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Penetrating Spinal Cord Injury

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Abstract

Penetrating spinal cord injury (SCI) is a relatively rare entity affecting mainly young males and military personnel worldwide. These injuries are the source of permanent disabilities to the affected patient and family and have substantial social and economic concerns. This chapter is an overview of the common penetrating spinal cord injuries, their incidence worldwide, causes, primary evaluation, and treatment including medical treatment and late definitive surgical treatment. It also describes common complications and strategies preventing secondary and collateral damage and disability.

Keywords: spinal cord injury, trauma, gunshot wound, paralysis, surgery, ATLS

1. Introduction

Spinal cord injury (SCI) and the lifelong disabilities associated with it are of a major concern to the society worldwide. Those injuries bear substantial personal and economic burden. Traumatic SCI is a subgroup of spinal cord injuries that affects mainly young males at their third decade of life, and its rate of incidence stays unchanged in the last three decades [1, 2]. Traumatic spinal cord injury can be divided into penetrating and blunt or non-penetrating injuries. Traumatic injuries have a steady incidence ranging from 12.1 to 57.8 cases per million annually [1, 2]. The most common etiologies are motor vehicle accident (MVA), falls from height, violence including gunshot injuries, and sport activities. Penetrating spinal injuries can be further divided into missile-penetrating spinal injury (gunshot, shrapnel, etc.) and non-missile-penetrating spinal injury (i.e., stabbing).

Penetrating gunshot injuries have been described as accounting for 17–21% of all spinal cord injuries [3]. Non-missile-penetrating spinal cord injuries are rare and account for less than 1.5%

of the total penetrating injuries [3]. The incidence of missile-penetrating SCI varies, and difference exists between its incidence in civilian population and military personnel population, where the latter is naturally more prevalent and influenced by eras of military conflicts [3].

2. Non-missile-penetrating spinal cord injury

Historically, the first non-missile-penetrating spinal cord injury (NMPSCI) was described by the Egyptians in 1700 BC. The Edwin-Smith papyrus was the first manual of military injuries in history and described different injuries and their proposed optimal treatment. Unlike other medical documents preserved from that era, the papyrus was based on medical procedures and not myths or prayers [4]. In the second century AD, the Greek physician Galen reported his experiments on monkeys when a horizontal cut through their spine resulted in loss of sensation and motion below the level of the injury [5].

The largest series of NMPSCI was published by Lipschitz [6] with two case series in 1955–1967. Other smaller series were described in 1977 and 1995 [7, 8]. These publications came all from the same country (South Africa), both at an era of severe violence that unfortunately flooded the country.

Unlike in the rest of the world, in South Africa penetrating SCI is still responsible to about 60% of all SCI (spread evenly between NMPSCI and MPSCI). MVA, which is the most common cause of SCI in the rest of the world, accounts only for one-third of the cases in South Africa today [2].

Most of the affected victims of these injuries are young men in their second and third decades [2, 3]. Generally speaking, while in the past, NMPSCI was rare in females, today the trend is changing, and over the past decades, it is seen more, especially in North America. Yet, about 80% of the affected victims of these injuries are males [2].

Knife is by far the most common assault weapon causing NMPSCI. It accounts for 84% of the cases [9]. Other sharp objects such as screwdrivers, scissors, garden forks, and bicycle spokes were reported as the assaulting weapon for NMPSCI as well [9]. Even a pencil was reported as a stabbing object that caused NMPSCI [10].

Previous reports described a series of NMPSCI caused by acupuncture needles [11]. The World Health Organization published a systematic review of acupuncture-related adverse events in 2010, in which 44 cases of dural and arachnoid bleeding, causing severe adverse events and death (three cases), were reported [11].

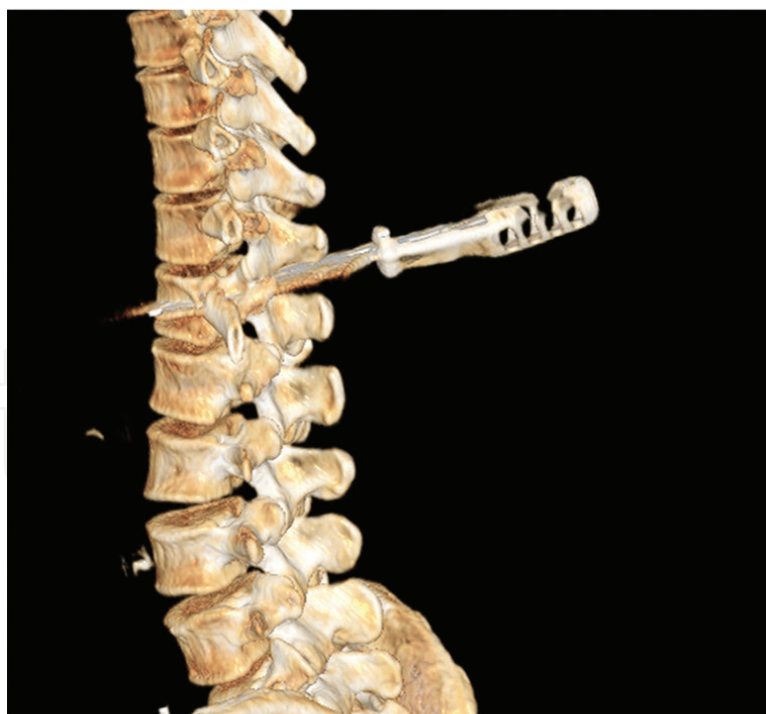
Most non-missile-penetrating injuries happened when victims were stabbed from behind with the thoracic spine being the most common site (up to 63%), followed with cervical spine (up to 30%) [12]. A recent study examined that there are no differences in stab wounds to the neck, between military personnel (during combat) and civilians. This probably emphasizes the role of incidence in this type of injuries [13].

