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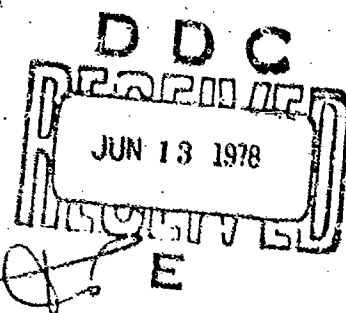
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STANDARDIZATION AND INTERPRETATION OF SPINAL INJURY CRITERIA

LEON E. KAZARIAN, DR. ING.

APRIL 1978



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STANDARDIZATION AND INTERPRETATION OF SPINAL INJURY CRITERIA

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INTRODUCTION

Aircraft crash, emergency egress from disabled aircraft, parachute opening shock, and ground landing impact are among the most frequent causes of spinal injury. The vertebral centra, the neural arches, the intervertebral disks, and the contents of the spinal canal may be affected. If the various components of the spinal column are displaced, acute or chronic spinal cord and/or nerve root compression takes place. Such compressive phenomena vary widely from slight cord compression to immediate transection. Epidural, subarachnoid, paravertebral, and intramedullary hemorrhages may also occur. The degree of injury is dependent upon a number of factors such as the magnitude, duration, and direction of the accelerative/decelerative forces, body posture muscular tone, and the configuration of the support and restraint system at the time of load application.

This paper deals with spinal injury. Its purpose is to identify the level, type, severity, and mechanics of spinal injury that are revealed by the study of clinical and operational accident data. A second objective of this paper is to shed light on the biomechanics of vertebral trauma and subtle fracture patterns. A third objective is to describe the process of degenerative "adaptive" musculoskeletal changes using various species of subhuman primates and apes subjected

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to $+G_z$ impact forces. The overall goal of this research is to define human acceleration tolerance in terms of standardized spinal injury modes and to assess spinal injury in terms of compression fractures, fracture dislocations, and radiologically invisible injuries. These types of data, information, and knowledge are fundamental before maximum protection, comfort, and safety can be incorporated into passenger or pilot seat and restraint system design. Such data are also required before analytical models can be contrived to mimic human spinal column, pelvis, and head response and to predict human tolerance.

DISTRIBUTION AND LOCUS OF SPINAL INJURIES

For kinematic and morphologic reasons, vertebral body and/or spinal cord damage varies in the cervical, thoracic, and lumbar spine. The cervical and lumbar vertebral bodies are relatively more mobile when compared to the thoracic vertebral bodies. The thoracic vertebral bodies differ from these other vertebrae in that the bony thoracic cage braces and thereby immobilizes and somewhat protects this spinal region. T_{11} and T_{12} are not fixed in a similar manner as T_1 through T_{10} . Vertebral body fracture and/or fracture dislocation occur most often where the relatively immobile and mobile spinal segments interplay. In man, these are the transregional vertebrae connecting the cervical thoracic and thoracic lumbar regions. Statistics on the incidence of vertebral body fracture show substantial differences in the distribution of injuries among the various spinal segments. The relative distribution of spinal injuries is best illustrated by comparing the injury complications of Kaplan, Nicoll, Ewing, and Jefferson as shown in Figure 1.

