

Chapter 2

The Pathological Findings in Traumatic Injury to the Human Spinal Cord

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Abstract

The anatomical pattern of damage following upon traumatic injury to the human spinal cord is dependent upon the manner in which the injury is sustained. Hyperflexion typically results in anterior spinal cord injury, hyperextension in central spinal cord injury, stab wounds in hemisection injury, and complete crush in total spinal cord injury. Secondary lesions may appear hours to years later and may result in serious additional disability. The presence of congenital spinal stenosis, cervical spondylosis, or ossification of the posterior longitudinal ligament may greatly enhance the likelihood of damage following blunt injuries to the spine.

Key words: Human spinal cord trauma, Traumatic paraplegia, Traumatic quadriplegia, Spinal cord injury, Spinal cord pathology, Human spinal cord injury

1. Introduction

Although methods traditionally employed to produce experimental spinal cord injury, such as the weight-drop technique, the clip compression technique, or the extradural balloon compression method (1), have no counterpart in humans, for purposes of reproducibility it is essential to be able to standardize the pattern and severity of injury in experimental paradigms, despite the fact that no two instances of human spinal cord trauma show precisely the same pattern of damage.

Epidemiologically, the manner in which spinal cord injury occurs in man varies according to the population surveyed. In most large peacetime series, motor vehicle accidents account for 40–50%, violence (gunshot wounds or stab wounds) for 7–23%, falls for 12–20%, and injuries sustained during sports or recreational

activities (particularly diving) for up to 24% (2, 3). How the injury is sustained may be an important determinant of the anatomical pattern of damage within the spinal cord.

2. Patterns of Injury

To the clinician caring for the patient who has suffered from traumatic spinal cord injury the neurologic deficits that emerge after the initial period of spinal shock has elapsed will provide important insights into the configuration of spinal cord lesions (4). The *anterior spinal cord syndrome*, which typically follows a *hyperflexion injury* (such as that frequently observed in the thoracolumbar region after a motor vehicle accident), is characterized by hypesthesia (resulting from damage to the anterior spinothalamic tracts), hypalgesia (resulting from damage to the lateral spinothalamic tracts), and spastic weakness (resulting from damage to the lateral corticospinal tracts), with relative sparing of posterior column (touch/proprioceptive) function (Fig. 1). The *central spinal cord syndrome*, which is ordinarily associated with a *hyperextension injury*, such as that observed in most diving accidents, is usually characterized, depending on the severity of the injury, by variable loss of posterior column function and spastic weakness that is more pronounced in the upper than in the lower extremities (Fig. 2). The *Brown-Séquard syndrome*, which is usually the result of a *penetrating injury* such as a stab wound (5), is due to incomplete hemisection of the spinal cord and manifests clinically as contralateral loss of pain and temperature perception and ipsilateral spastic

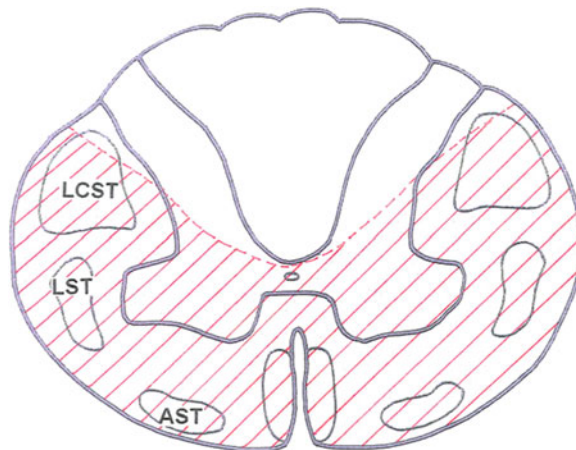


Fig. 1. Hyperflexion injury is typically associated with an *anterior spinal cord syndrome*, with spastic paraplegia and hypalgesia and sparing of posterior column sensation (LCST lateral corticospinal tract, LST lateral spinothalamic tract, AST anterior spinothalamic tract).