Victims are usually stabbed once, and the attacker usually withdraws the stabbing object from the victim's body. However, in some cases the stabbing object brakes inside the body,

and retained material occurs (**Figure 1A and B**). In the case of knives, the most common brakeage occurs at the handle or blade wedging a bone. The first one is usually very prominent from the victim's body and raises the dilemma of removing it at the scene [14].



(a)



(b)

Figure 1. Axial CT scan (A) and 3D CT reconstruction (B) demonstrating a screwdriver going through the T12 vertebra, through the cord, and coming out adjacent to the aorta. The patient was fully alert on arrival with no neurological deficits. The screwdriver was removed in theater without complications, and the patient was discharged 2 days later.

The possible neurological deficit ranges from asymptomatic dural tears through different nerve root injuries, ranging from neurapraxia to neurothemsis and ending in the worst cases with complete or incomplete spinal cord injury.

The most common incomplete NMPSCI reported was the Brown-Sequard syndrome [15, 16]. This syndrome was first described by Charles-Édouard Brown-Séquard, in farmers cutting sugarcane in Mauritius and sustaining hemisection of their spinal cord by long knives (1852) [17]. The syndrome is still the most common incomplete SCI [18].

Neurological injury to the spine may occur in two different mechanisms: immediate, through direct damage to neurological tissue, and delayed, following vascular injury to one of the feeding vessels in which a vessel that supplies the cord, most commonly the aorta or the Adamkiewicz perforant, is injured. The first one will cause most frequently an incomplete SCI, most commonly Brown-Sequard syndrome, while the last one is more likely to cause a complete SCI. The second pattern is the delayed onset which is caused most commonly from CSF leaks, edema, granuloma, scar formation, and infection. The delayed pattern can appear anytime from 2 years after the injury and up to 36 years as was described in a rare case of metal encrustation of a retained knife fragment in the spinal canal [19].

2.1. Primary evaluation: emergency department

All NMPSCI patients should be treated like other trauma victims according to the ATLS (Advanced Trauma Life Support) principles [20]. When the retained weapon is clearly prominent from the patient's body, the attention of the treating personnel tends to focus on it and distract them from acting according to the ATLS protocol. These injuries are sometimes less visible than it might be seen at first and may harbor other damages such as large vessels, heart, tracheal, or lung injuries that can affect hemodynamics, airway, and breathing and may be fatal. This is why any suspected patient should obtain an appropriate initial assessment and resuscitation before taking the next step. The initial assessment should not delay instance evacuation with minimal movements to the nearest hospital.

Extracting the penetrating object must not be done on site, not even at the emergency room, before obtaining proper imaging studies. These should include radiographs, sonography, and computerized tomography, according to the involved area. In case the patient is hemodynamically unstable and does not respond to initial resuscitation, an immediate transfer to the operating room with no further delay must take place.

NMPSCI always entails the risk of a retained foreign body material. It is well described in the literature [12, 21]. Patients presenting with delayed wound infections following stab wounds that were irrigated and primarily sutured without further evaluation were documented [22–24]. This is why many authors recommend routine imaging of any penetrating injury, even if only a skin or fascia discontinuity is observed, with no obvious damage.

2.2. Imaging

There are many imaging modalities that can be used to evaluate patients with NMPSCI. This includes plain radiographs, upper GI studies, ultrasound, computed tomography with or

without contrast, and MRI. It must be remembered that imaging cannot replace clinical evaluation, judgment, or resuscitation. Imaging should be considered only in a hemodynamically stable patient.

2.2.1. Radiography

Enicker and his colleagues [12] published a large series of stab wounds that accounted for one-third of all SCI in their center. Forty-nine percent of these patients had retained foreign bodies where a knife blade was the most common object. Knife blades are easily identified by plain radiographs; however, the availability of CT scan in most ER in the developed world has shoved aside its role in cervical trauma. It still has a role in the evaluation of thoracic injury mainly for the evaluation of the associated lung injury and not for the demonstration of the foreign body.

2.2.2. Computed tomography

Computerized tomography is the mainstay in diagnosis of penetrating SCI. It is a fast and reliable modality that can scan any part of the body. It has the ability to demonstrate the thoracic or cervical column with the surrounding organs that may be involved in the injury. The main disadvantage of CT scan is its poor ability to demonstrate direct damage or pathologic changes of the neural tissue.

