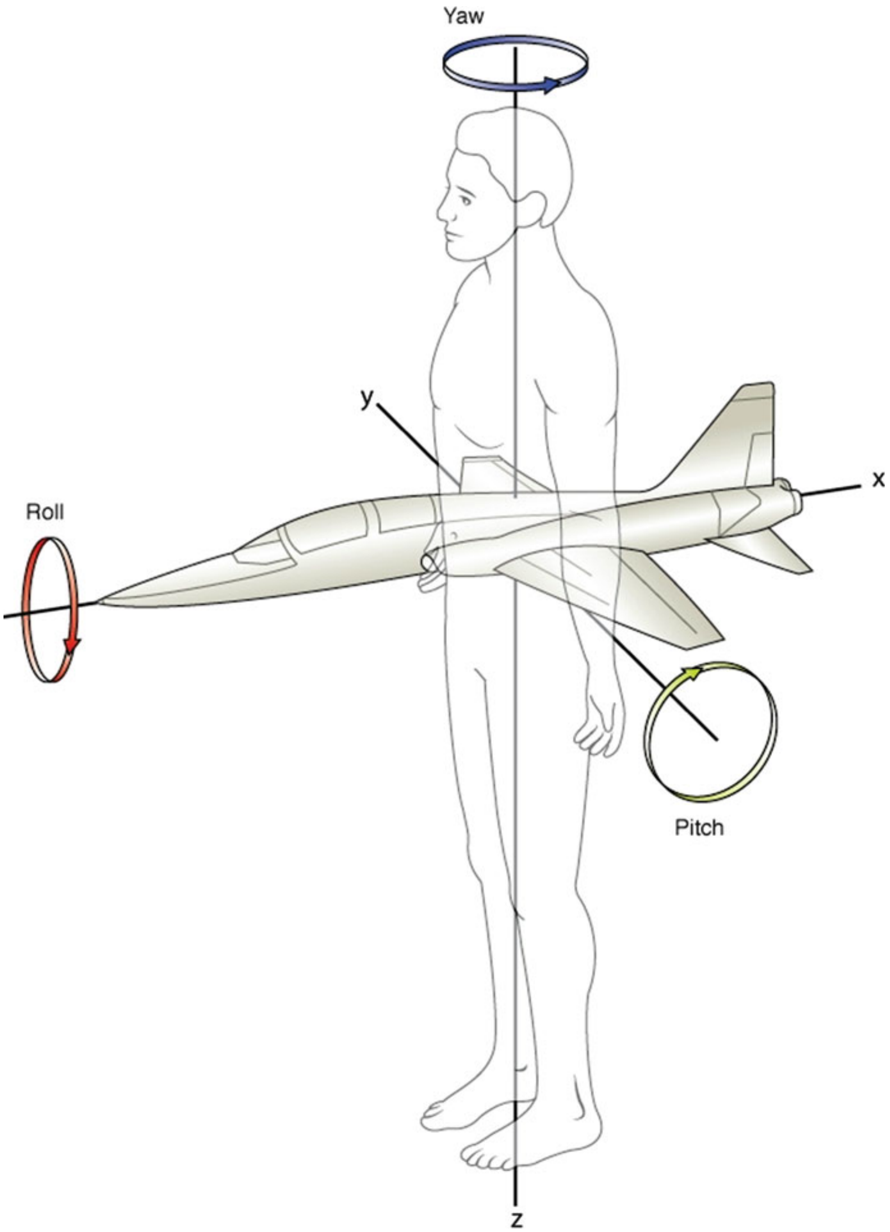


Fig. 5.11 In aerospace medicine, axes are applied to the human body as a pilot is seated in an aircraft, to parallel aviation sciences nomenclature. Reprinted with permission from Military Medicine: International Journal of AMSUS

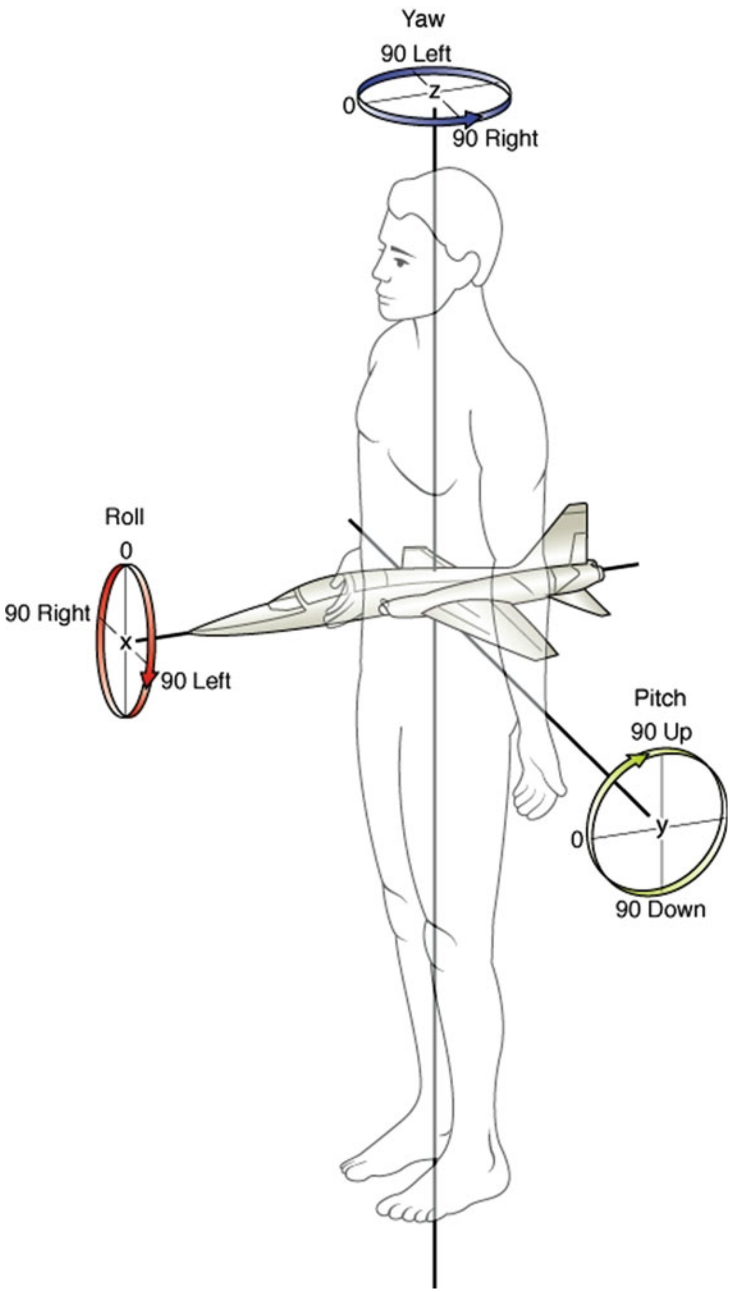


Fig. 5.12 Taking the descriptions a step further, degrees of planes relative to axes can be applied in all directions, about all axes. Reprinted with permission from Military Medicine: International Journal of AMSUS

Fig. 5.13 This drawing shows a para-sagittal plane of 25° pivoted about the anatomic *Z*-axis toward the left. Reprinted with permission from Military Medicine: International Journal of AMSUS

5.6 The Trajectory Mapping Is Accomplished in the Following Manner

When a radiologist gets to a validated path point such as ballistic fragment, entrance, exit, or fracture, the plane is pivoted about that point, in attempt to find other positive pathway identifiers. The case analyzed should have a simple path that is traceable. Many perforating injuries seen in combat from high-velocity weapons fit this criteria as they do not expend their energy in the body. Even paths that ricochet can often be analyzed. Many low-velocity injuries are more chaotic as they expend their energy within the body tissues and may not be traceable. Para-sagittal and/or para-coronal reference slices or "scouts" are often useful for showing the relative planar angles. See Fig. 5.19 once again for our first example para-sagittal of lowest axial plane (1), the most superior axial plane (2) at entrance wound (seen on another slice), and resultant para-axial plane (3) that was ultimately found by this process. This initial case highlights quantification of degrees around axis (Figs. 5.20 and 5.21). Basically, the entrance and exit are found on axial, the middle slice is determined, then the axial slice is tilted by MPR while using the sagittal (or coronal) view as a reference. This can be done from any combination of the three basic

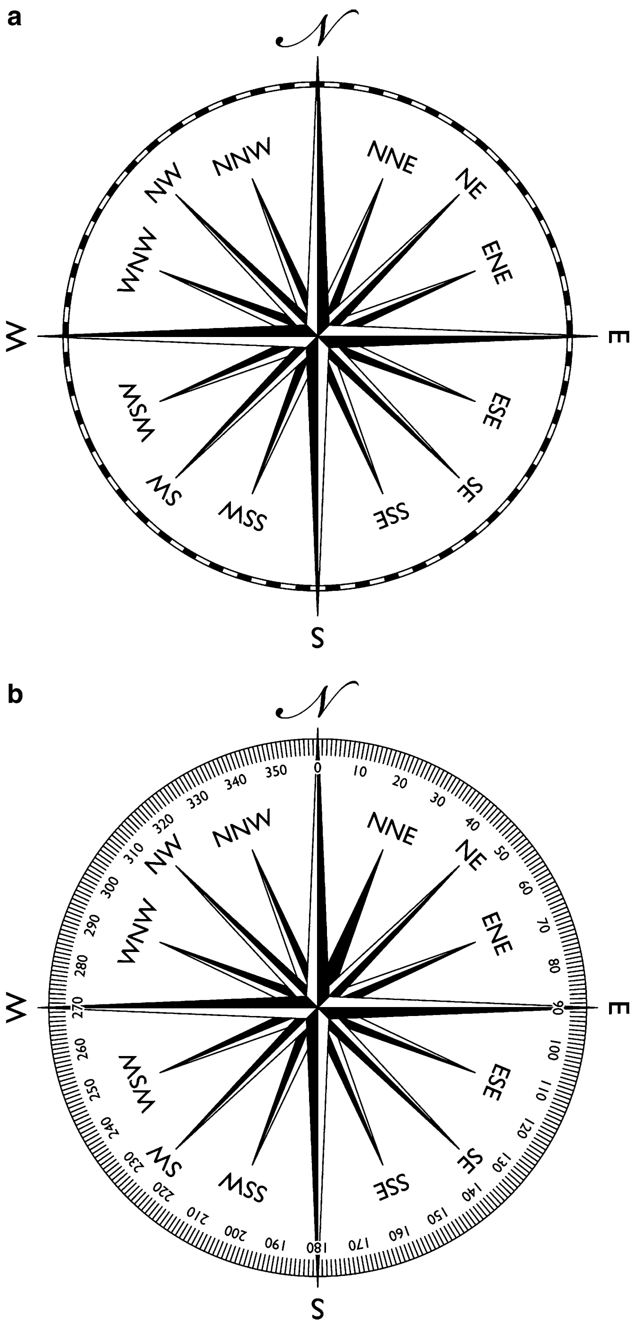


Fig. 5.14 (**a**) Cardinal headings of a compass rose. Drawing by Sofia Echelmeyer. Reprinted with permission from Military Medicine: International Journal of AMSUS. (**b**) Degree headings of a compass rose. Drawing by Sofia Echelmeyer. Reprinted with permission from Military Medicine: International Journal of AMSUS