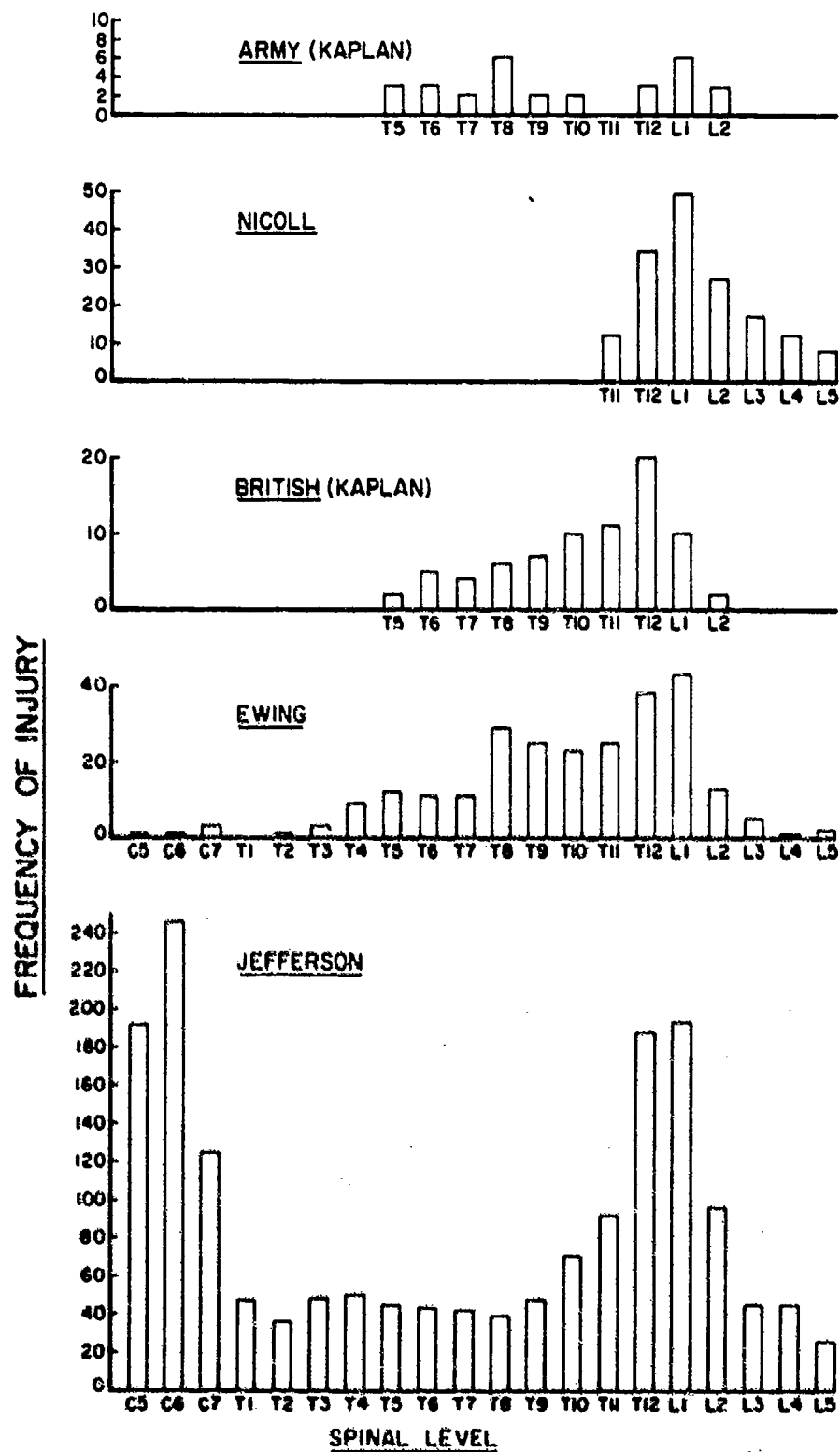


Figure 1 - Distribution and frequency of spinal trauma from clinical and operational statistics

Nicoll's and Jefferson's data show the distribution of spinal fractures arising from clinical cases. Ewing's data represent U.S. Navy ejection statistics and Kaplan's U.S. Army injury statistics. A cursory examination of these statistics reveals that the thoracolumbar spine is a region most susceptible to injury. The operational data reflects a bimodal injury distribution, whereas the clinical picture reflects only the T_{11} - T_{12} - L_1 peak. (That is, in addition to injury in the thoracolumbar region, there is also trauma incurred in the T_7 - T_8 - T_9 area.) The order of most spinal trauma appears to be the thoracolumbar transition (T_{11} - T_{12} - L_1) followed by the cervicothoracic junction (C_5 - C_6 - C_7) and the mid-thoracic spine (T_7 - T_8 - T_9). Figure 2 compares the various causes of spinal injury (aircraft or helicopter crash, ejection force) to the most common and least common sites of involvement (Delehaye).

CAUSE OF INJURY	MOST COMMON SITE	LEAST COMMON SITE
LIGHT AIRCRAFT CRASH	$T_{10} - L_2$	UPPER / MID THORACIC
HELICOPTER CRASH	$T_{10} - L_2$	LOW LUMBAR
EJECTION	$T_{12} - L_1$	UPPER / MID THORACIC

Figure 2 - Comparison between cause of injury and most and least common injury sites

TYPE AND SEVERITY OF VERTEBRAL BODY TRAUMA

Vertebral column fracture can occur in five fundamental modes: by slip, by pulling apart (separation), by torsional loading, by buckling, or by combination thereof.

Fracture may be complete or incomplete: the line of fractures may extend through the centrum or entirely across it, or the centrum may be fractured into several fragments or may be compressed. The fracture line may be vertical, horizontal, or oblique in any direction. Vertical fractures are found almost exclusively in the cervical and upper dorsal regions. The two latter accompanied by multiple fractures occur almost anywhere throughout the length of the spinal column. Transverse and oblique fractures often lie nearer the upper and lower borders of the vertebral centrum and are usually connected with violence involving limited asymmetric torsional forces. If the line of fracture is oblique, the displacement is inclined to the corresponding side usually by rotational injuries.

The manner of production of certain common traumatic lesions will be delineated and categorized into three groups: compression fractures, fracture dislocations, and radiologically invisible injuries. Keep in mind that fixed rules cannot be laid down, and generalizations are difficult.

Group 1 - Compression Fractures of the Vertebral Body

- A. Fractures of the vertebral body margins
- B. Anterior wedge fractures
- C. Lateral wedge fractures
- D. Cleavage fractures - type a
- E. Fractures of the transverse processes, spinous processes, and laminae
- F. Fractures due to muscle spasm

Group 2 - Fracture Dislocation

- A. Overriding of articular processes
- B. Dislocation of vertebral body with overriding of articular facet joints
- C. Subluxation of interarticular and intervertebral joints

Group 3 - Radiologically Invisible Fractures

- A. Schmorl's Node
- B. Neural arch fractures
- C. Cleavage fractures - type b

These groups are generally defined as follows: Group 1 includes all vertebral body fractures that do not involve the posterior wall of the vertebral centrum. This includes over 78% of all operational spinal injuries and better than 50% of all clinical injuries. Group 2 includes all dislocations and all fractures involving the posterior wall of the centrum, the articular facet joints, the spinal cord and nerve roots. (The likelihood of involvement of the posterior arch is proportional to the degree of angular collapse or wedging of the centrum.) Group 3 includes fractures which in most cases are not immediately radiologically visible. They are usually located incidentally on necropsy or autopsy--the clinical technique of identifying such fractures is not defined.