2.2.3. CTA

Saito and colleagues in their review [21] recommend CTA as the gold standard of imaging for penetrating SCI. It has all the advantages of CT plus the benefit of demonstrating blood vessels including extravasation, pseudoaneurysm, dissection, occlusion, and arteriovenous fistula. Angiography is still considered as the “gold standard” vascular imaging examination; however, CTA is gradually taking its place as an alternative. CTA has been proven to be as good as angiography and yet less invasive and faster which makes it suitable for diagnosis in such cases [21].

2.2.4. MRI

MRI is not used routinely as a diagnostic tool in these injuries. The main concern is potential migration of retained metal fragments that can further damage neurologic or other surrounding tissues. Other drawbacks are time, unavailability, and study quality in the presence of metal artifacts. On the contrary to its place in the acute setting, MRI has a major role in studying complications following the initial treatment. Patients who present with deteriorating neurological deficit, prolonged fever, CSF leak, or post-LP syndrome are expected to be further evaluated with an MRI.

2.2.5. Others

Other imaging studies may be used when clinical suspicion for specific collateral organ damage is raised. This may include sonography, Doppler, endoscopy, and barium contrast imaging studies. Those studies are not routinely used, and the need depends on the site of injury

(thoracic vs. cervical), clinical examination, and the results of CTA. Sonography is a quick, noninvasive, and readily available tool; however, the technique is highly operator-dependent, and air from the injury, artifacts from retained metallic fragments, and hematoma can limit its interpretation.

2.3. Treatment

As mentioned above, initial treatment of these injuries should be treated as any other traumatic injury, by the ATLS guidelines. After securing airway breathing and circulation, the spine surgeon can address the NMPSCI. The management of regimen to date is still controversial, which is understandable given the low prevalence of these injuries. To date no guidelines exist as for the proper management plan, and the published series described are too small to dictate any clear conclusions.

Most authors agree that in cases of progressive neurological deficits, radiographic evidence of neural tissue compression, or persistent CSF leak, early intervention should be considered. In case of spinal canal penetration with no neurological deficit or CSF leak, surgery is not mandatory.

There is no clear evidence that removal of the retained foreign body will improve the neurological status. The literature describes conflicting reports where in some, foreign body removal improves neurological status and in others, neurological improvement was seen even with retained small fragments. Unfortunately, no RCT (randomized control trials) are available to guide us which option is better. Therefore, each case should be evaluated independently. One should judge the potential damage of extracting the penetrating object compared with the probability of late complications in case of leaving it in place.

In most cases, decompressive procedures, most commonly laminectomies, hemilaminectomies, and dural exploration, are the procedures of choice, mainly because the injury comes from the back. In other rarer cases, mainly in the cervical spine, anterior decompression is indicated.

Most NMPSCI are considered as stable spine injuries, and in an awake and alert patient without distracting injury, clearance of the spine can be done by clinical examination [11, 13, 14].

The surgical management of NMPSCI is a controversial topic [2, 6, 12, 14, 15]. This is more so in cases with a complete SCI but exist also in incomplete SCI.

The literature supports the fact that early surgical intervention for spinal cord injuries caused by low-velocity missile-penetrating injuries (bullets) does not improve the neurological status [1]. There is no clear-cut evidence regarding NMPSCI given the infrequency of these injuries. Case reports describe improvement of the neurological status following emergent or late surgical removal of the foreign body, in some cases even months after the injury [12, 19]. However, this improvement can occur without intervention as well, as reported by others [2] who recommended observation only, in most of their patients. Surgical intervention in NMPSCI may reduce late complications such as decreasing infection rate, cerebrospinal fluid fistula, and arachnoiditis. Delayed myelopathy has been described years following injury with a retained foreign body up to 36 years after the primary insult [12]. When there is rapid

progression of neurological deficit or in case of incomplete SCI with radiographic evidence of cord compression (i.e., expanding hematoma, bony fragments, or a retained foreign body), it is a consensus to proceed with immediate surgical intervention.

Positioning a patient with a retained knife handle protruding from his upper back is a challenge. Intubation in an alert patient must be done on a lateral decubitus position, to avoid further damage. Fiber optic-assisted intubation is preferable in difficult cases.

Essential part of surgery is canal decompression. Ideally, it should be done from an uninjured part of the dura mater to the next uninjured space, one level distal and one proximal to the injured loci.

Direct repair of the dura in the immediate setting is controversial, especially in the thoracic spine. This area of the spine is the narrowest along the spinal column. Moreover, blood supply to this segment has been described as the watershed area. Direct repair of the dura mater in this zone raises concern of cord compression secondary to neural tissue swelling. This is why it was proposed by some authors to apply collagen matrix on the defect instead of primary closure. Others are more concerned with the risk of infection and thus repeal any use of sealing material [25].

2.4. Perioperative care

Intravenous administration of steroids in penetrating SCI has no role, and, moreover, it may raise the risk of infection [26, 27].