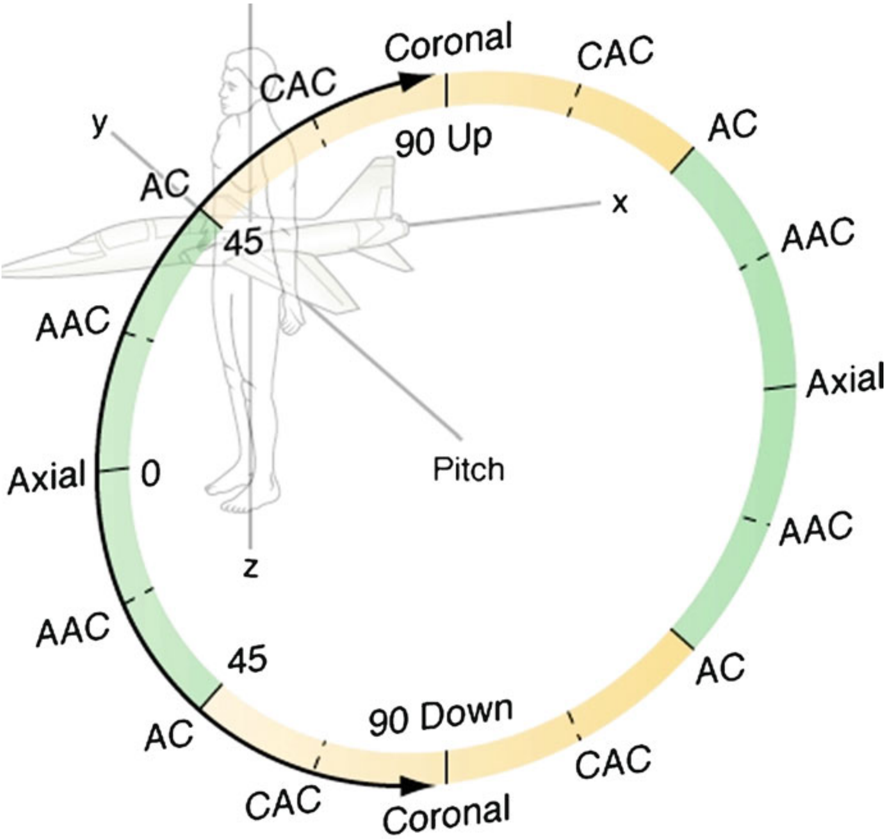


Fig. 5.15 Superimposing the anatomic *y*-axis with the aircraft example allows one to see how pitch can be described in a number of segmented, defined complex intermediary planes similar to how a compass can be further divided into NW and NWW. Drawing by Sofia Echelmeyer. Reprinted with permission from Military Medicine: International Journal of AMSUS

anatomic planes as a starting point. In addition to skin wounds as clues to missile path, fractured bones, remaining metal fragments, subcutaneous air can help determine path. Figure 5.22 shows the para-axial orientation in the body for descriptive purposes, and Fig. 5.23 to demonstrate quantification on one axis. These figures are reprinted from Folio et al [11].

The second plane can be seen by referring back to Fig. 5.13 as a para-sagittal plane yawed 25° left. A three-dimensional wound path (such as the path of a projectile or fragment) can be described by the intersection of two two-dimensional complex planes (see Fig. 5.24). The bullet path is described by the line of intersection between para-axial pitched up 14° and para-sagittal yawed 25° left. Figure 5.25 is a collage of the two complex planes along the bullet path, demonstrating the upward and rightward angle of the path in another graphic form. Many of the bullet paths currently seen in Iraq are caused by snipers shooting from a high position,

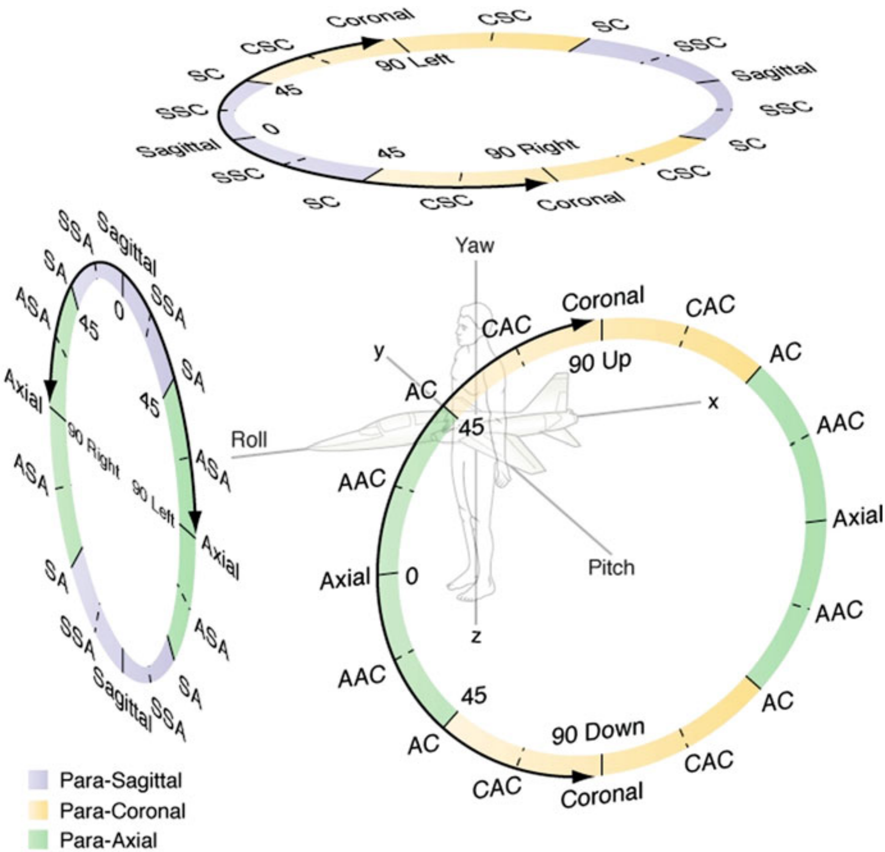


Fig. 5.16 This drawing shows how intermediary planes can be described about all axes. Reprinted with permission from Military Medicine: International Journal of AMSUS

such as atop a building or through a window. This can be seen by the extended bullet path in Fig. 5.26, where the first plane is a para-axial pitched up 14°.

5.7 Additional Cases Presented to Highlight Complex Plane Application

The following are some other examples of penetrating blast or ballistic trauma to highlight trajectory analysis and complex plane description. The next case is another penetrating lung injury, less severe than the first one presented. This is another example of superior to inferior trajectory, likely a sniper, with less bleeding than the first case. Figure 5.27 shows the permanent cavity with air as opposed to blood in the other case. The surrounding consolidative opacities represent contusion

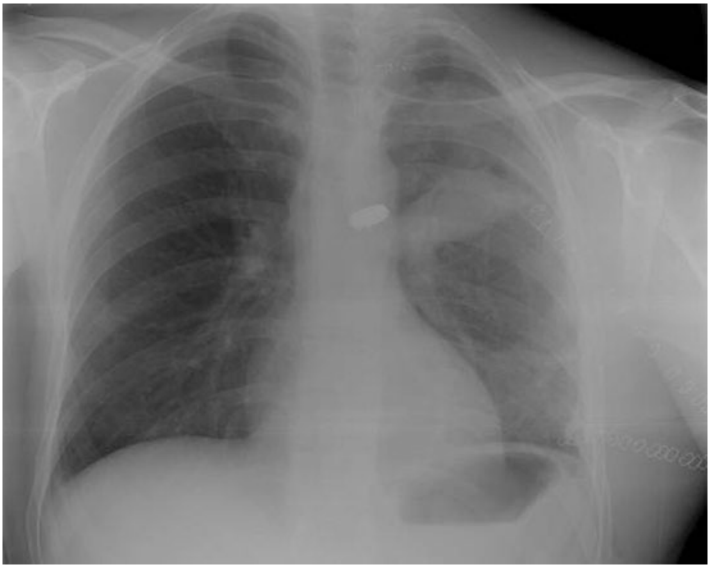


Fig. 5.17 GSW chest X-ray. Reprinted with permission from Military Medicine: International Journal of AMSUS

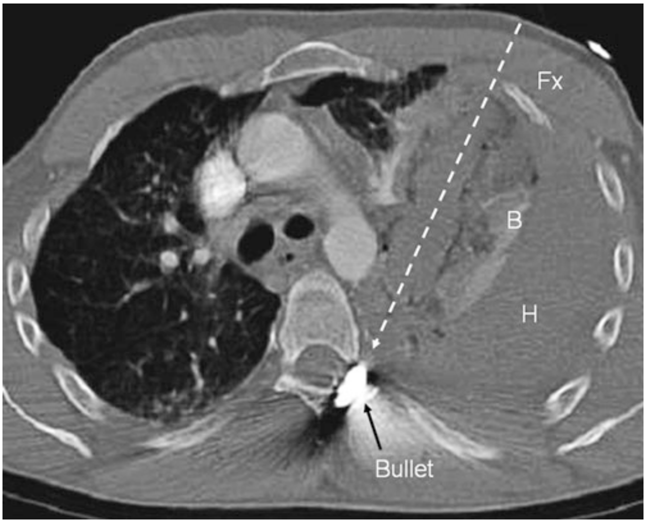


Fig. 5.18 Para-axial CT showing wound path. Reprinted with permission from Military Medicine: International Journal of AMSUS

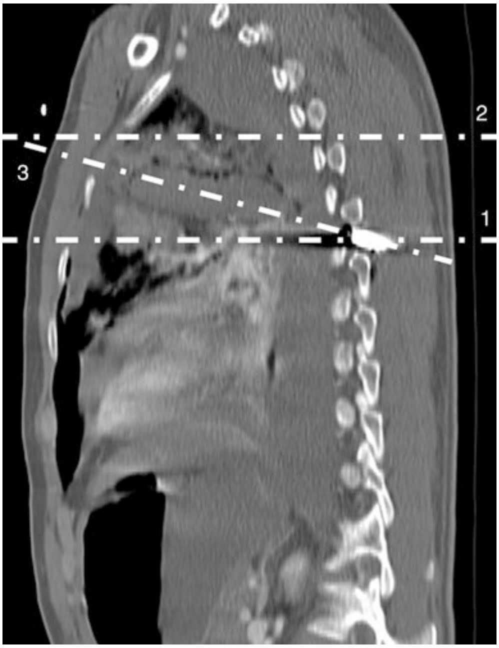


Fig. 5.19 Para-sagittal MPR showing downward angle from sniper shot. Reprinted with permission from Military Medicine: International Journal of AMSUS

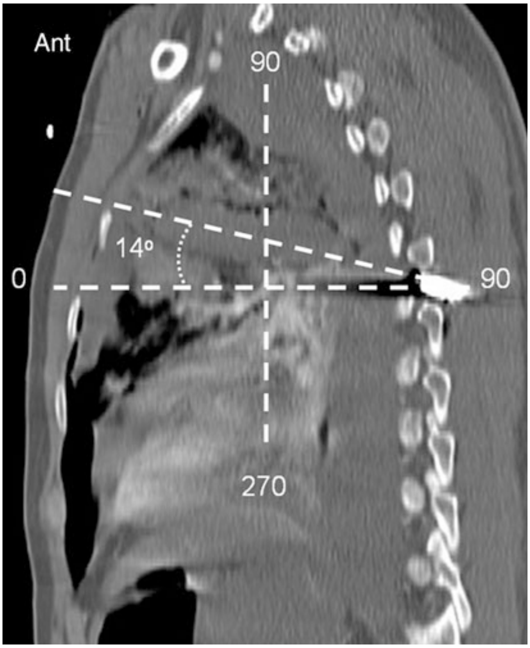


Fig. 5.20 The same para-sagittal MPR showing trajectory at 14° pitch down. Reprinted with permission from Military Medicine: International Journal of AMSUS

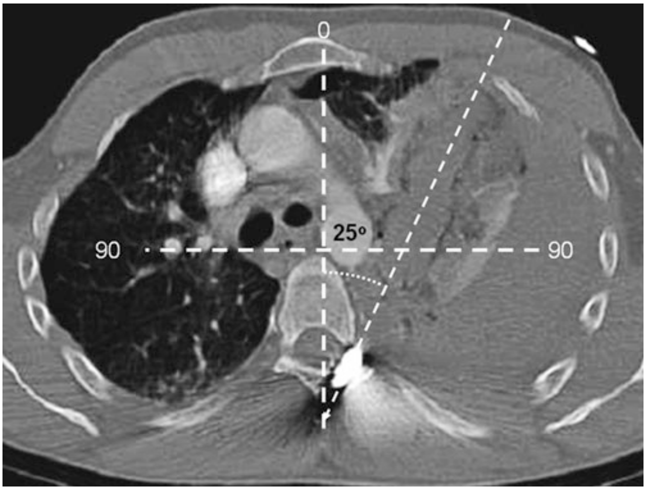


Fig. 5.21 The para-axial MPR showing trajectory 25° toward the patients left. Reprinted with permission from Military Medicine: International Journal of AMSUS