Compression Fractures of the Vertebral Bodies - Group 1

The type and severity of compression fractures are dependent upon the direction of load application and degree of vertical column flexion. The greater the component of bending (spinal flexion), the greater the wedge deformation. In general, there is no fracture of the laminae or pedicles. When spinal bending is not present, the vertebral body may be compressed uniformly (like an accordion), which usually occurs whenever

the direction of the loading force is acting uniformly in the vertical direction.

Fractures of the Vertebral Body Margins

These injuries involve the vertebral rims, as illustrated in Figure 3, and appear most exclusively along the superior rims of the thoracic and lumbar vertebral bodies. Such fractures occur most often at the summit of the arc ($T_5-T_6-T_7$) formed when the thoracic column is flexed. These fractures usually occur as a result of the application of forces in and around the base of the neck and through the shoulders.



Figure 3 - Marginal ring fractures of the thoracic vertebrae

Anterior Wedge Fractures

These fractures represent the most common nonfatal aircraft crash and egress injury. The anterior portion of the vertebral body of one of the vertebrae tends to collapse and in the process is crushed by the vertebral body of the next vertebrae above. Examples of anterior wedge compression fractures are shown in Figure 4. As the spongy bone is crushed, the vertebral body may be spread apart in the anterolateral direction or the vertebral bone may be compacted together. There may also occur variable amounts of damage to the intervertebral disks in the area of the fracture. The anterior longitudinal ligament usually remains intact, but it may be stripped from its points of attachment. The typical injury usually occurs in the region of C₅-T₁ and T₁₁-L₁₂. It is considered to be clinically benign and results in complete recovery. Nevertheless, in such injuries, pain and discomfort may be significant and may result in a temporary disability lasting 6 to 8 weeks or more. The extent of wedging depends upon the mechanics of the application of the force vector as well as other factors, such as (1) the structural geometry of the posterior arches, their direction, and their configuration; (2) the anatomical condition of the intervertebral disks; and (3) the support and restraint system geometry.