Preventive antibiotic treatment in the perioperative period is controversial. The incidence of meningitis following NMPSCI is very low [2]. However, the incidence of soft tissue infection around the stab wound is high. There are no evidences as to what is the recommended antibiotic therapy for these injuries; thus, no protocol was published. In the Lipschitz study [6], only 4 out of 252 patients developed meningitis and 2 developed superficial abscess. The authors did not describe whether these patients were treated with antibiotics around the surgery. They mentioned that antibiotics were prescribed to these six patients, only after sepsis was diagnosed. Our policy is to treat these patients empirically, like with open fractures, with a wide range of antibiotic therapies. When canal penetration is evident, we include CSF-penetrating agents such as third-generation cephalosporin, for 3 days.

2.5. Complications

Complications can be related to the spine injury itself or to the surrounding organs.

Spine-associated complications are continuous CSF leak; infection (less than 1% will develop chronic abscess and osteomyelitis) and rarely meningitis; chronic epidural granulation (sometimes will present as progressive myelopathy); and there are reports of arachnoiditis and syringomyelia. Retained foreign body reaction may present as late-onset myelopathy due to foreign body migration. Metal particles such as copper or silver may cause a marked inflammatory reaction, while nickel and lead particles can be a source of an intermediate reaction. Oxidation of metallic fragments and rust deposit were also described [28].

Extra-spinal complications are head injuries (5% of patients have low GCS on admission, and, hence, it may mask the diagnosis of SCI), vascular injury (most commonly, the carotid artery, but there are cases of injury to the vertebral artery as well) [29, 30], brachial plexus injury (it may superimpose cord injury), trachea and esophagus injury (the hypothesis is that these patients are too sick to survive), and thoracic organ injuries such as hemothorax, pneumothorax, and hemopneumothorax with a self-resolving emphysema. Less common injuries involve the major vessels, pericardium, and even the heart. Chylothorax and tear of the diaphragm were rarely described.

3. Missile-penetrating spinal cord injury

Missile-penetrating spinal cord injury (MPSCI) can be a devastating event and may cause severe and long-term morbidity and mortality. As in other SCI, these injuries have a substantial economic and psychosocial burden to patient, their family, and society.

MPSCI was first described in 1762 by a surgeon named Andre Louis that removed a bullet from the lumbar spine of a patient, who later on regained motion in his lower extremities [9].

Many famous fatalities of MPSCI are known throughout the history. Among them was Lord H. Nelson who was shot by a French sniper in the Trafalgar battle. The injury was to his shoulder, and he was described as experiencing immediate paraplegia. He died shortly after. Other known cases were the American presidents, J.A. Garfield and A. Lincoln. As a general rule, these injuries have a high rate of mortality and hence discouraged any treatment for many centuries [31]. Only at the end of World War II, surgeons started to treat it aggressively. Pool had reported [32] 57% marked neurological improvement with laminectomy compared with only 4.5% spontaneous improvement with previously untreated patients. Later, studies that were published following the Korea and Vietnam wars had shown no benefit of laminectomies in cases of complete and incomplete SCI. They concluded that surgery should be considered only in grossly contaminated wounds and for patients with progressive neurological deterioration [33–35].

MPSCI can be divided by the kind of the penetrating missile, that is to say, bullet vs. shrapnel or any other foreign body that penetrates, by blast, the patient body. Another way to classify these injuries is by the muzzle velocity of the shooting firearm: high versus low. The third option would be to classify them by the amount of penetrating particles—a solitary missile penetration versus multiple, usually combined with a blast injury. Segregation can also be done for civilian versus military injuries.

3.1. Epidemiology

Military MPSCI epidemiology depends greatly on military conflicts around the world. Like any other military injury inflicted, it is more common in areas of worldwide conflicts and less common in peaceful areas.

Civilian MPSCI are easy to quantify. This is now the third most common cause of spinal injury in civilian population accounting for one-fifth of all spine injuries after MVA and fall from height [36, 37]. They also account for 13–17% of all causes of spinal trauma [10, 38–41].

In both civilian and military injuries of the vast majority, more than 80% of affected victims are men, with the highest incidence at their third decade [42–46]. The most common involved level is the thoracic spine (approximately 50%), and the least is the lumbar spine [3, 37, 47–49]. The incidence of thoracic spine injuries tends to reduce in more developed armies with better personal protective equipment [50].

3.2. Ballistics

The term “ballistics” refers to the scientific analysis of projectile motion and is divided to three main stages:

- Internal ballistics refers to the projectile’s behavior within the barrel of the firearm.
- External ballistics deals with the projectile’s path and motion while in the air.
- Terminal ballistics describes what happens upon the impact with the target.

Wound ballistics is considered a subgroup of terminal ballistics and is the main concern of medical personnel [43, 51, 52]. Wound (terminal) ballistics, together with the characteristics of the damaged tissue and its reaction to the penetrating missile, dictate the severity of the injury and treatment strategy [53, 54].