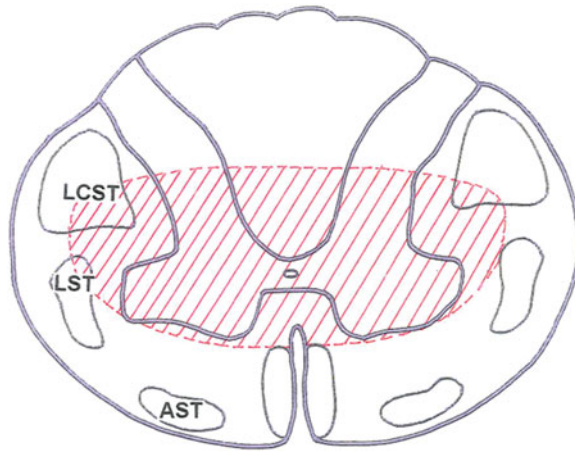


Fig. 2. Hyperextension injury leads to a *central spinal cord syndrome*, which is characterized, in cervical injuries, by spastic weakness that is more prominent in the upper than in the lower extremities and by hypalgesia with variable loss of posterior column sensation.

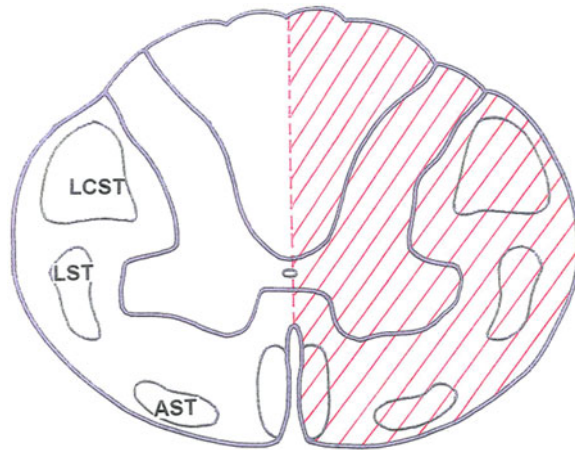


Fig. 3. The *Brown-Séquard syndrome*, i.e., ipsilateral weakness and loss of posterior column sensation with contralateral hypalgesia, is usually the result of a penetrating injury such as a stab wound.

weakness and loss of proprioception (Fig. 3). The *complete spinal cord syndrome*, which may follow upon a *complete crush injury* to the spinal cord, is characterized by complete, permanent spastic paralysis and loss of all sensory function below the level of the injury (Fig. 4).

2.1. Penetrating Injuries

Penetrating injuries are those in which the integrity of the dura and leptomeninges are breached by the injuring agent which, in peacetime civilian life within the United States, is most frequently a bullet or a sharp object such as a knife blade. The resulting neurological

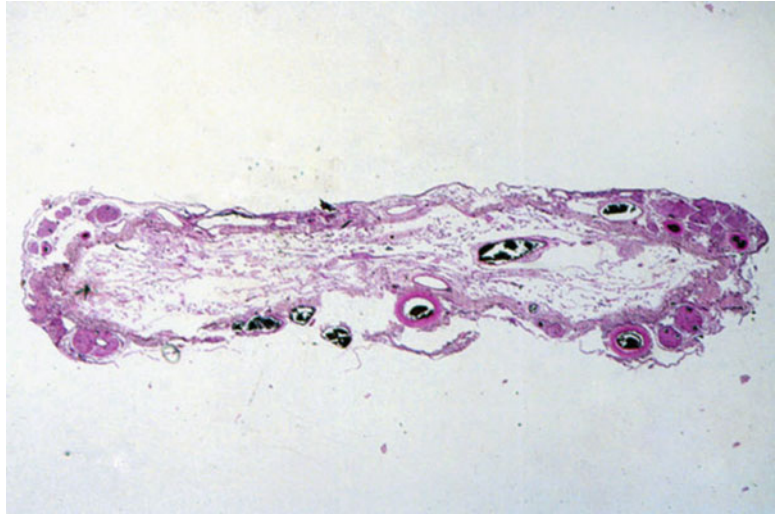


Fig. 4. Spinal cord at T10 in a man with a *complete spinal cord syndrome*, 39 years after a shell-fragment injury to the spine. Only the leptomeninges and leptomeningeal blood vessels are visible; no spinal cord parenchyma remains (hematoxylin and eosin stain).

deficits will depend heavily upon the extent and level of the injury. Missiles may penetrate the spinal cord directly or injure it by driving bone fragments into it. Closed injuries may also breach the dura and leptomeninges by producing vertebral fractures and driving bone directly into the spinal cord parenchyma.