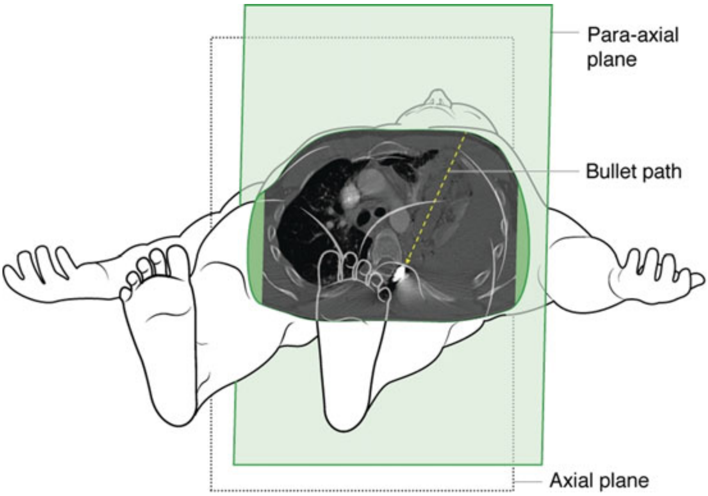


Fig. 5.22 This drawing shows how the para-axial CT is oriented in the body. Reprinted with permission from Military Medicine: International Journal of AMSUS

from the tumbling of the bullet approximating the temporary cavity. The trajectory appears to go through the intact scapula, this is due to a different position of the scapula during the injury. This gunshot was from anterior to posterior, entering the patient's left infraclavicular region, exiting further to the patient's left posterior

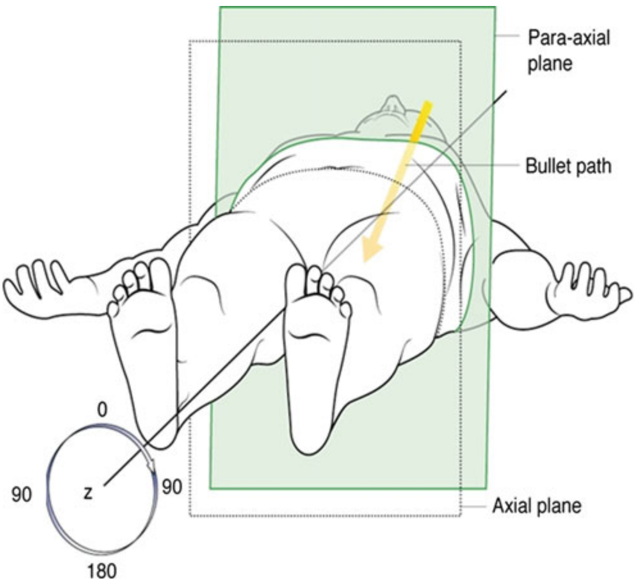


Fig. 5.23 This drawing shows the orientation of the para-axial slice, the para-sagittal rotation of the GSW trajectory. Reprinted with permission from Military Medicine: International Journal of AMSUS

chest. Figure 5.28 shows the quantitative para-sagittal orientation on the para-axial CT MPR.

The next case is of a casualty suffering a grenade injury to the face and neck that has been well described [12]. Figure 5.29 demonstrates the para-axial plane that lines up the fragment entrance and resting place near right lateral ventricle. On closer inspection and planar reformation, the para-sagittal trajectory plane was further determined, eventually enabling accurate incident analysis. See Figs. 5.30 and 5.31 for artists' rendition demonstrating how trajectory detection allowed me to discover damage to the carotid siphon, the tilt of the head during the blast, and the location of the grenade when it detonated. This case highlights how parallel para-axial interpretation based on reference fragments helps find other missiles and associated vascular damage.

A case illustrating a simple but definite path is seen on para-axial images of the liver of a child in close proximity to a blast that has also been well described [13]. Note the large irregular fragment in the right upper abdomen in Fig. 5.32. The projectile traveled anterior to posterior, from right to left. The right elbow was part of the trajectory path evident on the CT scout (Fig. 5.33 shows them both on the same trajectory plane) by severely comminuted fracture and metal fragments. This is further delineated on CT (Figs. 5.34 and 5.35). The right anterior rib at this level is fractured, indicating inclusion in path making this easier to map the missile path. Note the right arm also demonstrates some metallic remnants. The right arm was

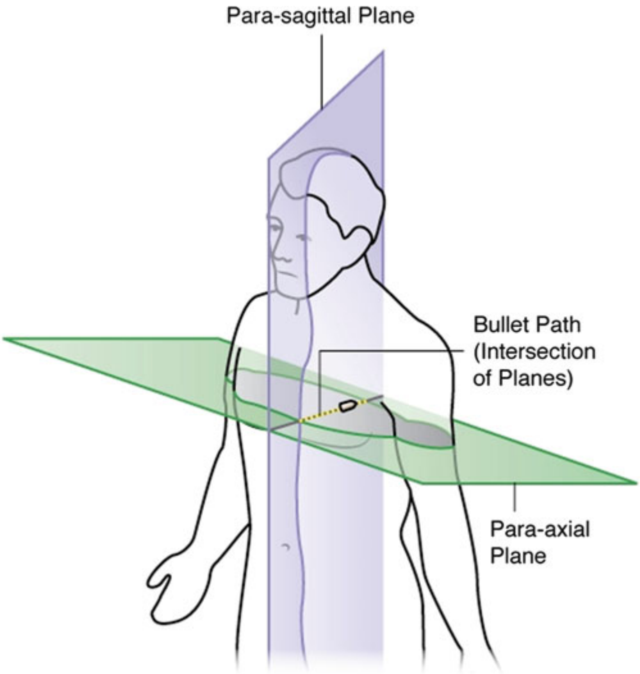


Fig. 5.24 The two complex planes intersecting to create the line representing the trajectory. Reprinted with permission from Military Medicine: International Journal of AMSUS

closer to the body and more anterior at the time of the blast. The determination of arm position can also be helpful in incident analysis with multiple victims from a firefight.

When it comes to recreating the scene or determining multiple missiles' paths in individual victims, another useful determinate that is well described is the keyhole fracture in the skull [14]. See Figs. 5.36 and 5.37 for example, trajectory determination based on orientation of the keyhole that is well described by Jackson. Figures 5.38–5.41 show forces and vectors of initial bullet and resultant bone fragments (which then become the "missile"). Velocity of projectiles is as much of a factor in certain injuries as size [15]. Types of rifles, bores, and bullets are also important factors in wound ballistics [16–18].

One blast victim caught a projectile across his back, perforating the right scapula, traveled through his mid thoracic spine, then through two left ribs evidenced by fractures. Figure 5.42 shows the para-axial reformat showing the entire path on one slice. The projectile then traveled through left arm as well (seen on images not included). The 3D view (Fig. 5.43) shows the path. Scapular involvement (or lack thereof) can sometimes help determine the position of the arms at the time of injury (Figs. 5.44–5.46).

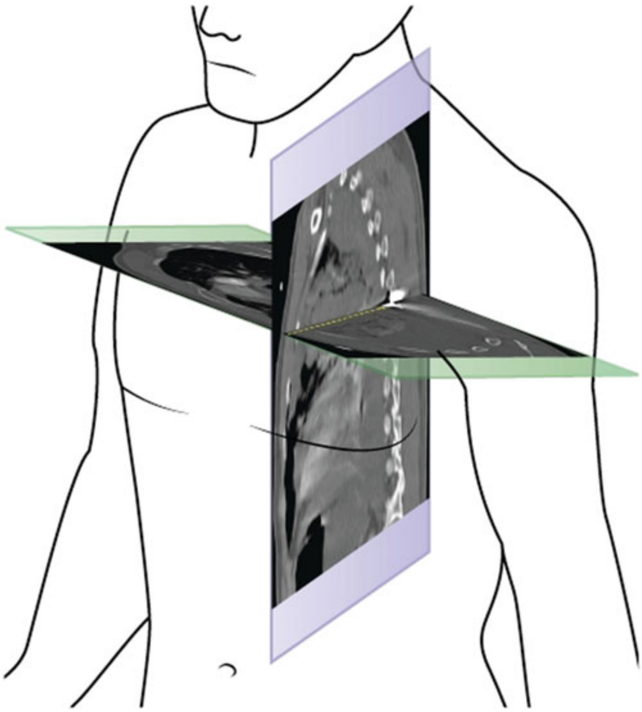


Fig. 5.25 A collage of the two complex plane CT MPRs demonstrating how they intersect at a ray vector describing the trajectory accurately. Reprinted with permission from Military Medicine: International Journal of AMSUS

5.8 Abdominal Trajectories

In the following case, determining the trajectory helped establish associated organ injuries by increasing conspicuity with association along the wound path of a large blast fragment. This case has been well described in the literature [19]. Figures 5.47–5.49 shows an intraperitoneal fragment entered from the back of this child. The para-coronal reformat (Fig. 5.50) demonstrates the path from the left back through the lower pole of the left kidney, through the splenic vasculature (based on a devascularized spleen), the pancreatic tail, diaphragmatic crus then finally residing adjacent to the aorta just superior to the left renal vein. Peritoneal fluid is seen bilaterally; however, there is no evidence of major vascular extravasation. This patient was re-triaged to the operating room at a higher priority level than other patients with less severe injuries (Fig. 5.51).

This next casualty was exposed to a blast from the back and has been described [20]. Figure 5.52 is the scout CT showing the large fragment in the lower abdomen. In Figs. 5.53–5.55para-axial reformats demonstrate a large metal fragment that ended

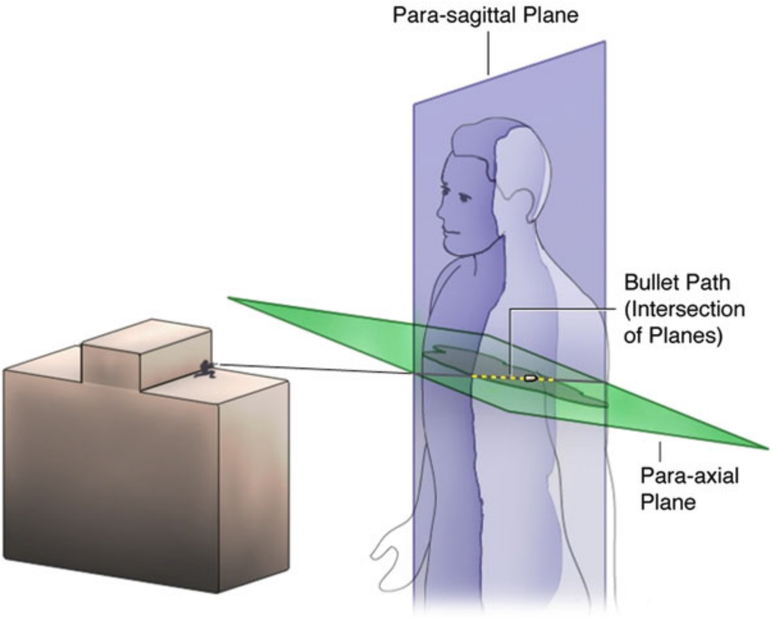


Fig. 5.26 The trajectory extrapolated to the sniper location from a height–distance perspective, and aspect relative to the body at the time of the shot. Reprinted with permission from Military Medicine: International Journal of AMSUS

Fig. 5.27 Para-axial CT MPR nicely demonstrating the permanent cavity (linear lucency representing lung laceration) and the temporary cavitation effects of the tumbling bullet

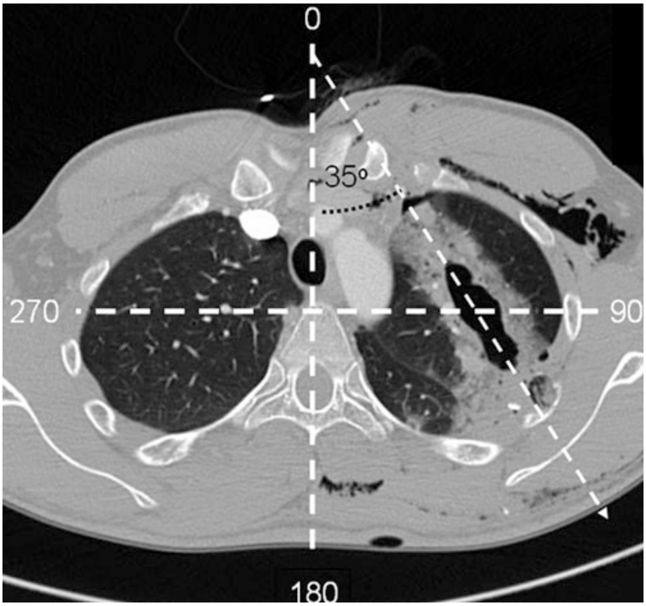


Fig. 5.28 Para-axial CT MPR demonstrating the para-sagittal orientation of the wound path and resultant trajectory

up in the anterior left psoas muscle. The reformats helped demonstrate the lack of intraperitoneal involvement, i.e., this fragment path was shown to be mostly muscular in its trajectory (paravertebral musculature, quadratus lumborum, then psoas). The fractured transverse process, subcutaneous air and soft tissue aberration were all supporting evidence of the missile path. The radiologist in this case worked closely with the ED physician and trauma surgeon to help lower the re-triage status to the operating room since there was likely no bowel perforation or major intra-abdominal process. The operating rooms were full with more critically injured casualties waiting. This again highlights the value of the radiologist presence in the ED and operating rooms with regular interaction of protocolization and preliminary results.