Although surgeons are naturally mostly concerned with the terminal ballistics, understanding of the entire bullet course is crucial, since it has a direct effect on its introduction into the body and the extent of tissue damage.

3.2.1. Internal ballistics

All bullets are fired through a barrel, which is usually a tube of variable length with internal spiral grooving. The bullet is accelerated down the barrel to reach its final exit velocity due to high pressure expanding gases from the combustion of its propellant [55, 56]. During its path within the barrel, the bullet acquires its spin as it is engaged by the spiral grooves of the barrel. This spin is essential for the appropriate orientation of the bullet during its flight [57].

Bullets are usually classified as “high” or “low” velocity, which corresponds to the type of firearm they were shot from—a rifle or a pistol, respectively [58]. Low velocity usually refers to subsonic speed of about 350 m/s, while high velocity can reach up to 600–900 m/s [57].

The bullet itself, and most importantly—its mass, also influences wound ballistics, since the mass and velocity both comprise the well-known formula of kinetic energy = $1/2 mv^2$. Thus, a bullet fired from a handgun of 6.35 mm caliber, with a muzzle velocity of about 350 m/s and a mass of about 3.5 g, carries the energy of about 85 J. On the contrary, bullet fired from an assault rifle, such as the 7.62 mm caliber AK-47, with a mass of 8 g and muzzle velocity of about 800 m/sec, may reach the energy of about 2100 J—almost 25 times more than a handgun [59].

3.2.2. External ballistics

Once leaving the barrel, a bullet is subjected to several forces that might influence its energy-delivering capacity. First, it is affected by the escaping gases just as it is exiting the barrel

[60] that might destabilize it and thereafter to the drag forces as it traverses the air, which increases with rising velocity [51].

This combination of forces acting on the exiting bullet creates an overturning moment, which causes the bullet to diverge from its original line of trajectory. This divergence is called “yaw,” and it is expressed by the angle between the bullet’s axis and the velocity vector [36, 61]. Because of the bullet’s spin, yawing results in complex spiral revolution of the tip about its center of mass. Eventually, if the distance the bullet travels is long enough, yawing becomes irreversible, and tumbling occurs—meaning the bullet advances base-forward [62, 63].

It is quite clear that as the distance between the firearm and the target is shortened, these are less so-called disturbances to the bullet’s path, and hence it can deliver more energy upon the impact. Muzzle velocity decreases significantly after 45 m for most pistol bullets and after 100 m for rifle bullets [64]. Unfortunately, most civilian gunshot wounds (GSW) are inflicted from an average distance of only 10 m [65].

3.2.3. Terminal ballistics

Terminal ballistics is directly influenced by the internal and external ballistics, which delivered the bullet to meet its target in a certain condition. As discussed above, the energy entailed within the bullet upon the impact is the main characteristic that will influence its effect within the body and will determine the extent of the injury [66].

The other aspect that determines the amount of injury transferred to the body is the resistance to penetration of the body and the characteristics of the body surface and tissue. The ability of the body surface to resist penetration is influenced in turn by two factors—the presented area of the bullet, which increases with rising yaw up to a maximal impact surface when the yaw angle reaches 90°, and the bullet deformation upon impact, which has to do with its internal metal composition and structure [67].

As the bullet penetrates the skin, the energy transfer between the bullet and the tissue begins. As a result of the high level of resistance and drag that meets the bullet with its entrance, a high-pressure crushing effect develops in front of the bullet’s tip, sometimes called the “shock wave,” and together with the mechanical damage that occurs, while the bullet cuts through the tissue—these create one level of tissue damage [58, 68]. In contrast to the high pressure that develops in front of the bullet, as the bullet keeps on advancing, a vacuum is created in the back of the bullet, which in turn causes the tissue to collapse back.

This change of pressures causes the “cavitation” effect, which basically refers to the tissue’s reaction to the very rapid change of pressures—the tissue first expands and then collapses back, leaving a tract within the tissue which is slightly larger in diameter than the bullet. The magnitude of the cavitation is directly related to the rate of energy transfer into the tissue and to the degree of yaw—the bigger the yaw, the bigger the cavitation [69].

The outer appearance of the body after the impact is not always suggestive of the true damage that lies within. With low-velocity handguns, the bullet usually does not cause cavitation, and

the damage is usually due to the mechanical impact of the bullet. Sometimes, there is not even an exit wound and the bullet stays within the tissue. Alternatively, high-velocity rifles usually have an exit wound, and they leave behind them a distinct tract, usually very damaged and often contaminated because of the “suction” effect of the wound. One might find cloth fragments in a wound cavity [70].

3.3. Initial evaluation and management

As in any other trauma, MPSCI should be first treated according the ATLS principles [71]. This initial evaluation will reveal concomitant injuries. Rapid evacuation to a hospital is crucial. This is especially true for the military scenario, in which more than one injury is the rule. The Prehospital Trauma Life Support and the Military Trauma Life Support (PHTLS and the MTLT) emphasize the importance of rapid evacuation from the scene of injury. It recommends that only securing airway and breathing together with partial circulatory control (control external bleeding) are done at the scene, and, thus, instead of doing the whole “ABCDE” scheme, the team should perform stages A, B, and half C (“scoop and run”).