2.2. Nonpenetrating Injuries

Acutely fatal injuries tend to occur at high cervical spinal cord levels and may show very little in the way of dramatic pathological findings, as the continuity of the vertebral column and spinal cord is typically restored immediately following the injury (6). Damage to the vertebral column should alert the examiner to the possibility of structural damage to the spinal cord proper. Surprisingly little may be seen (7). Epidural, subdural, or subarachnoid hemorrhage or damage to external blood vessels such as the vertebral or anterior spinal arteries is seldom observed. The main finding may only be extravasation of erythrocytes into the spinal cord parenchyma, which may evolve, on rare occasion, into frank hemorrhage (hematomyelia). Histologically, recognition of the presence of structural damage to the tissue itself requires that the victim survive for at least several hours after the injury.

3. Primary Spinal Cord Lesions

In those instances in which the injury is not immediately lethal and in which the afflicted individual survives for more than a few hours, histological abnormalities are more readily observed. For purposes of this discussion it is convenient to separate lesions into two

categories, namely, those that develop at the time of impact (primary lesions) and those that develop afterward (secondary lesions).

For primary lesions, some investigators use the same terms as those used for traumatic brain injuries, i.e., concussion, contusion, laceration, and compression (8). Not all of these terms are in common usage, however, because of differences among investigators in the way they are defined. The word *concussion*, for example, is applied by some to transitory spinal cord dysfunction in the absence of structural damage and by others to injuries in which damage may be moderately severe (8, 9). Given the limited opportunity to examine human material in such circumstances, it would probably be wiser to restrict its usage to those clinical situations in which, following traumatically induced spinal cord dysfunction, there is rapid and complete neurological recovery (10).

The word *contusion*, by analogy with its use in association with craniocerebral injuries, implies that the spinal cord has impacted against the bony wall of the spinal canal, a situation that seldom if ever prevails in actuality. Injury following upon contact between the spinal cord and its bony encasement is virtually always due to bony displacement (e.g., fracture or dislocation), in which case the term *compression* or *crush injury* is more appropriate.

Spinal cord *laceration* is seldom observed in the absence of a penetrating injury and, when it occurs, is most often the result of bone fragments being driven into the spinal cord following a vertebral fracture.

Spinal cord *compression* is generally due to fracture/dislocation or subluxation within the bony vertebral column. Vertebral body continuity may be restored completely immediately following the injury. When acute it may lead to the development of a cylindrical core of necrosis within the ventralmost portion of the posterior column that tapers, in conical fashion, above and below the level at which compression has been maximal (9, 11–13), much in the manner in which a tube of toothpaste has been squeezed (14) (Fig. 5). This type of lesion has sometimes been referred to as “pencil necrosis” (15, 16). With very severe injuries the spinal cord may be transected or completely crushed, although this is rare. Usually, some residual parenchyma can be observed traversing the site of maximal injury (3, 17).

4. Secondary Spinal Cord Lesions

Provided that the spinal cord is not transected or completely crushed, the earliest change that is visible by light microscopy is the presence of pericapillary extravasation of erythrocytes and serum constituents (6). These hemorrhages may become more numerous over the next few hours, but frank hematomyelia is uncommon.



Fig. 5. Acute spinal cord compression. Note the “cores” of displaced tissue within the ventral portions of the posterior columns (Klüver–Barrera stain).