5.9 Ricochet Trajectories

Figure 5.56 highlights a perforating fragment from the back through the right leg that ricocheted superiorly off the right iliac wing that has been well described [21]. Multiplanar reformation in two separate para-axial planes showed that the path was deflected superiorly after striking the iliac wing (Figs. 5.57 and 5.58). This required two reformats: inferior and superior para-axial orientations. This is not uncommon when bone is in the missile path. These reformats helped show that the fragment

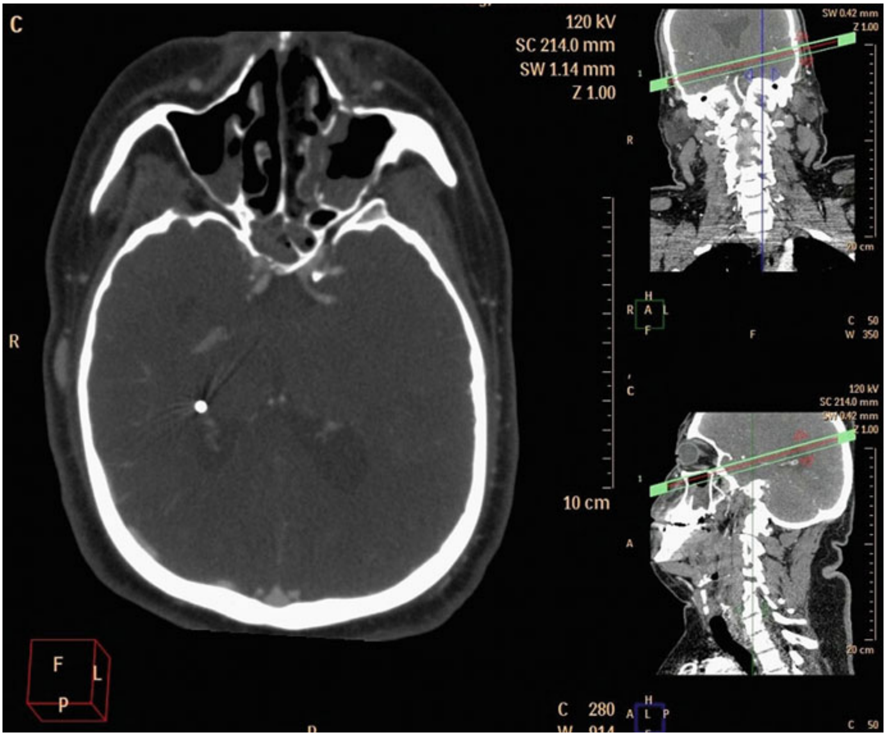


Fig. 5.29 Para-axial CT showing entrance and fragment resting location on one plane. Without lining these up, it would be challenging to determine the damage to the cavernous carotid as we did here

remained extraperitoneal. Although trajectory determination is not as crucial in the abdomen as head, neck, and chest, it can still help identify mystery fragments, or provide clues to potential ureteric, bowel, and/or vessel damage. It should be kept in mind that missiles often ricochet against bone and often change paths as in the previous case. Missiles have also been known to penetrate vasculature and embolize outside the range of entry [22]. For this reason, an even number guide can be applied to demonstrate the need to continue a hunt for an uneven fragment/wound count [23].

Figure 5.59 shows a CXR in a tangential spine injury where ballistic entered through left pectoral muscle anteriorly, between anterior ribs, through lung with a superior to inferior tract, then hit T4 on the left, ricocheted superior exiting also on the left (Figs. 5.60–5.62). This was another sniper shot, missing major vasculature and the spinal canal, and ricocheting superior once again, with fragments further verifying exit from spine through the back. This case has been well described in the literature [24].

Figures 5.63 and 5.64 demonstrate a missile trajectory through the spinal canal at a high level (C4) with slight deflection. Quantitative description of the trajectory to

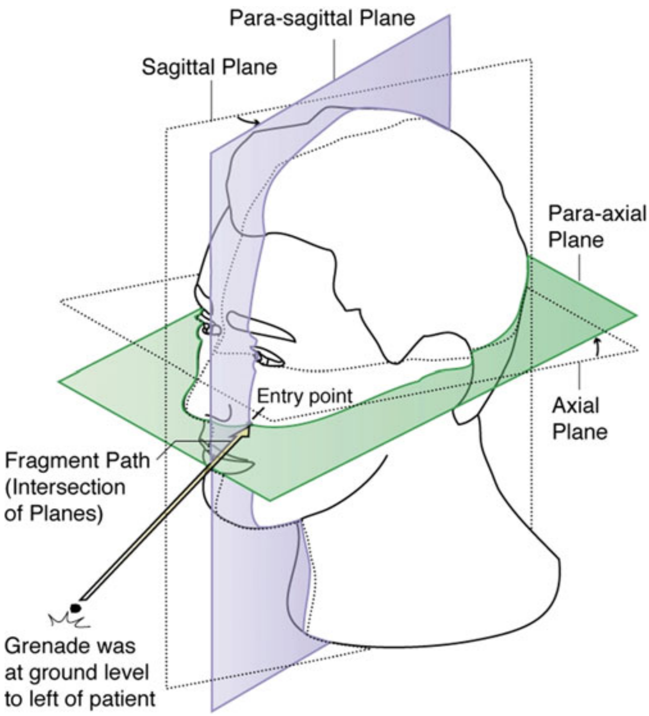


Fig. 5.30 Drawing showing the blast fragment entrance and trajectory to the face that ended up in the left lateral ventricle

include anatomic locations included in the pathway, provide descriptive text for a report or more importantly dynamic triage in combat. For example, some deployed locations in the battlefield have CT capability, however, do not have a radiologist on site. There are often times the CT data cannot be transmitted due to regular power outages, bandwidth limitations, security patches, or business rules. Having the textual report and precise location of trajectory and fragment and anatomic locations could help triage nonsurvivable injuries for urgent helicopter evacuation to higher surgical capabilities. Following trajectory mapping described here, one can appreciate a single ricochet at a slight angle after impacting the left cervical lamina.

To help validate the wound path identification, angle, and resultant trajectory determination, initial research on phantoms and anatomic ballistic simulators by Folio and Fischer et al is demonstrating consistent determinations of known sniper trajectories [25]. Ballistic testing of synthetic legs (donated by Operative Experiences, Inc. out of Kennedyville, MD) originally designed for teaching surgery is showing excellent correlation of angles shot by a .30-06 rifle (similar muzzle velocity as weapons used by terrorists). See Fig. 5.65 for sniper bench/clinometer,

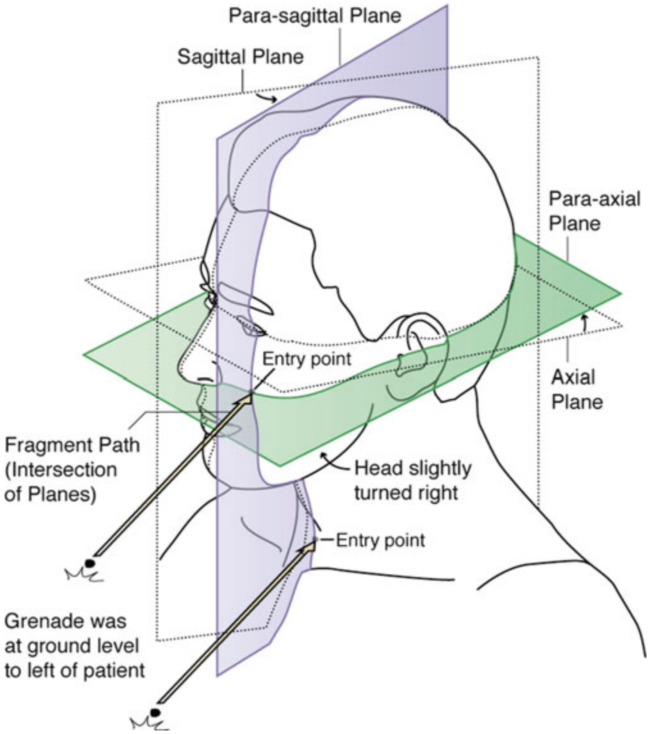


Fig. 5.31 This similar drawing now includes the second fragment, best explained and identified by finding the first fragment and trajectory. Reprinted with permission from Military Medicine: International Journal of AMSUS

Fig. 5.66 for sniper/range, and Fig. 5.67 for target in controlled environment using laser range finders and clinometers for accurate angles. Figure 5.68 shows how realistic the synthetic anatomic models respond to gunshot wounds. The appearance is similar to what I have experienced in Iraq. Figure 5.69 shows measuring the angle with the PACS angle tool on a para-coronal image aligned along the wound path. Initial data show that the angles measured by radiologists are within 5° of actual angles shot.

5.10 Description of Mapped Planes

After completion of construction of the planes, finding the trajectory of the missile path, the radiologist can better explain the involvement of surrounding anatomic structures such as vessels, nerves, etc. This is paramount to immediate damage control trauma surgery. Existing planar orientation boxes on some PACS systems

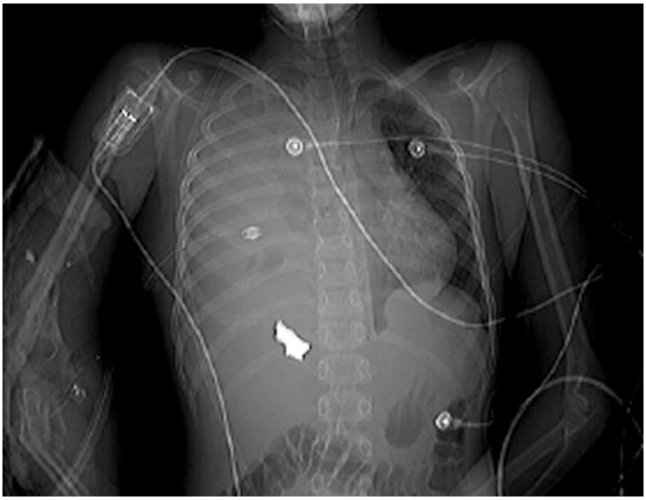


Fig. 5.32 Frontal chest CT scout shows a large metallic fragment in the RUQ. In addition to the large hemothorax on the right, there is tracheal deviation from increasing pressure in the left hemithorax from bleeding on the right. Diaphragm disruption is suspected based on fragment location and entry clinically. Note fracture of right humerus with associated fragments near elbow from fragment entry angle on an axial plane. Reprinted with permission from Military Medicine: International Journal of AMSUS