After arrival to the hospital, these patients are initially evaluated in the trauma bay by a multidisciplinary team. Following initial resuscitations and stabilization, physical examination is undertaken. The sensitivity and specificity of this were shown to be high, in detecting spinal cord injury (100% and 87%, respectively) [72]. It should be emphasized that civilian and military scenarios are different. In the civilian, most injuries are inflicted by low-velocity weapons with a solitary injury and less comorbidity. The evacuation period is normally short, and most patients arrive conscious to the emergency room. Neurological examination in this setting is more feasible and accurate. The opposite is true for the military scenario where most injuries are of high-velocity nature, and usually there is more than one injury. Usually, since most of casualties have a longer period of evacuation, they are brought to the trauma bay intubated, and thus their neurologic assessment is limited. The clinician should rely mostly on the anamnestic report of the evacuation team that considering the circumstance might not always be accurate.

After securing airway, birthing, and circulation, and after an initial neurologic assessment was performed, the patient should be completely exposed to inspect the entire body. Documentation of the entry and exit wounds should be done. It should be kept in mind that in high-velocity weapons, more than one exit wound may be found. In a low-velocity weapon, no exit wound is usually the rule.

Treatment for associated injuries to other organs should be addressed.

Tetanus prophylaxis history should be inquired and treated accordingly. In cases of unknown immunization, tetanus immunoglobulin is required in addition to toxoid treatment.

Antibiotic treatment is usually given; however, no consensus for the type and duration of treatment exist. Evidence to support different antibiotic treatments in cases of organ perforation such as the larynx/esophagus in cervical injuries compared with abdominal viscera in thoracic injuries is low. There is, however, some evidence to support administration of a wide range of antibiotic treatments as prophylaxis [73]. Interestingly, a Cochrane review

concluded that evidence exists for antibiotic treatment only for the first 24 h after initial debridement [74].

Most of the evidence exists for low-velocity injuries. There is less evidence guiding treatment recommendation in high-velocity injuries. We normally recommend empirically regimen of 3 days of prophylactic antibiotic which is discontinued if no sign of infection is observed.

3.4. Imaging

The mainstay of imaging for MPSCI is the CT scan. In some cases a retained metal fragment can be found in chest and pelvic X-ray routinely done in the trauma bay; however, these can provide limited information regarding concomitant injuries and spatial orientation.

3.4.1. CTA

CTA is usually available, is relatively quickly obtained, and gives sufficient information on other visceral injuries as well as bleeding. The only disadvantage is its inability to demonstrate neurological tissue with high accuracy. It should be reemphasized that an unstable patient should not be referred to CT prior to resuscitation and hemodynamic stabilization. In case of failure to achieve hemodynamic stability, patient should be taken to OR without any further delay. We routinely use CTA in any penetrating trauma as part of our protocol given the advantage of demonstrating major vessel injury and extravasation.

3.4.2. MRI

MRI has the ability to demonstrate neurologic tissue including direct and secondary injury. However, this is a time-consuming modality and probably not suitable for initial assessment in these scenarios. Some concern exists regarding retained metal fragment migration and further neurologic damage when performing the MRI. Copper and lead are the most common materials for bullet manufacturing. These materials are non-ferromagnetic and should not affect MRI [75]. The literature shows that MRI (up to 1.5 T) is safe to use in case of retained bullets [76–79]. Nevertheless, we recommend that the decision should be done on a case-to-case basis, especially if the penetrating missile is not a bullet.

3.4.3. Others

As mentioned above, other imaging studies may be used when clinical suspicion for specific collateral organ damage is raised.

3.5. Definitive treatment

Management of acute missile-penetrating SCI is multidisciplinary. The treatment is guided by many factors, but first and above all, the patient's respiratory and hemodynamic stability are defined by the ATLS guidelines. A hemodynamically unstable patient, whose primary resuscitation has failed, should be transferred immediately to angiography or surgery suite

without further delay. In a stable patient, treatment should be guided by the presence of other factors such as neurological status, mechanical stability of the spine, CSF leak, risk for infection, and other systemic injuries.

3.5.1. Indication for surgery

There are no clear clinical guidelines to direct the treatment pathway in MPSCI, and hence each case should be treated individually. Some issues, however, should be considered:

Wound care: in high-velocity GSW, an extensive wound debridement and lavage should be performed in the OR given the expected large infected cavity and “wound suction effect” inserting debris into the wound [8, 45, 80]. A low-velocity, civilian-inflicted GSW (gunshot wound) can be treated locally in the ER and observed.

Loss of neurologic function: progressive loss of neurologic function with radiographic evidence of neural tissue compression either by hematoma, bone fragment, or foreign body is an absolute indication for surgery [81–85]. There is no doubt that the initial neurological status will dictate the fate of the patient’s neurological function [84]. There is only minor evidence that demonstrate neurological improvement following early (24–48 h) intervention. This is especially true if the insult occurs in the cauda equine area [82, 83, 86]. However, there is more evidence to show that there is no improvement following surgery, especially if the injury occurs between the levels of T1–T11 and definitely in complete injuries due to high-velocity GSW [49, 62]. In low-velocity civilian injuries, these types of injuries might have better prognosis, depending on what was the initial clinical presentation.