Swollen, injured axons may become visible as early as 30 min after the injury, as evidenced by immunoreactivity for β -amyloid precursor protein, owing either to axonal retraction bulb formation after transection or to impairment of axoplasmic flow through otherwise anatomically intact axons (18, 19). Between 8 and 24 h post-injury small numbers of neutrophils begin to appear and the white matter becomes progressively more edematous, as evidenced by pallor of myelin staining. Macrophages appear at 24–48 h and steadily increase in numbers thereafter, and GFAP-positive reactive astrocytes appear at 48–72 h. At 24–48 h there is extensive coagulative necrosis with prominent neuronal ischemic cell change. Following this there is tissue breakdown progressing to cavitation. Neovascularization begins at approximately 1 week. In both human and experimental material there is evidence to suggest that, in the brain (and, presumably, also in the spinal cord), there is prolonged activation of resident microglial cells that may persist for months to years after injury (20, 21).

Although experimental studies have demonstrated a number of physiological and biochemical abnormalities, including impairment of microcirculatory perfusion (22, 23) and of autoregulation of blood flow (24), release of vasoactive amines and of excitotoxic neurotransmitters (25–27), Ca^{++} and K^{+} ion shifts (28, 29), and generation of oxygen-free radicals (30, 31), such abnormalities have not, for obvious reasons, been documented in human spinal cord-injured subjects.

Traumatic demyelination, i.e., loss of myelin with relative axonal sparing, though well studied in experimental models of spinal cord injury (3–34), does not appear to be as prominent in human

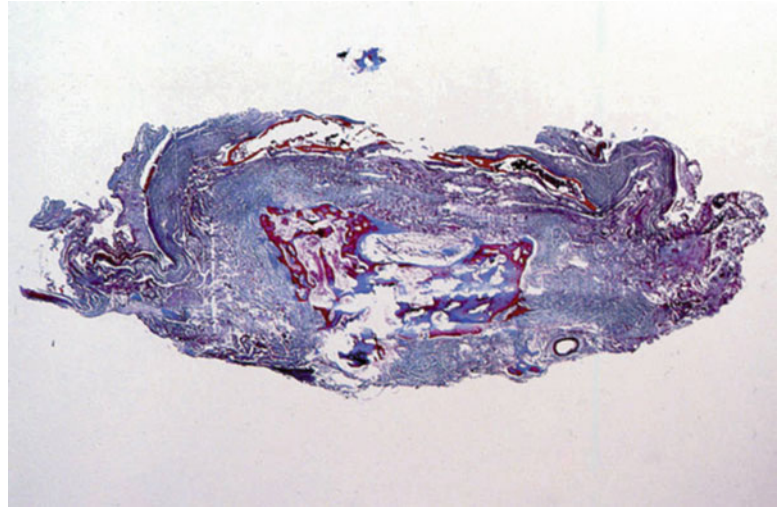


Fig. 6. Spinal cord at T10 ten years after a fall, showing complete replacement of the spinal cord by collagenous connective tissue (*blue*). Heterotopic bone formation is present within the central portion of the scar (Masson trichrome stain).

material (3, 18). When it occurs, it typically does so in close relation to the site of primary impact, and then only around isolated axons. Evidence of oligodendroglial apoptosis has been described in human material (35). Remyelination of central axons, when observed, appears to be achieved by Schwann cells rather than by oligodendrocytes, a process sometimes referred to as “schwannosis” (3, 18, 36).

Collagenous scar formation occurs whenever the pia-arachnoid is breached. If the damage to the spinal cord parenchyma is extensive, the collagen may encroach upon what remains of the parenchyma to such an extent that it appears to replace it completely (Fig. 6). The collagen is presumably elaborated by arachnoid cells and is limited to the subarachnoid compartment, as evidenced by the presence of a layer of arachnoid cells between the mass of collagen and the dura (37) (Fig. 7). A recent study in experimental animals suggests that pericytes may also contribute to the appearance of collagen (38). The presence of scar tissue tethers the spinal cord and renders it less mobile within the spinal canal, making it more vulnerable to complications such as posttraumatic syringomyelia (see below).

Traumatic neuromata are present in great abundance where damage to spinal cord parenchyma is maximal (Fig. 8). These neuromata are presumed to represent regenerating sprouts, mainly from the centrally directed neurites of dorsal root ganglion cells (39–41).