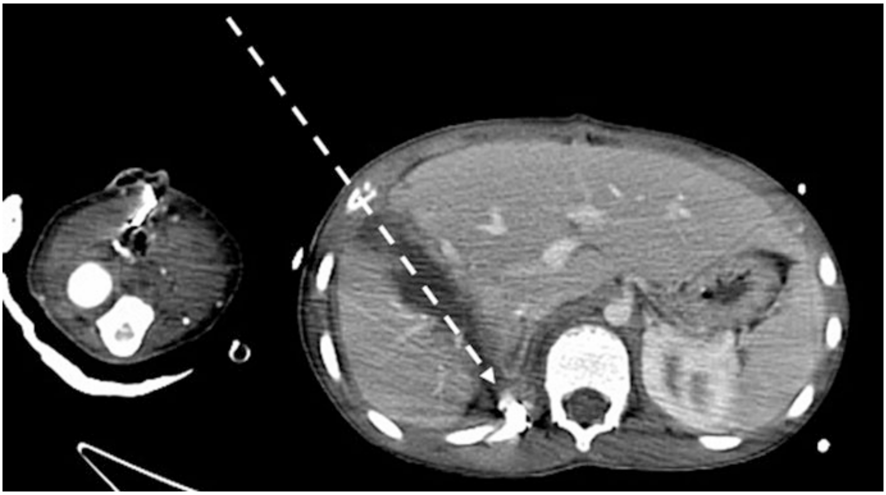


Fig. 5.33 Para-axial slice showing path of projectile (*dotted arrow*) from a blast fragment going through the liver from anterior right toward midline posterior. Additional metallic remnants in the right arm anteriorly support the entry direction and planar trajectory. Reprinted with permission from Military Medicine: International Journal of AMSUS

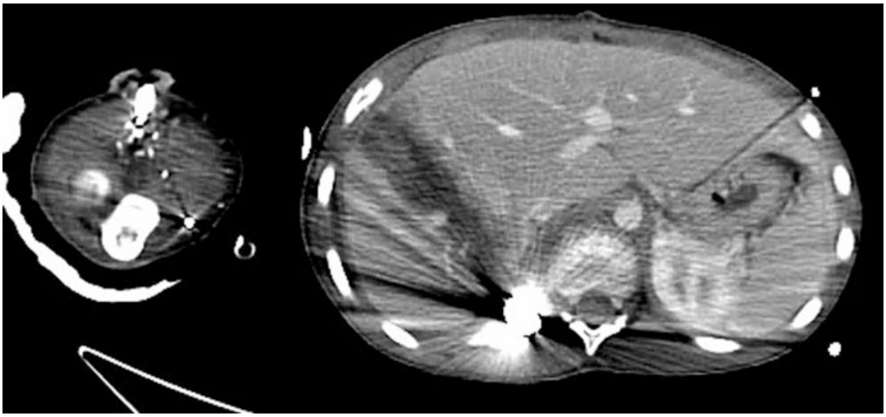


Fig. 5.34 A lower Para-axial MPR showing the large fragments and destruction possible with these traveling at high speed

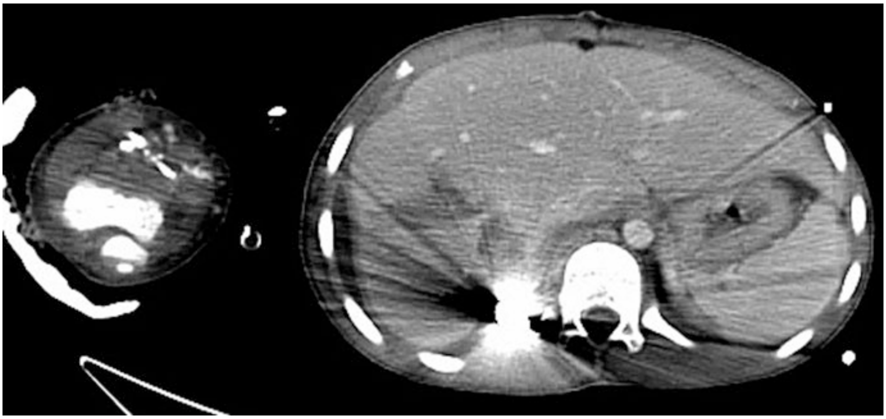


Fig. 5.35 A lower Para-axial MPR showing the large fragments and destruction possible with these traveling at high speed

attempt to show the plane of reformation, however, the authors believe that real-time animation models would be more effective in helping radiologists orient surgeons and other providers. This system, once integrated into reading workstations should immediately paint the picture in the users mind as to the exact orientation of the plane displayed. The grenade injury described above should highlight this application well. Such system allows for the description of any complex plane, intersecting line, or even point. This has application beyond military and penetrating trauma in that many other specialties, modalities, and medical sciences deal with descriptive planes, lines, or point locations.

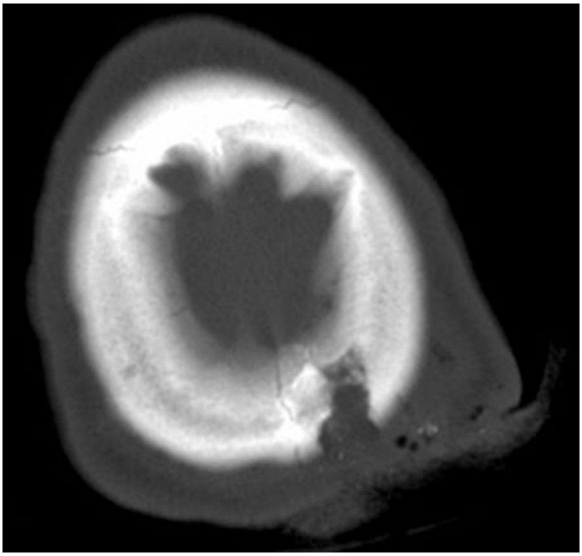


Fig. 5.36 Axial CT of high convexity of patient with GSW grazing top of skull. Note the keyhole shape (note that keyhole upside down) to the defect indicated shot came from behind and slightly above patient

Fig. 5.37 Axial CT of brain showing acute bleed from indriven bone fragments from same patient, indicating severity of injury. The wound can appear trivial clinically, however, the keyhole shape should alert radiologists to alert ED physicians of urgent need for immediate neurosurgical involvement. Reprinted with permission from Military Medicine: International Journal of AMSUS

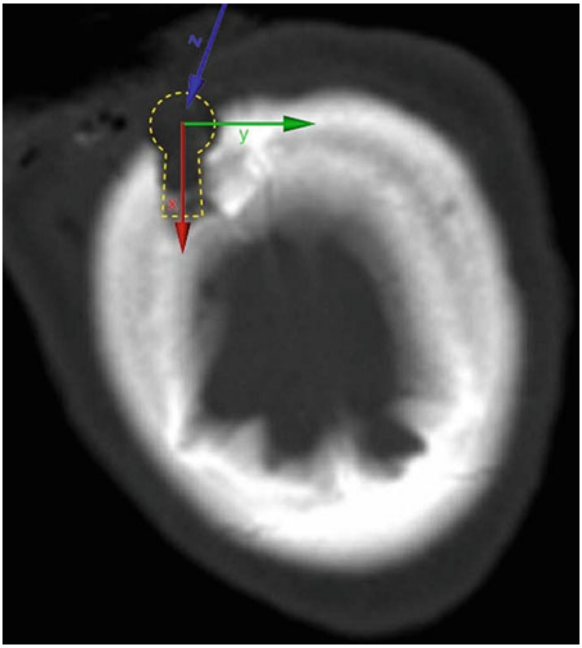


Fig. 5.38 The same high convexity axial CT, now turned upside down to show upright orientation of keyhole for instructional purposes. Reprinted with permission from Military Medicine: International Journal of AMSUS

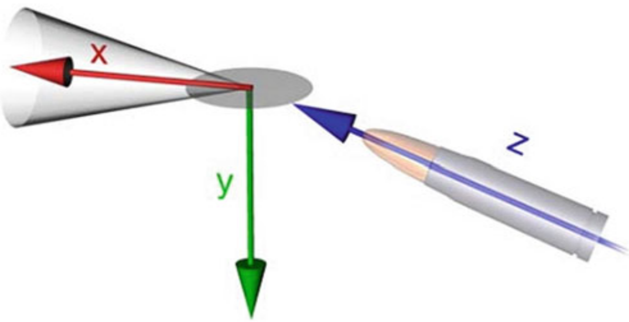


Fig. 5.39 Artist drawing of resultant force vectors of bullet striking (disregard shell of bullet) curved bone (these can also occur to curved hollow long bones such as femur). Reprinted with permission from Military Medicine: International Journal of AMSUS

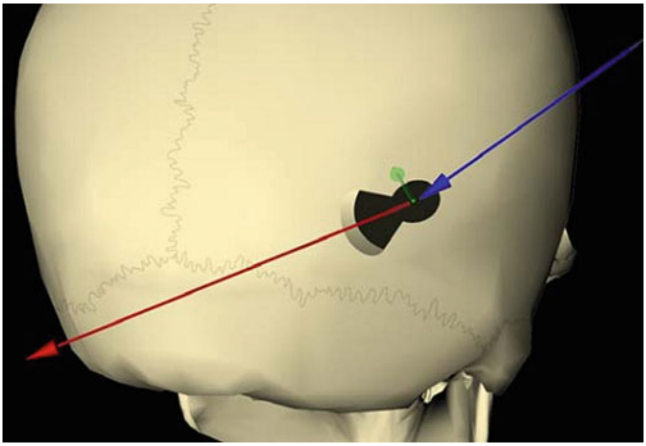


Fig. 5.40 Drawing of skull with different (from the patient highlighted here)) angle of bullet trajectory. This bullet traveled from anterior-superior toward posterior-inferior. Blue arrow shows trajectory before impact ("entrance"), and green arrow shows direction of indriven bone fragments (the "projectile"). Note beveling of "exit" wound (*red arrow*). Reprinted with permission from Military Medicine: International Journal of AMSUS

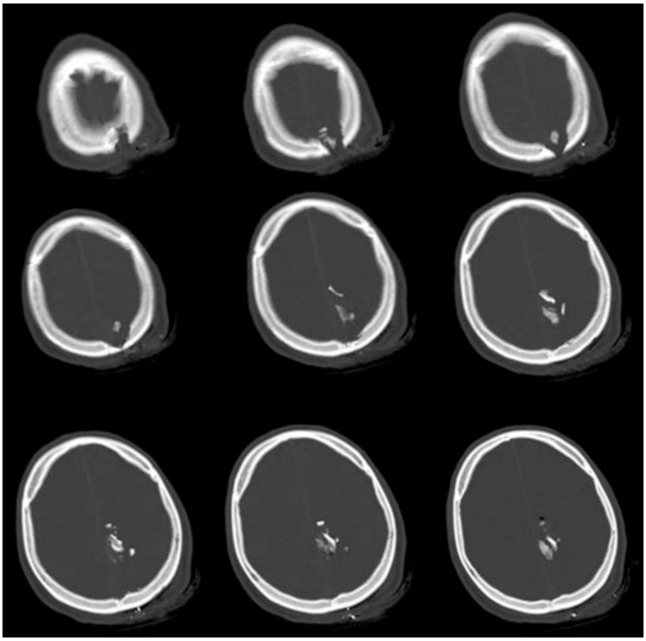


Fig. 5.41 Series of axial CT in bone windows highlighting the indriven bone fragments that cause the brain damage. Reprinted with permission from Military Medicine: International Journal of AMSUS

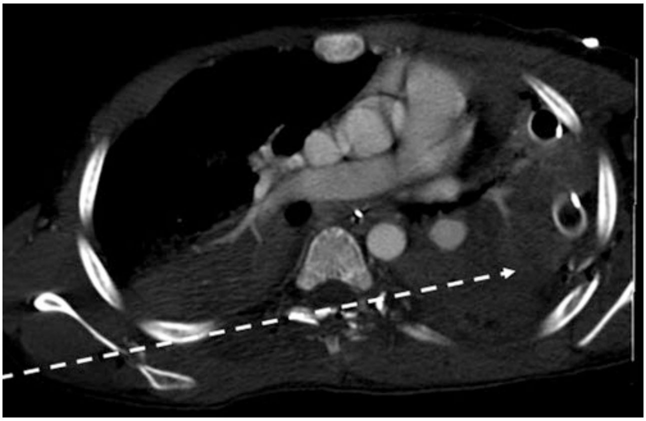


Fig. 5.42 CT axial bone windows show the wound path of this GSW victim across his right scapula, through his thoracic spinal elements traversing the left lung and out through his left ribs evidenced by fractures. Fractures and damage along the path help determine the wound path and resultant trajectory

5.11 Further Quantification and Application of Coordinate System Relative, to a Standard Reference

The following takes the complex planes one step further in quantifying fragment orientations and specific locations. A reference point was chosen with the following background to support this decision. Spinal curvatures and structure–function relationships utilize planes and plumb lines to describe and quantify stability [26]. The sagittal vertical axis (SVA), for example, is defined by the C7 plumb line on a lateral radiograph and is used to evaluate the sagittal profile of patients with scoliosis. The C7 plumb line should ideally intersect the posterior superior corner of the sacrum (PSCS), and is termed neutral. Anterior/posterior (horizontal) displacement of the C7 plumb line from the PSCS is termed positive if anterior, and negative if posterior.