Despite the above details, some subgroups of patients may benefit from surgical intervention, even in the presence of a complete or nonprogressing injury. This includes complete injuries of the cervical spine where a potential recovery of an affected level is anticipated or when the injury raises a mechanical issue that might be solved with surgery (**Figure 2**). When intervention is considered, one should remember that it has been shown to result in about 20% of complications compared to 7% for nonsurgical treatment [87]. Clinical discretion should be used in all cases.

Foreign body removal: foreign body, e.g., bullet fragments, shrapnel, and intact bullets, is considered an absolute indication for removal in cases of incomplete SCI, definitely when it is progressive. When there is imaging evidence of cord compression, early intervention has been shown to be beneficial in many studies [47, 51, 88].

Removal of bullets in cases of complete and static SCI is not efficient and will not restore any neurological function [47, 62, 86].

Another possible indication for bullet removal from the spinal canal is the concern of fragment migration (**Figure 2**). This might happen early [89] or late [90, 91] in the course of injury, as shown in some sporadic cases. In both cases, neurologic deterioration had resolved following the surgery. That is why some surgeons suggest preventing this complication by surgically removing the foreign body, especially in cases with easy access and expectedly low complications.

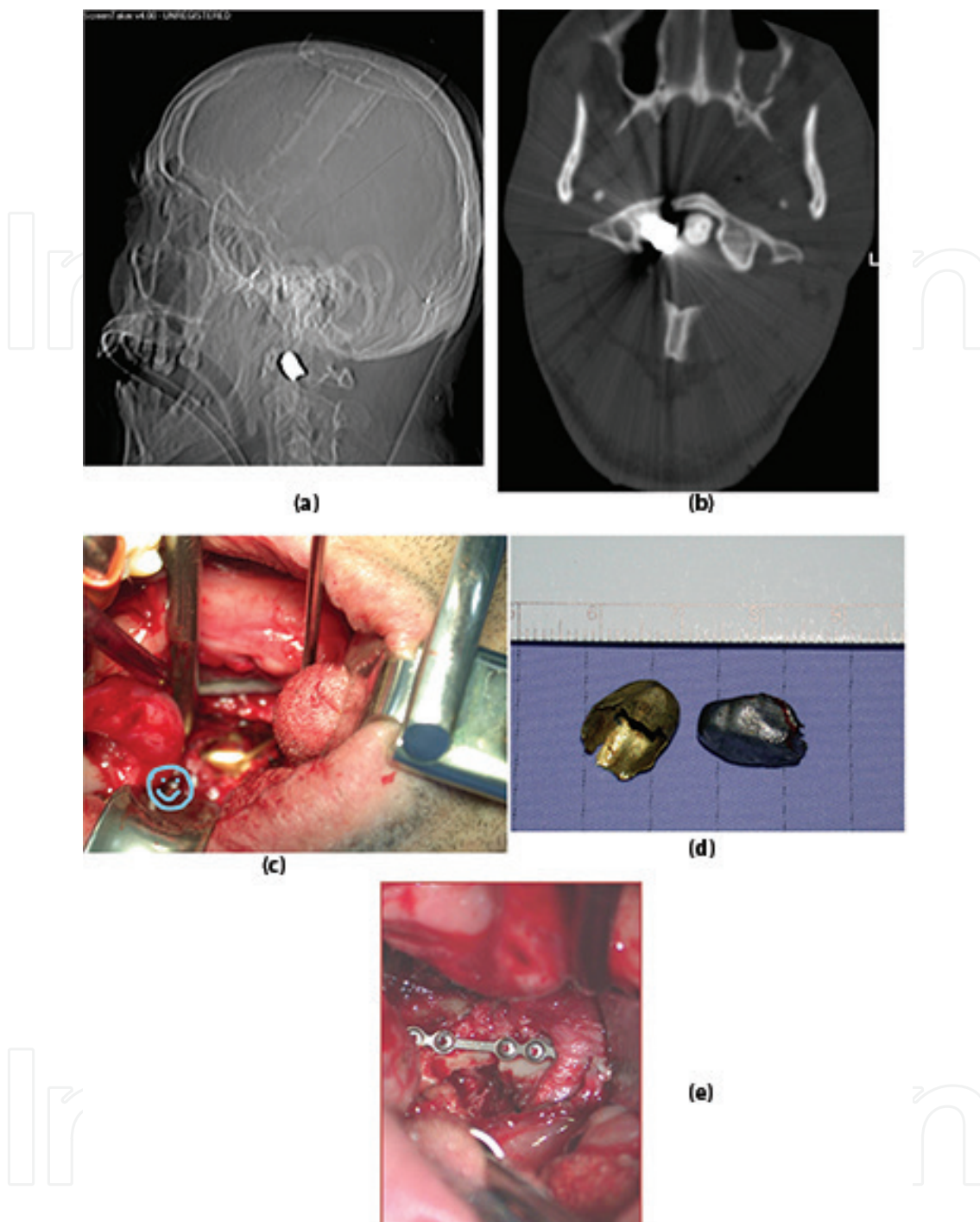


Figure 2. A 30-year-old patient, who sustained a low-velocity gunshot wound. He had a few entry wounds in his head and neck. He was conscious, alert, and hemodynamically stable with normal neurological status. The following images describe the evolution of events. (a) Plain radiograph showing the patient's skull with a bullet located at the center; (b) axial CT scan showing the broken arc of C1 with the bullet located next to the dens; (c) trans-oral approach to C1 vertebra with the bullet at the base of the surgical dissection. The smiley gives the orientation of the patient's face; (d) the bullet is shown outside of the patient's spine; (e) C1 ring following osteosynthesis.

The presence of foreign body inside the spinal canal was not shown to be associated with increased risk of infection, regardless of the previous path of the bullet, prior to its final location in the spinal canal [92, 93]. Thus, we do not consider bullet removal as an indication for

surgery in order to prevent potential infection. Metal toxicity is usually not a concern since most materials used to manufacture bullets and shotgun pellets today are often made of copper or lead.

Lead toxicity or plumbism was shown to happen in cases of retained bullets in joint spaces and intervertebral disks [94, 95]. The symptoms can include anemia, abdominal pain, anorexia, nephropathy, lethargy, encephalopathy, and motor neuropathy, all of which can appear intermittently or continuously. Symptoms develop insidiously and can appear even 40 years after the exposure [96], making the diagnosis often challenging. Missiles retained in bone and soft tissues are usually asymptomatic.

Spinal instability: low-velocity spinal GSW involving the vertebral column are normally stable and do not mandate surgical stabilization. Risk of instability is higher with high-velocity injuries. Preventive stabilization should be considered if instability is anticipated following the surgery. There are reports claiming that stabilization may improve neurology [44], and other reports state that it may facilitate rehabilitation [37].