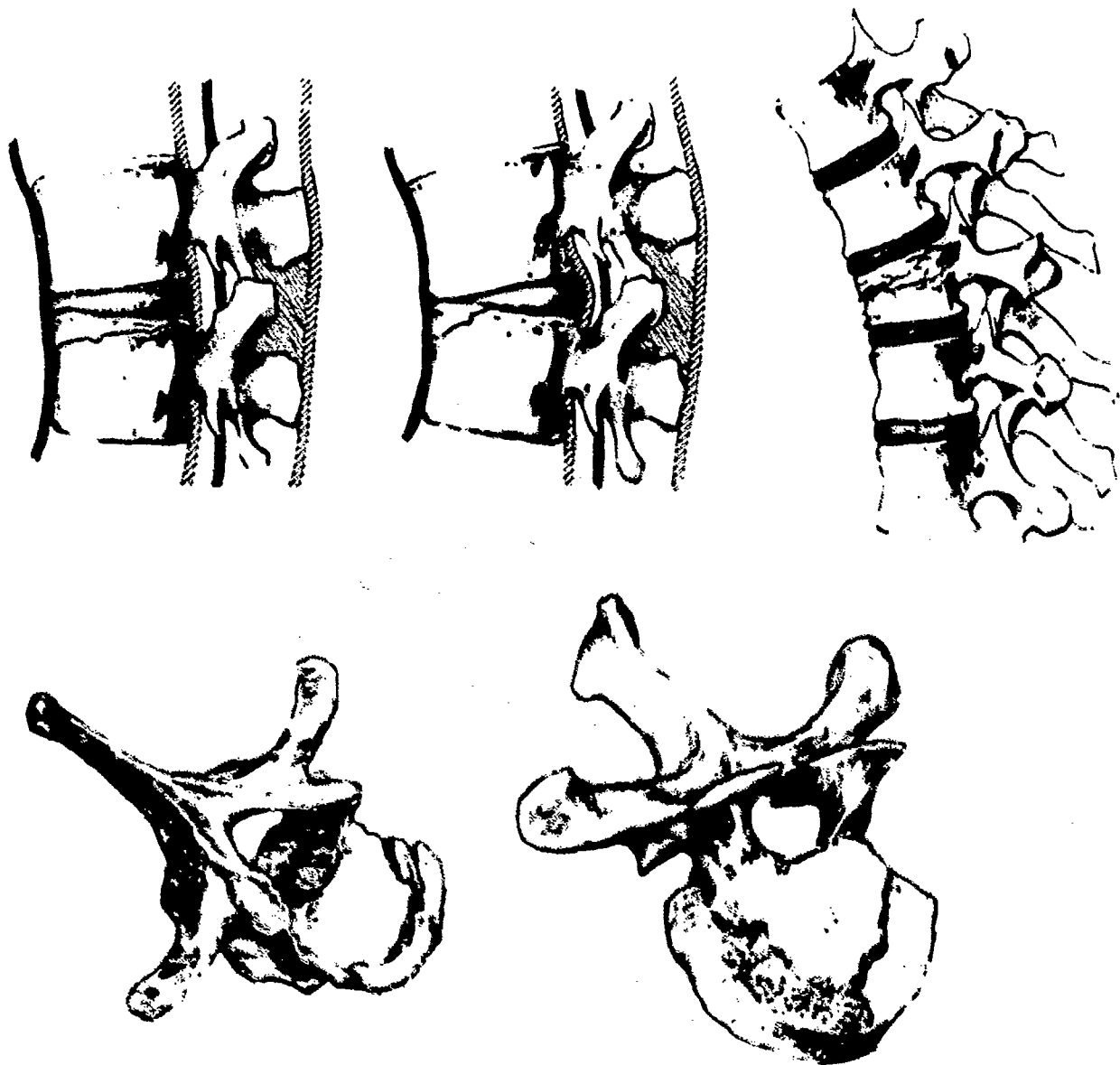


Figure 4 - Various degrees of marginal ring fractures due to torso hyperflexion

Multiple anterior wedge fractures, as illustrated in Figure 5, are also seen when the action of the torso is uncontrolled following impact deceleration.

Lateral Wedge Fractures

Lateral wedge fractures differ from the anterior wedge fracture in their anatomical characteristics. Lateral wedge fractures usually

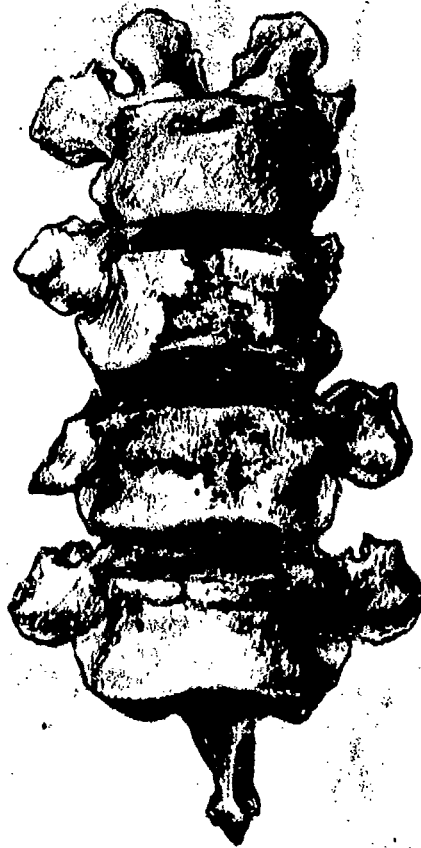


Figure 5 - Multiple anterior lip compression fractures due to torso hyperflexion

occur as a result of flexion, compression, and some dorsal rotation. The unilateral wedge is often accompanied by transverse process fractures and rotational intervertebral joint subluxation, which may also involve neurological tissue. Damage to the cord may occur, whereas this is not the usual case with the anterior wedge fracture.

Cleavage Fractures of the Vertebral Centrum

Figure 6 illustrates a typical cleavage fracture. From the front view it is invariably "Y" in type with well-defined cleavage planes.

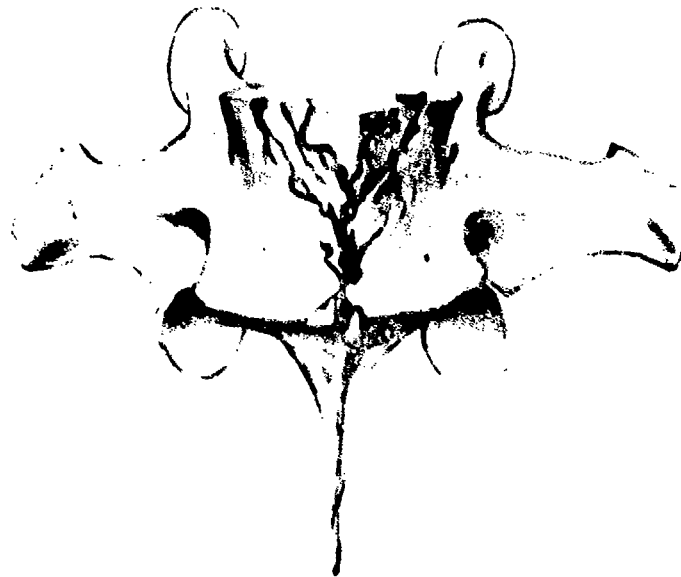


Figure 6 - Typical cleavage fracture due to $+G_z$ spinal impact

This type of fracture occurs most often when a uniform axial load is applied to the vertebral bodies in the spinal column. It is probably due to an increase in hydrodynamic pressure which is created within the vertebral body as a result of load transmission up the column in opposition to the inertia characteristics of the torso above the injured level. The end result is an explosion of the centrum by that mode which requires the least amount of strain (a cleavage fracture). The ligamentous structure remains intact.

Fractures of the Transverse Processes, Spinous Processes, and Laminae

Fractures of the transverse processes are usually the result of indirect muscular violence. Such fractures are usually multiple, and the lower lumbar vertebrae are most frequently involved. Transverse process fractures may occur with or without other bony fractures.

Fractures of the spinous processes are usually due to direct injuries. They are not uncommon in the cervical and lumbar regions. The tearing of spinous processes via muscular pull occurs mostly along the cervicothoracic mortice. The levels most frequently involved are T₁, C₇, and T₂, and in that order. Fractures of the laminae are produced most commonly by hyperextension and/or severe muscular contraction (Figure 7).