I chose the PSCS as the center point for a few reasons: it is a consistent region near the skin surface posterioly and previously described as an anatomic/physiologic landmark. Also, in severe combat casualty care, it is my experience that this region is maintained and consistent in surviving combat casualties. See Fig. 5.70 for a drawing of the C7 plumb line to include the PSCS. It is the intersection of the SVA and the mid sagittal planes that define the proposed reference point. Figure 5.71 shows example application of specification of fragment locations from angle and magnitude from the reference point. Figure 5.72 shows how 3D localization can be represented by a vector ray (in degrees) with magnitude (cm) on the *x*-, *y*-, and *z*-axis. Once the process is automated to identify, quantify, and localize spatial coordinates accurately, prior datasets already dictated can be analyzed for fragment specific patterns from an epidemiological perspective. In addition, automated detection and

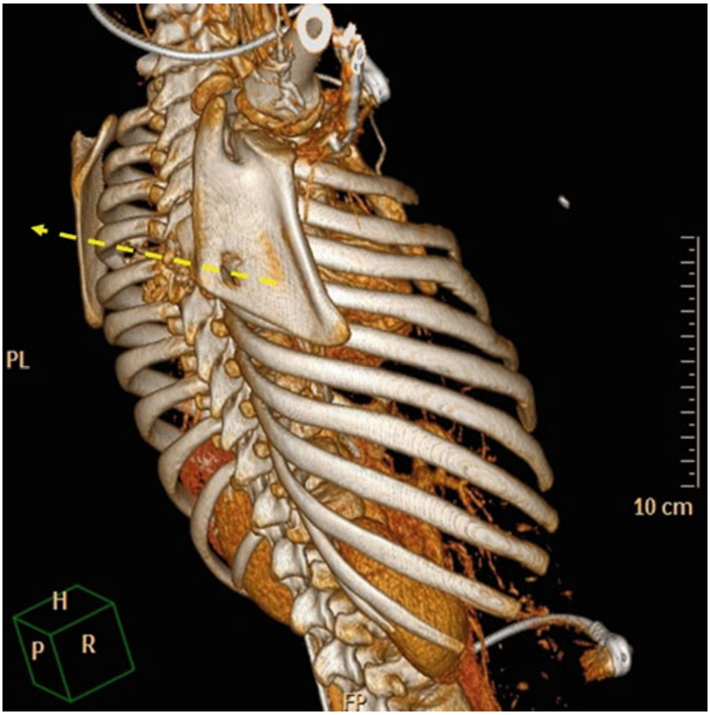


Fig. 5.43 Volume rendered 3D image showing pathway through scapula and ribs. In a similar, however, much less severe case, a bullet entered the left back of another patient, perforated the left scapula, tangentially skimmed a rib resulting in a focal contusion of the left lung, just missing spine, before finally lodging between the right scapula and the ribs (see Figs. 5.44 and 5.45). The bullet skimming the left ribs also caused a localized hematoma to the left upper lobe lung

localization reporting can supplement the radiologist report, saving radiologists time, while providing more objective data.

To validate consistent localization of points in three dimensions, I put together a CT phantom using a plastic tub, wooden dowels with nail heads (stem trimmed) at the tips at random locations in x, y, and z planes (see Fig. 5.73). These points were measured by three independent observers on the phantom itself, then by radiologists on CT. Preliminary work is showing consistent measurements to within millimeters. This will be compared to patient data and movement of fragments over time. Missile embolus and migration was already described earlier in this chapter.

Determining and describing trajectory angles with standardized terminology and retained fragments using standard polar coordinates may help the study of individual incidents as well as for an epidemiologic baseline in recording and comparing gunshot and blast trajectories for years to come. The proposed systems have some limitations in that the plane description is new, our terminology based on available literature and not validated beyond experience in a combat hospital. In addition, some patients suffering GSW or blast injury have complex paths that

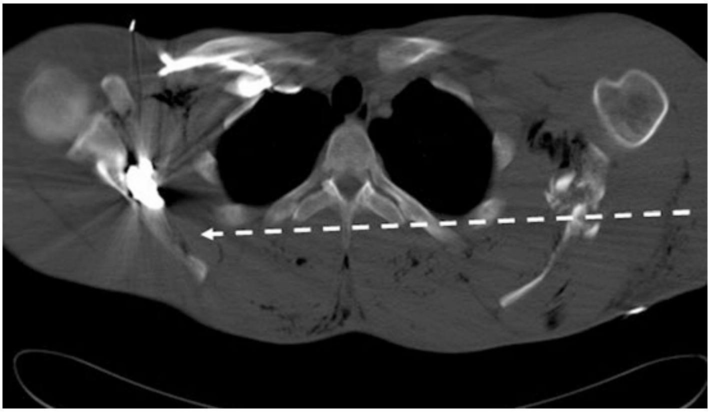


Fig. 5.44 Another patient with a GSW across the back, this time through the left scapula, skimming the left ribs and resting just anterior and medial to the right scapula

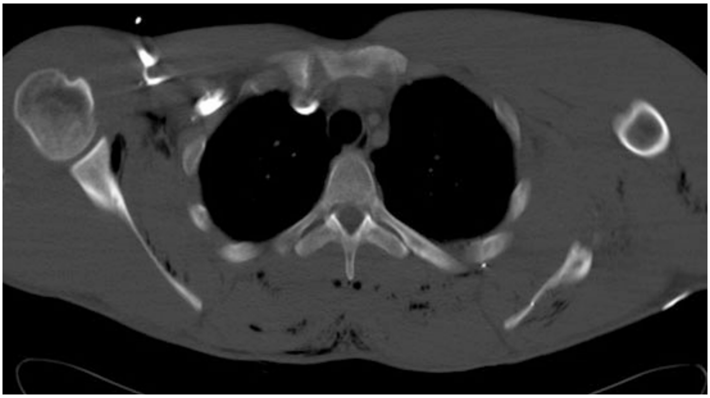


Fig. 5.45 Axial CT bone windows slightly lower than Fig. 5.44 demonstrating a tiny metallic fragment just posterior to the left posterior ribs. This highlights how using all clues can help determine wound path. Not the extensive subcutaneous emphysema highlighting the wound path as well

may have chaotic pathways or ricochets that do not lend themselves to analysis described here. Complex ricochets were much less common in our population, however. In addition, there seems to be a superior to inferior analytical probability relationship in that the more superior a pathway, the more probably a trajectory can be determined. Further research is needed to test quantification and reproducibility.

Not all ballistic missiles travel through tissues in a predictable manner. For example, some explosions result in fragments that are too numerous to count or

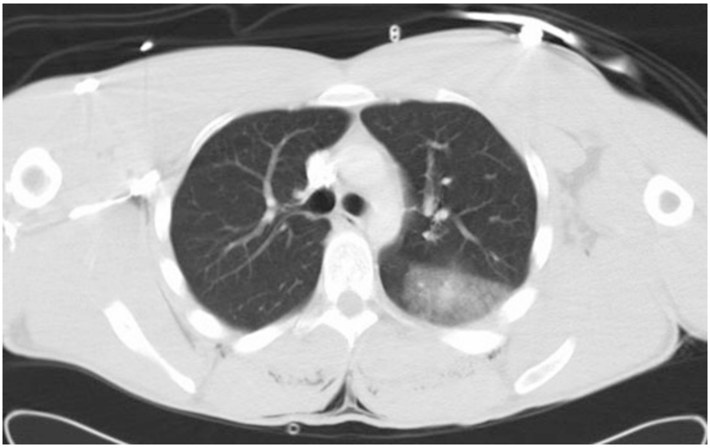


Fig. 5.46 Axial CT lung windows showing a wedge-shaped consolidation of the LUL posteriorly representing a lung contusion from the impact of the bullet

Fig. 5.47 Axial post IV contrast CT of a child that suffered extensive organ damage from a blast fragment. Note the peritoneal fluid representing blood, intra peritoneal air and retrocrural air, devascularized spleen, and pancreatic hematoma. Reprinted with permission from Military Medicine: International Journal of AMSUS

evaluate effectively. By determining reporting size thresholds used in virtual autopsy, protocols on reporting can allow simplification of otherwise complex situations as to not get bogged down trying to report on hundreds of fragments.

These situations could result in increased time to analyze and post-process images, possibly negatively impacting efficiency. Established realistic protocols

Fig. 5.48 Axial CT through the level of the retained blast fragment showing close proximity to the aorta, just above the renal arteries. Note again extensive peritoneal fluid with sparing of major vasculature. Reprinted with permission from Military Medicine: International Journal of AMSUS

Fig. 5.49 CT more inferior showing damage to left kidney, some subcutaneous air in left soft tissues, and extensive peritoneal fluid. Generalized shock bowel is present, however, the IVC is maintained due to aggressive hydration since just after the injury. Reprinted with permission from Military Medicine: International Journal of AMSUS

will guide radiologists to most effectively analyze the majority of cases and know when exact determination of peppered fragments (for example) are just not possible to effectively record.

The authors are currently working on development of systems to help delineate trajectories of penetrating wounds from blast injuries using an automated computer

Fig. 5.50 Coronal MIP showing the fragment orientation to the aorta. MIPS can be helpful in showing orientation, however, should not be relied upon for determining active bleeding or other precise localization. Reprinted with permission from Military Medicine: International Journal of AMSUS

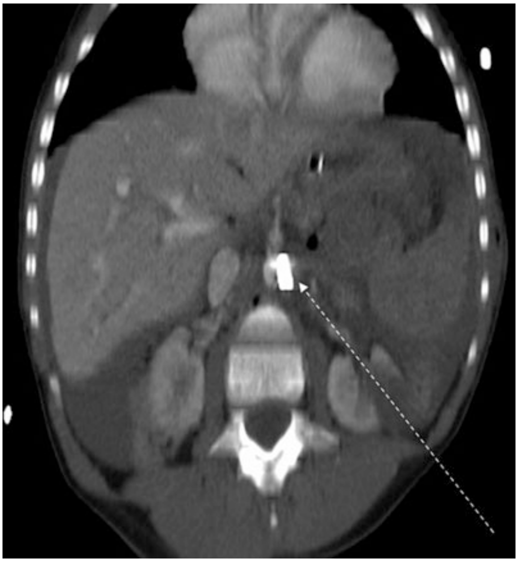


Fig. 5.51 Para-coronal MIP showing the blast fragment pathway from left flank through kidney, tail of pancreas, and final resting spot near aorta. These help trauma surgeons find the fragment with least amount of exploration and least surprise. Reprinted with permission from Military Medicine: International Journal of AMSUS

Fig. 5.52 CT delayed scout of two large metal fragments in mid-lower abdomen. There was no evidence of ureter involvement on delayed imaging. Reprinted with permission from Military Medicine: International Journal of AMSUS

assisted plane derived from pattern recognition. Recent advancements will allow precise automated recording of trajectories to help individual patients by a standard reporting system that can follow war casualties through the echelons of care. Automated analysis of remaining fragments of wounded soldiers for example, will streamline the otherwise tedious job describing these subjectively, with consistent accepted coordinates. It is hoped in our current projects to validate 1 cm location accuracy in x, y, z planes (ray and magnitude) and 5° angular resolution on trajectory angles.