CSF leak: should bullet or other foreign bodies enter the spinal canal, durotomy is suspected. If a clinical presentation of post-LP syndrome (positional headaches, diplopia, photophobia, nausea, and neck stiffness) presents, surgical exploration should be considered. The preferable treatment is direct repair of the dural defect. This might prevent fistula formation, secondary meningitis, cord herniation, and neurologic impairment. If primary repair is not feasible, like in the ventral cervical and thoracic cord, fibrin glue combined with synthetic or local graft should be used. Submuscular drains are controversial. Position restrictions (upright for cervical injuries or reclining for lumbar) are not mandatory and case specific. Subarachnoid continuous drainage is optional as primary treatment for minor tears or as an adjuvant to surgical repair.

The optimal timing of surgery for any indication is debatable [97–99]. Early surgical intervention has been reported to have less complication, while late intervention (more than 2 weeks) was associated with a high rate of arachnoiditis and spinal abscess [83].

No significant benefit of steroids has been shown [3]. A Cochrane review that shows some neurologic improvement in SCI following steroid administration (up to 8 h of injury) excluded penetrating injuries [100].

Empiric Intravenous antibiotic should be given for a minimum of 3 days and up to 2 weeks, in most cases. The covered spectrum should be wide in order to treat Gram-positive, Gram-negative, and anaerobic bacteria. This treatment was shown to prevent most infections including trans-colonic and trans-oral injuries [41, 81].

4. Summary

This chapter is an overview of two relatively rare-penetrating spinal cord injuries, their epidemiology, mechanism of injury, initial evaluation, and emergency primary and late definitive treatment. We also reviewed the complication and prognosis of each injury.

	NMPSCI	MPSCI (high velocity)	MPSCI (low velocity)
Incidence	1.5% of SCI	17–21% of SCI	17–21% of SCI
Primary evaluation	ATLS Extracting the penetrating object must not be done on site	MTLS “scoop and run”	ATLS
Preferred primary imaging	CTA/X-ray	CTA	X-ray
Surgical treatment	OR/observation depending on neurological status and comorbidity	OR mandatory	ER/OR
Antibiotics	IV antibiotics (empiric)	IV antibiotics	PO antibiotics/observation
Steroids	No	No	No
Complication	CSF leak, infection (less than 1%), pneumo-/hemothorax, vascular (common)	Multiple organs-common. Spine instability, infection	Not common
Common incomplete SCI	Brown-Sequard syndrome	Any	Any, not common

Table 1. Summarized table comparing evaluation, treatment, and complications between NMPSCI and MPSCI.

In order to emphasize the differences between these entities, we present a summarized table that compares between them (**Table 1**).

Conflict of interest

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speaker bureaus; membership, employment, consultancies, stock ownership, or other equity interests; and expert testimony or patent-licensing arrangements) or nonfinancial interest (such as personal or professional relationships, affiliations, knowledge, or beliefs) in the subject matter or materials discussed in this chapter.

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