Figure 7 - Transverse process fractures of the lower lumbar vertebrae

Fractures Due to Muscle Spasm

Vertebral fractures can also occur simply as a result of violent muscle spasm, without the application of any external mechanical forces. Such fractures are most frequently observed in the upper thoracic spine, usually between the fourth and the eight thoracic vertebrae. Figure 8 illustrates the actions of the coordinated muscle contraction that act on the spinal column and may be explained as follows: spinal flexion occurs from the sudden contraction of the large flexor muscles between the "poles" of the body while the extensor muscles of the back maintain their position. Such fractures are distributed in the region of T₄-T₈.

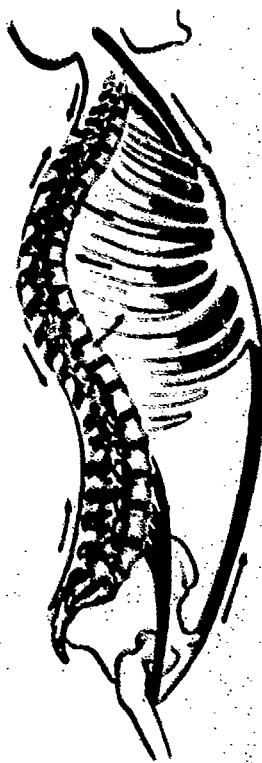


Figure 8 - Illustration of muscle contraction and thoracic spine fractures

Fracture Dislocations - Group 2

Fracture dislocations are the most serious injuries met in the spinal column. Any region of the spinal column can be involved, but in the majority of aircraft crashes and ejection injuries, the lesion occurs in the thoracic-lumbar and cervico-thoracic regions. The fracture pattern usually consists of a crushed vertebral centrum of one or more vertebral bodies with partial, or incomplete, forward or sideward dislocation of the upper vertebra on the lower one. Classification of fracture dislocations can be divided in two types: stable and unstable. If one facet does not override the other, the fracture is considered as stable. The displacement is essentially one of angulation; the continuity of the spinal column remains essentially intact. Unstable fractures of the spine depend upon the degree of trauma to the posterior longitudinal ligament and the articular facet joints. The greater majority of fracture dislocations are accompanied by extensive soft tissue lesions of the muscle and ligamentous structures. Spinal cord lesions with paralysis below the fracture level is not uncommon.

Flexural and torsional torso reactions often produce rupture of the posterior longitudinal ligament and fracture of one or both of the articular facet processes. It allows the upper vertebral body to horizontally rotate upon the lower vertebral centrum, often avulsing the cartilaginous end plate of the adjacent intervertebral disk (Figure 9). This type of fracture dislocation is considered as unstable and is a most common cause of cervical spinal cord, nerve root damage. The results are grave and the expectation of life is short.