Once a ballistic localization and planar lexicon is agreed upon and algorithms are developed, automated quantification systems will allow expeditious accountability of all fragments and recorded trajectories of all wounded warriors in a

Fig. 5.53 This large fragment lies within the left psoas. The reformatted images helped demonstrate the lack of intraperitoneal component, i.e., this fragment path was shown to be mostly muscular. The fractured transverse process, subcutaneous air and soft tissue aberration were all supporting evidence of the missile path. Reprinted with permission from Military Medicine: International Journal of AMSUS

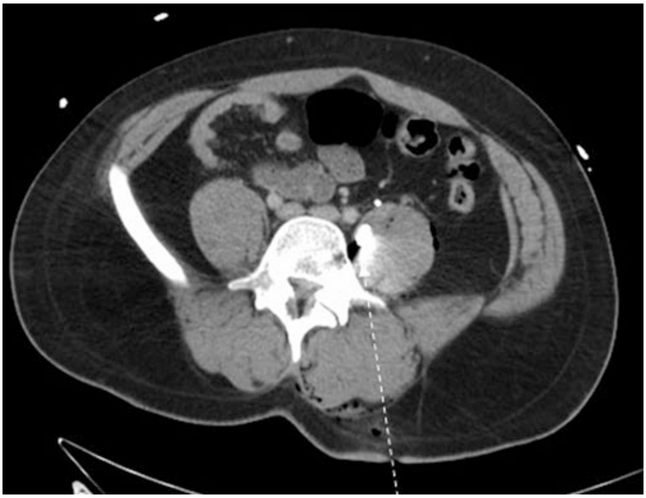


Fig. 5.54 Although the fragment size, irregularity and location appears concerning when not considering trajectory as it lies near major vessels, when surgeons were convinced it came through the back and not traversing cord or vessels, this patient was re-triaged at a lower priority since other casualties were in need of immediate surgery at the same time

Fig. 5.55 Note metallic peppered fragments in left paravertebral musculature (along the arrow) supporting the trajectory path

Fig. 5.56 This superior para-axial CT reformat illustrates a perforating fragment that entered to the back, traveled through the right posterior flank avoiding the peritoneum and ricocheted off the right iliac wing. Note small nondisplaced fracture of anterior iliac wing. Reprinted with permission from Military Medicine: International Journal of AMSUS

Fig. 5.57 Upward angled para-axial CT reformat showing the exit path verified by exit wound (skin near arrow). Multi-planar reformation showed that the path was deflected superiorly (dotted arrow) after striking the right iliac wing. This required two reformats, both in para-axial orientations. Reprinted with permission from Military Medicine: International Journal of AMSUS

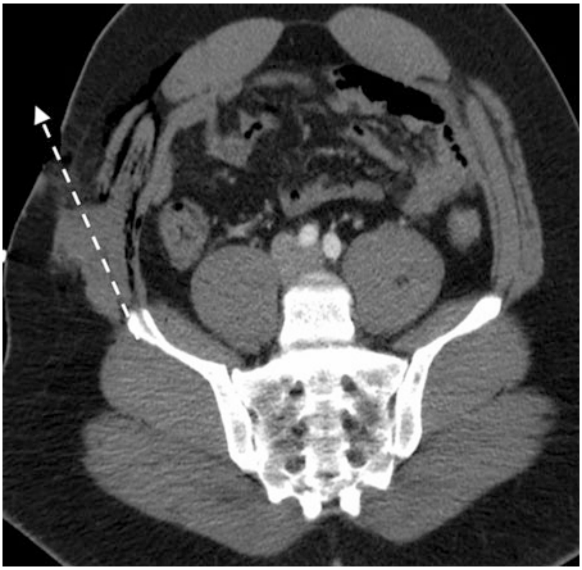


Fig. 5.58 Another upward angled para-axial CT reformat further supporting exit path. Reprinted with permission from Military Medicine: International Journal of AMSUS

Fig. 5.59 Scout CT substitute for chest radiograph demonstrates obliteration of normal left subclavian stripe and thickening of the left apical region consistent with localized hemothorax from GSW to the left chest. Some overall haziness to the left thorax is from superimposing hemothorax and decreased overall volume of left lung. There are some retained fragments, localized consolidation from the wound path in the perforating injury (entrance anterior, exit posterior)

consistent recording fashion. In addition to helping each soldier, sailor, airman, and marine exposed to blast or gunshot, a standard and accurate database will establish epidemiological patterns forming a research baseline for years to come.

Included here several cases of penetrating injuries from combat hospitals highlighting wound ballistics and trajectory analysis, while introducing descriptions of complex anatomic planes now possible with advanced imaging in combat. We have shown how application of complex planes can accurately describe wound trajectories in a more quantitative and repeatable fashion. This descriptive system should enhance communication between radiologists and other physicians. Furthermore, standardized and quantitative descriptions of trajectories based on use of complex planes and coordinates now possible with MDCT introduced here may help in long-term study of gunshot and blast injuries.

Using a standardized plane-based data acquisition and analysis approach, we will be able to precisely locate a fragment, estimate its size, and delineate its three-dimensional shape, which provides guidance for triage nurses, trauma

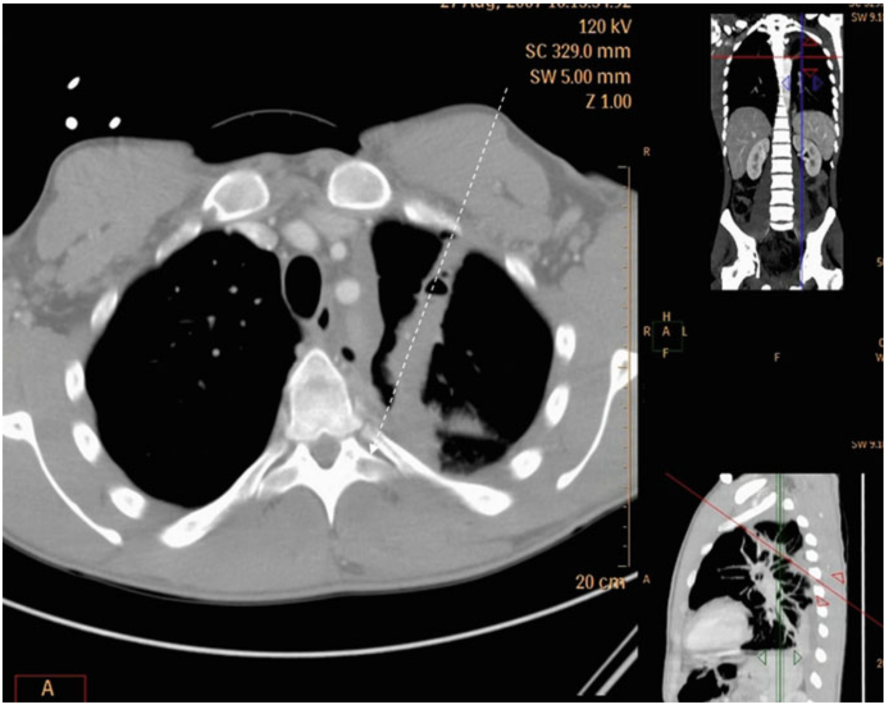


Fig. 5.60 Para-axial reformation of ballistic trajectory showing small air-fluid level in resultant cavity, contusion, and associated hemothorax. The coronal and para-sagittal scout reference images help orient providers to the extent of the missile pathway. Also note the superior to inferior trajectory (*red line* on para-axial image *lower right*), and the posterior (dependent) localized hemothorax

surgeons, and follow-up evaluations through the echelons of care. This will have obvious implications for the long-term prognosis and follow-up of such injuries. Precise planar description of missile paths will help standardize communication between radiologists, trauma surgeons, and ED physicians. Our complex-plane-base approach will also enhance incident analysis in forensic medicine including sniper attacks, military combat firefights, and random gunshot injuries.

Knowing the para-axial or otherwise complex planes of known fragments may help solve for unknown fragments by keeping the same para-axial orientation during interpretation. In addition, consistent reporting, standard nomenclature, and possibly quantification should allow for more descriptive recording of GSW and blast fragments, especially since many of the original image datasets are often lost during transition of wounded warriors through the echelons of care. More research is needed in this specific area.

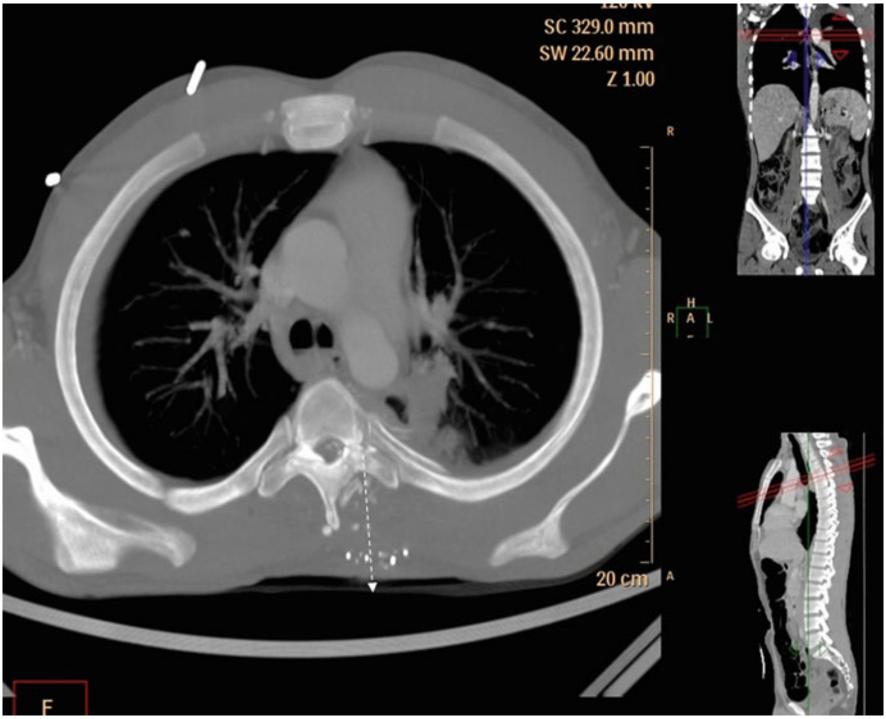


Fig. 5.61 This para-axial MIP shows the bone fragments dispersed after the bullet hitting lateral aspect of the bony spinal elements. Note rib alignment indicating downsloping para-axial orientation, hence upward deflection of bullet after impact with spine. The arrow shows the ricocheted trajectory

5.12 Decision Support Tools, Expert Systems

Online decision support tools seem to be on the rise. When I was at the Uniform Services University, I developed a teaching tool called RoboChest (from Adobe® RoboHelp®) built with directory structures to allow students and residents to dig as deep as they like on an area of interest in the chest X-ray. It attempts to impart to the students a systematic methodology of evaluating abnormalities shown on chest X-rays, the most common type of medical imaging performed, and interpreting those findings in light of the clinical setting.

The chunked information in a structured lexicon is designed to link from a larger project called "ChestWeb," an expert system to help guide image interpretation. This content follows the organization of how material is presented to medical students at the USU's F. Edward Hebert School of Medicine.

I believe this type of approach is effective and efficient in teaching principles of radiographic image interpretation.

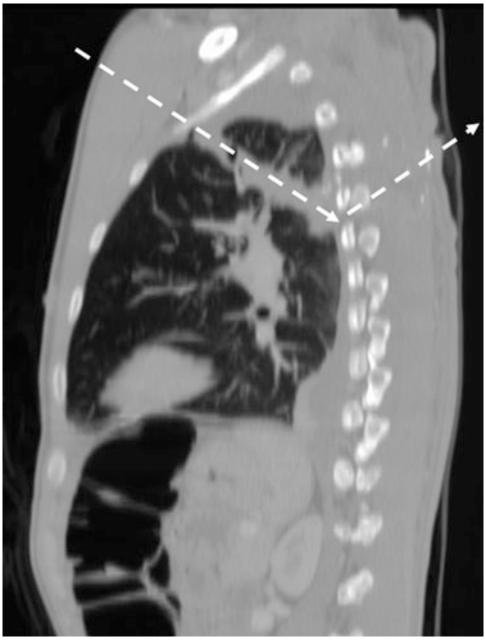


Fig. 5.62 Para-sagittal reformat along the angled thoracic wound path showing initial downward trajectory (from a sniper, since anterior to posterior, and superior to inferior), until impacting vertebral elements, then ricocheting superiorly (*shorter dotted arrow*) for a more superior exit than expected. Note the moderate amount of hemothorax dependently

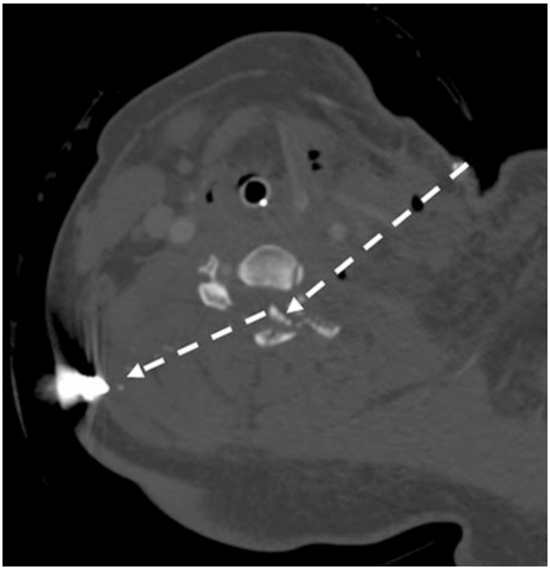


Fig. 5.63 Para-axial CT bone windows showing the sniper bullet's trajectory though the spinal canal at C4. Note retained bullet near the skin surface on the patients right