Wallerian degeneration of ascending tracts above and descending tracts below the level of injury represents degeneration of those axonal

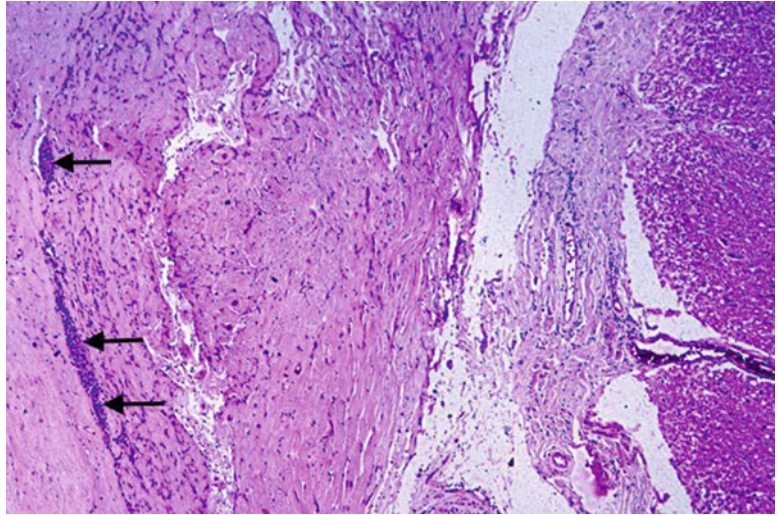


Fig. 7. Spinal cord at C6 in a patient rendered quadriplegic 9 years previously in a motor vehicle accident. Dura is on the *left* and spinal cord on the *right*, with collagenous connective scar tissue in between. Note the layer of arachnoid cells (*arrows*) between the scar tissue and the dura, thereby localizing the collagen within the subarachnoid compartment (hematoxylin and eosin stain).

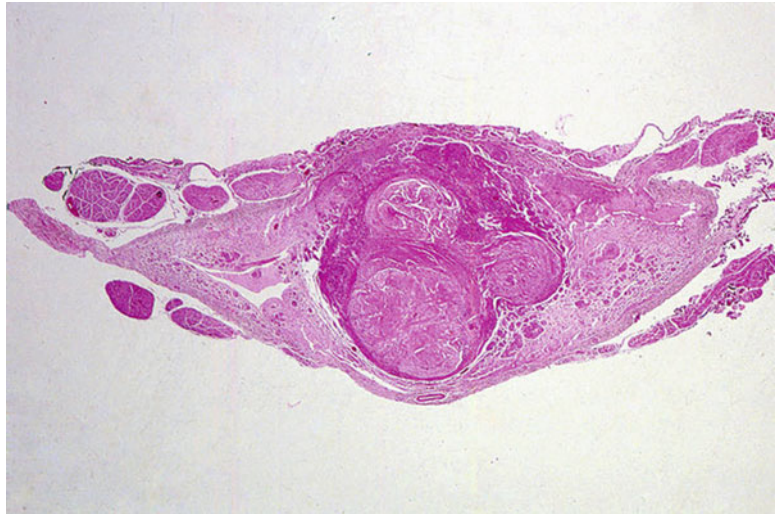


Fig. 8. Spinal cord at C6 in a patient rendered quadriplegic 45 years earlier in a motor vehicle accident. Note the presence of numerous traumatic neuromas (hematoxylin and eosin stain).

segments distal to the site of transaction. The evolution of this process, which may take place over a period of years, is much more attenuated than it is in the peripheral nervous system. Marchi staining permits detection as early as 10 days after injury, but this is not commonly done nowadays. CD68-immunoreactive macrophages are seen 1–4 months after injury (42, 43) and are accompanied by reactive