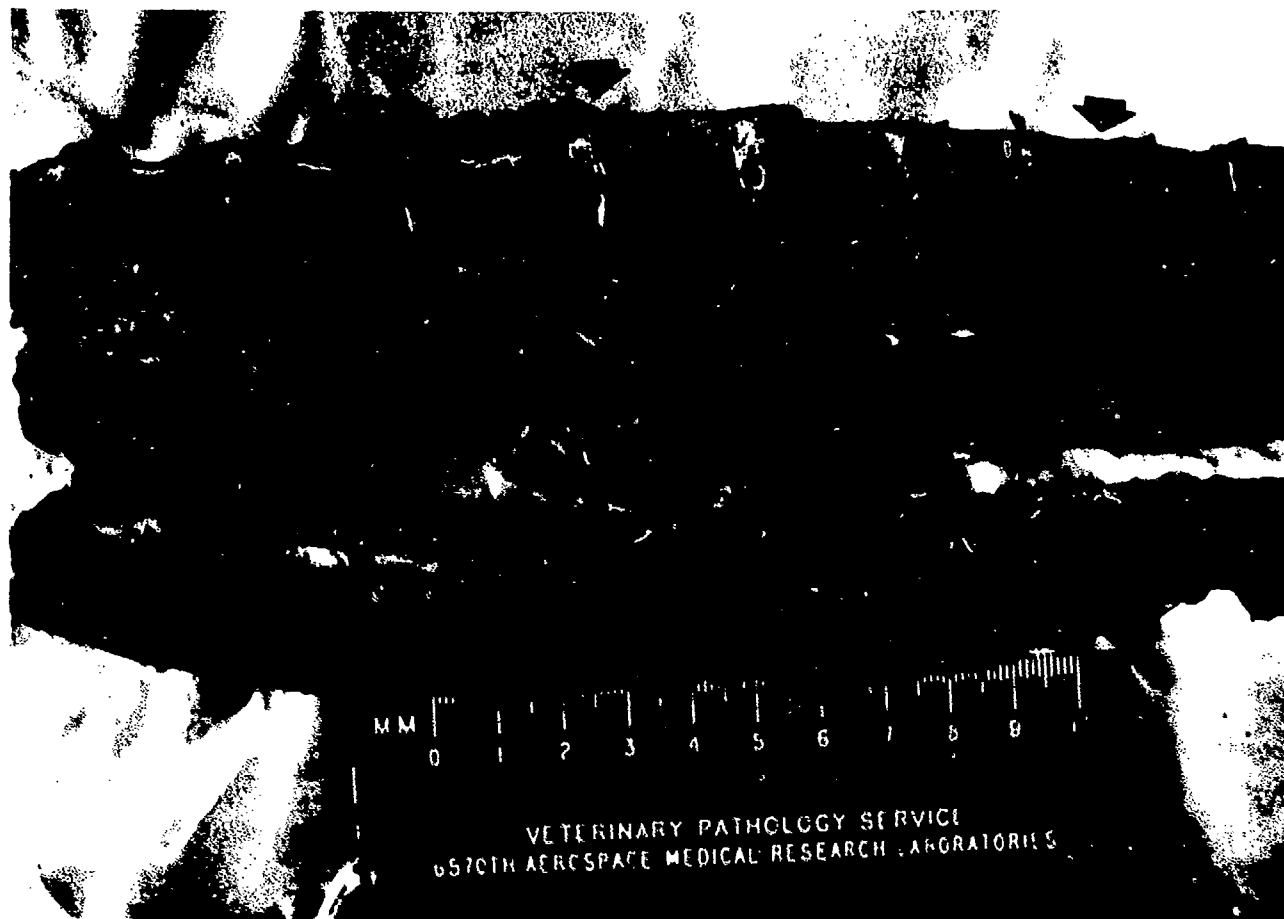


Figure 9 - Sagittal section of vertebral column illustrating avulsion of lumbar vertebra. Cleavage fracture is also evident in the upper thoracic spine

Radiologically Invisible Fractures - Group 3

The clinical diagnosis of certain trauma to the vertebral centrum and posterior arch must be resorted to by inference, autopsy, or necropsy, since roentgenograms cannot be depended upon to show even gross lesions involving the centrum, pedicles, articular processes and the laminae. For instance, cleavage fractures without gross displacement are impossible to distinguish by ordinary roentgenography. Figure 10 illustrates a fractured vertebral body collected at necropsy from a baboon in which a cleavage fracture is present; there was no neurologic involvement, and the fracture was located, incidentally, following inspection of the macerated skeleton. The animal was killed two months following +G₂ spinal impact. The body of the vertebrae, being cancellous bone and having an abundant blood supply, was thought to heal rapidly. However, in this case as in six others, there was no bony solidarity up to four months following spinal impact. In this single case, the fragments of vertebral bone were pulled apart and the space filled with soft callus tissue (arrows). Necropsy findings have repeatedly shown that cracks, fractures, and dislocations of the vertebral arch are very effectively concealed.



Figure 10 - Fractured vertebral body two months following exposure to
10⁶ g_z spinal impact

Schmorl's Node

The nucleus pulposus may be displaced from the intervertebral disk in any direction and may involve varying amounts of tissue. Herniation of nuclear material through a cartilaginous end plate and into a neighboring vertebral body may occur as a result of exposure to high-g, short-time duration deceleration. Isolated end plate fractures occur but are seldom diagnosed because of the difficulty of demonstrating them radiologically.

The developmental stages of intervertebral disk prolapse can best be observed with sagittal and horizontal tissue sections. The early stages are shown in Figures 11 and 12, illustrating fresh hemorrhages into the cavity of the nucleus pulposus three and four months following impact exposure. Later stages are demonstrated in Figure 13.



Figure 11 - Fresh hemorrhaging is still evident within the nucleus pulposus following subacute $10G_z$ spinal impact



Figure 12 - End plate disruption in the area of the nucleus pulposus
following subacute spinal impact

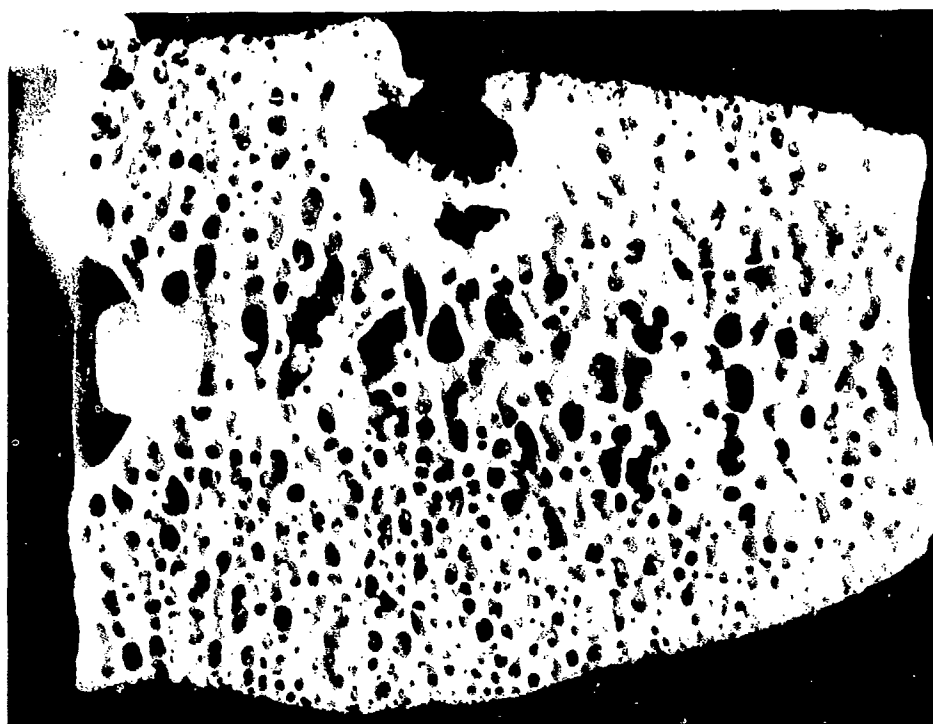


Figure 13 - Developmental stages of Schmorl's nodes in the rhesus monkey and baboon thought to be due to $4G_z$ spinal impact.
 A. Top surface of a vertebral body with ² a cavity measuring approximately 5 mm x 2 mm. B. Sagittal section of a vertebral body illustrating the results of prolapsed disk tissue on hard tissue architecture