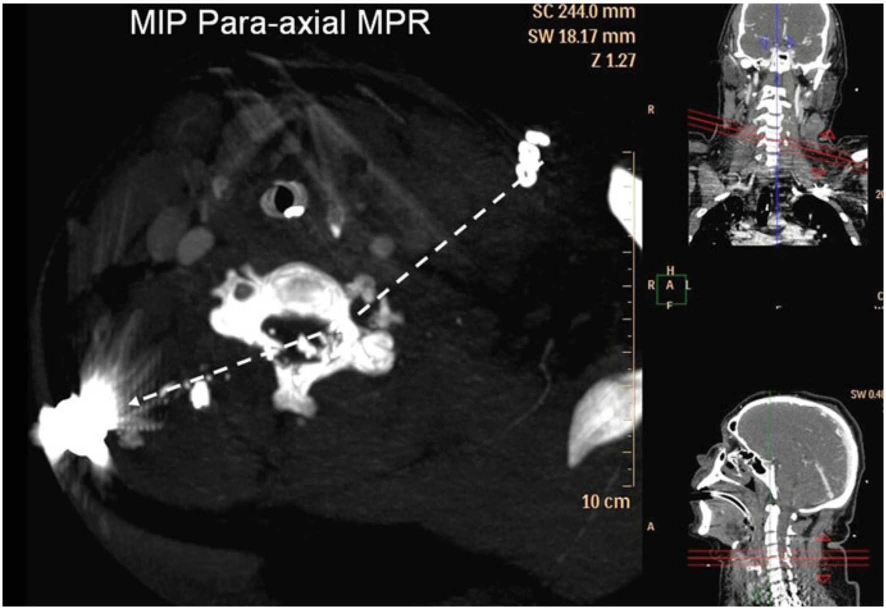


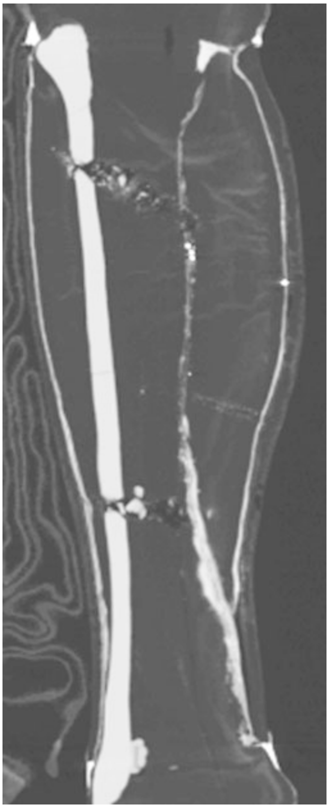
Fig. 5.64 Para-axial MIP reformat verifying the sniper bullet's trajectory though the spinal canal at C4. The fractured vertebra and remaining bullet indicate the slight deflection of the pathway after impacting the bone

Fig. 5.65 In this figure, I am determining the angle of the sniper bench with a clinometer. We also measured the zeroed-out barrel of the weapon just prior to shooting downrange at the target (Photo by Dr. Mike Frew)

Fig. 5.66 This photo shows the sniper aiming at the synthetic targets downrange. The spotter is using binoculars to evaluate accuracy of the shot, and a camera is mounted on a tripod near the target for slow motion analysis (Photo by Dr. Les Folio)

Fig. 5.67 The anatomic ballistic model was fastened to a stable bench as the target. Various known sniping angles were accomplished (Photo by Dr. Les Folio)

Fig. 5.68 MD CT para-coronal reformation along the path of a 40° trajectory. The facial planes are as dense as the synthetic bone because this particular model was used for training emergent faciitomies for deploying military surgeons



The goal of these systems is for medical students to reproducibly describe radiographic abnormalities detected on plain film CXRs. The lexicon is designed to provide the students with clinically significant differentiation of abnormalities detected. The content is chunked in a directory structure that relates specific combinations of distinct radiographic findings to classes/groupings based on findings.

5.13 Telehealth on the Battlefield

Teleradiology is an important part of casualty management up the echelons of care. It is imperative that image data movement, archiving, and matching textual data is moved along with the patients that are transported to follow-on medical centers. An overview of the status of teleradiology was presented at a conference in 2007.

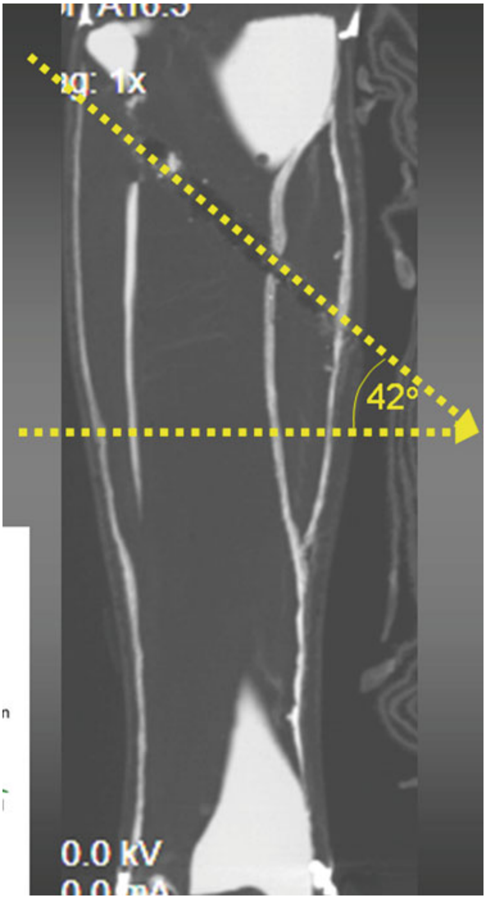


Fig. 5.69 Another MD CT para-coronal reformation reconstructed along a wound path showing how the PACS angle tool can easily determine the angle of the sniping

Additionally, more information on the triservice status on telehealth can be found in Military Medical Technology [27]. I also have led teams into Iraq and other countries to help develop teleradiology issues [28].

As is often the case in combat medicine, interim solutions proliferate as providers do whatever they can to best treat their patients. This includes assembling montages of CT images to send via e-mail using mp4 [29]. Another technology that helps display more efficiently and quickly is Universal Trauma Window [30]. This is a technological solution to the Damage Control Radiology mentioned previously in this book.

Some practitioners take digital photos of dermatology lesions for consults on perplexing cases when no dermatologist is available. These solutions are novel, secure, and compliant, but they demonstrate the need for a more uniform solution that can be replicated.

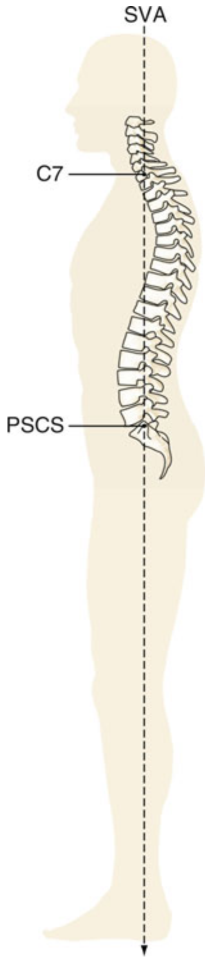


Fig. 5.70 Drawing of the spine from the side showing how the PSCS is used for postural exams and research. Prior reference to this consistently localized area led to selection for a standard reference point for fragment localization

Some evolving solutions include online health vaults that are being studied with the US Army [31]. These could answer the RIS-HIS interoperability issues using the compression and window technologies described above.

Finally, one technology that may have application in blast and ballistic imaging is total body scanning. The StatScan by Lodox [32] can obtain AP and lateral plain radiography of the entire body in seconds. Experience at UMM Baltimore Shock Trauma is promising [33].

In summary, recent advances on the battlefield have contributed significantly to record survival rates. While difficult to attribute each advance with actual percentage of increased lives saved, it is obvious that all of these advances have contributed their part to the heroic results combat medics and those supporting them have achieved.

Fig. 5.71 Artist drawing demonstrating how fragments can be consistently localized in 3D using the reference point for epidemiologic tracking over time. A fragment score can be assigned as well for the individual

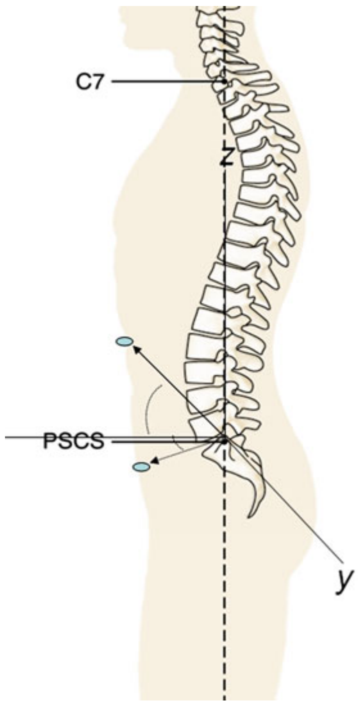
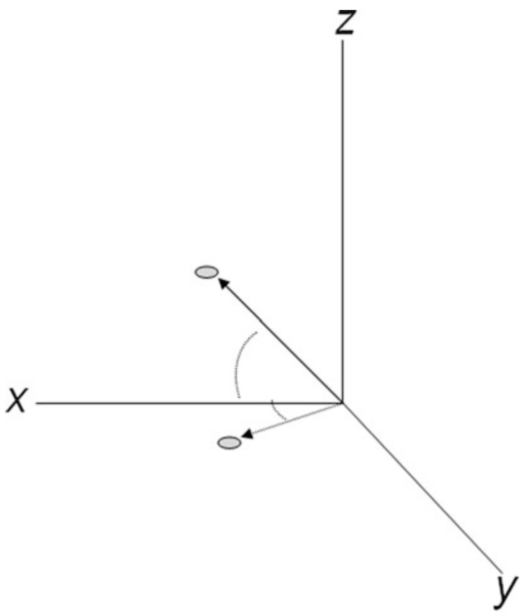


Fig. 5.72 A basic vector magnitude using *x*, *y*, *z* coordinates can be assigned to each fragment for precise localization that can be added to patient's records and for future consistent data mining



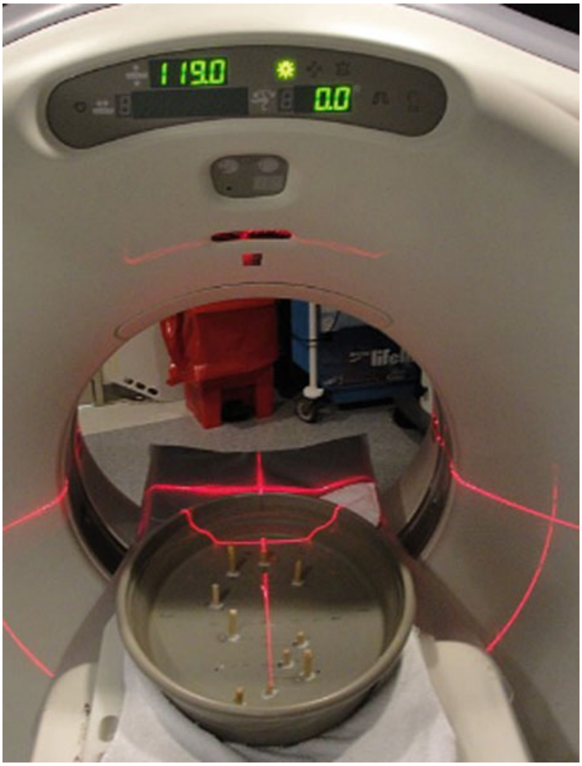


Fig. 5.73 The blast belly phantom I created for one study to allow measurements of 3D localization of simulated blast fragments. This was filled with water for attenuation fidelity and will be measured by radiologists for accuracy

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