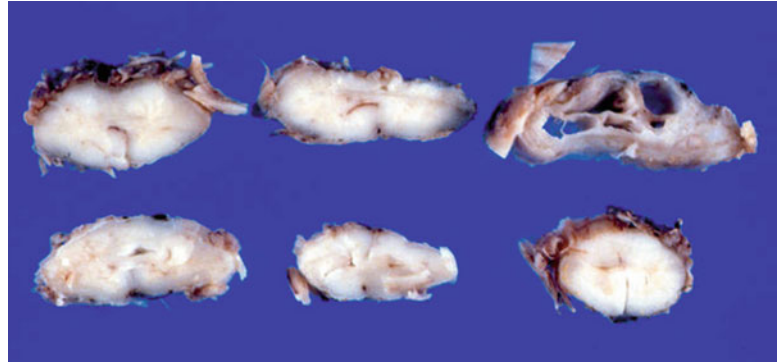


Fig. 9. Spinal cord at C3, C4, and C5 (*top row*) and at C6, T4, and T10 (*bottom row*) in a C4/C5 quadriplegic who sustained his injury 37 years earlier in a motor vehicle accident. A syringomyelic cavity extended from the level of the injury down to T10.



Fig. 10. Spinal cord at T11 showing a syringomyelic cavity in a man who became quadriplegic after a motor vehicle accident 43 years earlier (Masson trichrome stain).

astrocytosis (44). Pallor of myelin staining of affected tracts may not become pronounced until 6 weeks to 2 months have elapsed.

Delayed posttraumatic syringomyelia is of singular clinical importance, as it may increase significantly the extent of neurologic impairment. The condition is characterized by the development, after an interval of several years, of one or more syringomyelic cavities extending either upward or downward for variable distances from the original site of injury (45) (Fig. 9). The consequences can be dire. If, for example, the cavity extends upward from a thoracolumbar lesion, a paraplegic patient may be rendered quadriplegic. The frequency with which this complication develops is not known but is probably over 20% (46). The syringomyelic cavity, which contains no lining epithelium and which is bordered by a zone of isomorphic gliosis (Fig. 10), has no direct communication

with the central canal, fourth ventricle, subarachnoid compartment, or, necessarily, cavities formed at the original site of injury. The mechanism by which posttraumatic syringomyelia develops is not known, but the view has been expressed that progressive tearing may follow upon the effects of episodic elevation of venous back-pressure (such as that induced by coughing, sneezing, or Valsalva maneuvers) upon a spinal cord that is tethered by adhesive arachnoidopathy (37, 45).

5. Cervical Spondylosis

Patients with cervical spondylosis are predisposed to develop damage to the spinal cord after traumatic injury that may be relatively minor (37). Increasing age is accompanied by progressive dessication and disruption of the integrity of intervertebral discs, particularly at the C5–C6 and C6–C7 interspaces, where spine mobility is greatest (47–49). The resulting narrowing of disc spaces leads to direct contact between adjoining vertebral bodies and the formation of bone spurs (osteophytes) which, if directed posteriorly, will narrow the spinal canal (50, 51). Such narrowing would predispose the afflicted individual to parenchymal damage to the spinal cord following upon a hyperextension or hyperflexion injury that would ordinarily be considered to be relatively minor (51). The pattern of spinal cord damage may vary according to the location of the bone spurs (52). Classically, with centrally positioned spondylotic protrusions, parenchymal damage, which is usually the result of hyperextension, is characterized by the presence of an ovoid spinal cord contour and of a “butterfly” pattern of tissue necrosis that affects the lateral columns, the lateral spinal gray matter, and the ventral portions of the posterior columns (50, 51, 53–56). The manner in which this pattern of damage develops is unknown, although a variety of vascular mechanisms have been proposed (57–59). Quencer and colleagues (60) have suggested, in a correlative MRI pathological study, that hyperextension-associated buckling of the ligamenta flava into a spinal canal that has already been narrowed by cervical spondylosis may lead to axonal disruption at the sites indicated above.

6. Concluding Remarks

The anatomical distribution of the lesions within the traumatized spinal cord will be determined by the manner in which the injury is sustained and will, in turn, determine the resulting signs and symptoms. The primary lesions that develop at the time of injury

will be followed by secondary lesions that may appear hours or years later, with potentially major clinical consequences. Predisposing factors such as congenital narrowing of the spinal canal and, particularly, cervical spondylosis and, among East Asian subjects, ossification of the posterior longitudinal ligament (61) render some individuals more susceptible than others to the development of parenchymal damage to the spinal cord following upon blunt injuries to the spine.

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