The initial production of the intervertebral disk prolapse does not produce changes in the density of the vertebral body. Furthermore, the loss of nuclear tissue is to such a small degree that it does not lead to a measurable decrease in intervertebral disk space height. The roentgenographic visualization of an intervertebral disk prolapse is possible only after the reactive mechanisms of the body have produced a bony casing around the prolapsed material (Figure 14). With time there occurs a decrease in intervertebral disk space height and a corresponding narrowing and reduction in the vertical height and diameter of the intervertebral foramina, respectively, which is caused by a slight displacement of vertebral bodies accompanied by loosening of the longitudinal ligaments. To establish a relationship between trauma and intervertebral disk prolapse, control and serial roentgenograms are required, because roentgenographic examination carried out immediately following an exposure to impact yields no conclusive evidence about any morphological changes caused by trauma.

Neural Arch Fractures

Neural arch fractures encompass a broad spectrum of injuries to the pars interarticularis, lamina, spinous and transverse processes and are most commonly associated with vertebral body compression and torsion. Such fractures are usually secondary to compression fractures; subsequently arthritic changes are inevitable. Recognition of neural arch fractures on a roentgenogram is difficult. Neural arch fractures occur rather often in the cervical spine. This form and level of fracture may be due to the geometric variations (height vs width)

of the vertebral centrum and the absence of well-defined spinous, transverse and oblique processes, which provide an additional measure of protection. When the arch is fractured, the intermediate portion bearing the spinous process may be driven into the spinal canal, thereby penetrating or crushing the spinal cord.

Articular Facet Disruption

The articular facet joints are a part of the vertebral column. They may also be subjected to trauma. Joint injury can occur with or without vertebral compression injury. Again, there is not sufficient clinical information as to how frequently these joints are fractured, because their location is often not amenable to direct diagnosis and roentgenograms provide little or no additional data. In our impact studies with primates and apes, unilateral or bilateral facet disruption was most frequently located following necropsy and later examination of water-macerated specimens. One particular case is noteworthy. A baboon was killed three years following exposure to a subacute rectangular acceleration time profile. Initially, minimal vertebral body trauma was detected. At two months after impact, serial radiographs revealed a slight loss in facet density in the lower thoracic region. The intervertebral disks in the immediate region were measured and were noted to have decreased in height. Six months later (total time 8 months), a slight erosion and perhaps (with question) unilateral facet scalloping were noted. An irregular linear area of rarefaction extending transversely across a facet joint at the T₁₁ level was seen. The orientation of the articular facet joints around the narrowed disk was oblique in relation to a horizontal plane; the joints were asymmetric



Figure 14 - Schmorl's nodes in a thoracic vertebra illustrating bony casing (arrows)

and incongruous about a vertical plane. A slight increased bony density was unilaterally present in the adjoining articular facet planes. This contrasting coincidence of increased facet density in one area and of facet rarefaction in another part of the same vertebral arch formed a basis to suspect that some type of hard tissue remodeling activity was present. In the 18-month post impact radiographs, the vertebral bodies further approximated each other, and the overlapping articular facet surface contact area increased.

The vertebral arch above the suspected area had rotated within the superior articular processes of the inferior vertebral joint. A slight loss had occurred in the normal physiologic curve. The length, as well as the bony density, of a single superior articular process at the suspected level of injury had increased. The animal was killed 36 months following spinal impact. Microdissection showed the intervertebral disks to be normal, except for a posterior herniation of nuclear material (size of a lentil bean) into the spinal canal at the level of articular disruption. A definitive comparative attenuation of articular cartilage was seen in the small joints. A bony reaction had been set up to counteract the process of abrasion between three vertebral body levels. No secondary soft tissue changes were grossly observed. The carcass of the primate was skeletonized, and the spinal morphology distinguished in Figure 15 was brought to light.

The posterior joint surfaces were not entirely congruous, and the unilateral asymmetry of the adjacent superior and inferior articular surfaces were suggestive of individual horizontal, vertebral

body rotation. The left inferior articular process had atrophied, while the right inferior process increased in its convex surface contact area. The right superior articular process of the inferior vertebral body had also increased in surface area and had a well-defined interarticular concavity. The left superior process of the inferior vertebral body had increased in length, and its articular process surface was less defined. One may speculate that the vertebral joints underwent these asymmetrical changes as a result of chronic mechanical overloading in an attempt to adapt to a new kinematic environment. Facet fractures were found to occur both along and with compression fractures of the vertebral bodies. Fractures of these accessory processes were found most frequently following torsional (asymmetrical) loading. Currently there exists no clinical index for quantitating the severity of trauma that may be involved in these injury mechanisms.

These results point out that further investigation on the incidence and severity of articular facet disruption is required.



Figure 15 - Spinal morphology of baboon showing articular facet disruption

Cleavage Fractures of the Vertebral Centrum (b)

Zigzag splits, stellate tears, open areas, and oblique fissures have often been located incidentally in cartilaginous end plates on necropsy immediately following subacute axial spinal impact.

Figure 16 is a photograph showing a fissure in a single cartilaginous end plate of a thoracic vertebra. No hemorrhaging was visible with the naked eye. When the end plate was removed from the vertebral body, depressions and cracks were often present within the vertebral centrum, as illustrated in Figure 17. Whether or not such splits or cracks are due to spinal trauma or to a normal degenerative process remains uncertain. However, because these continuity losses are so widespread (especially in younger primates and apes) and have not been observed in nonimpacted animals, it is suggestive that these lesions may be the result of spinal impact.



A



B

Figure 16 - A. Normal cartilaginous end plate. B. Cartilaginous end plate with stellate tears

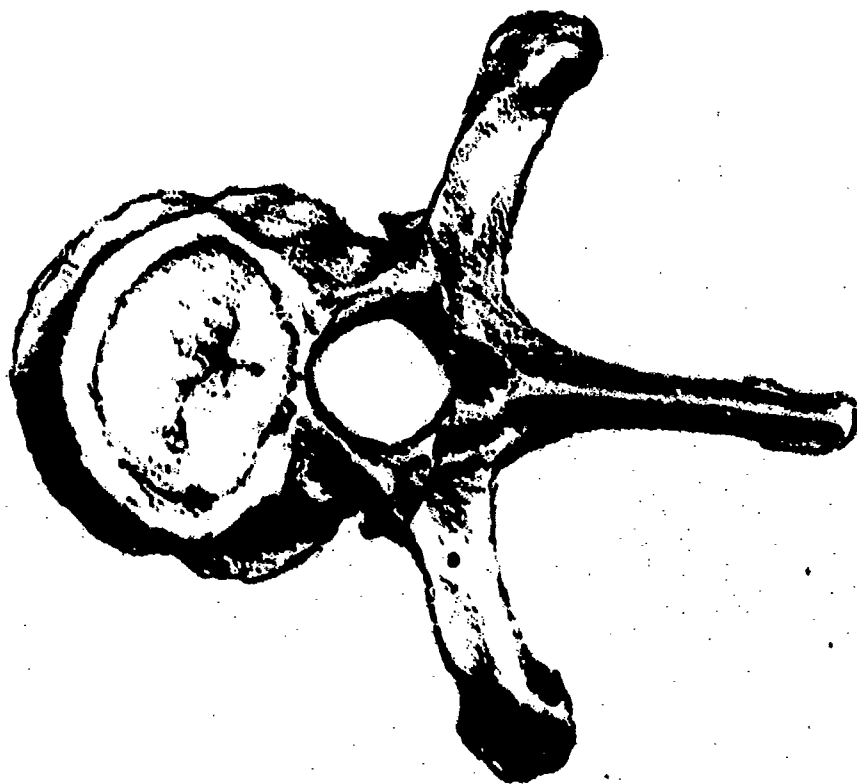
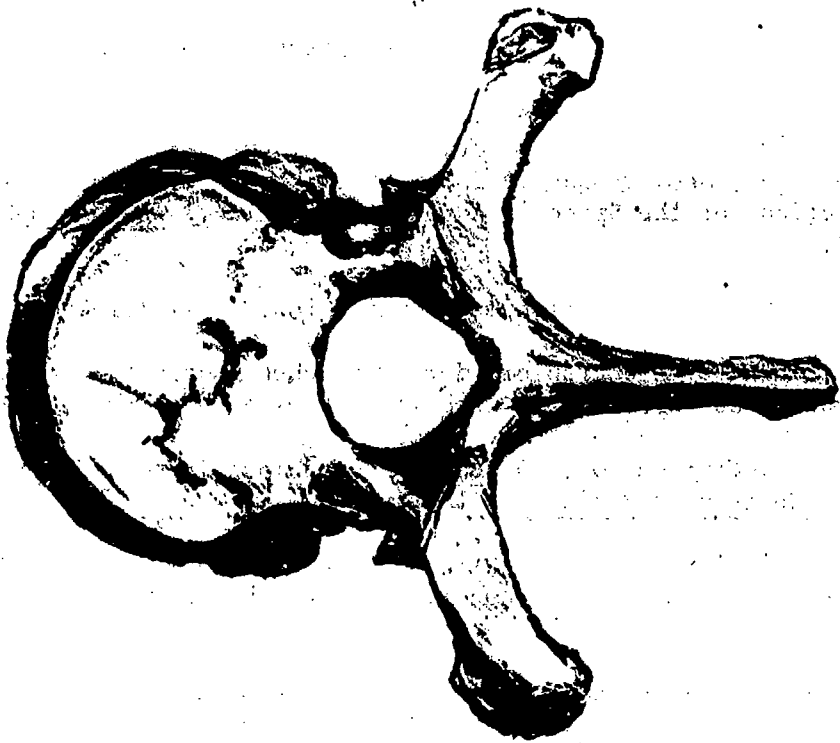


Figure 17 - Minute cracks radiating from the region occupied by the nucleus pulposus

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