FRACTURE/DISLOCATION OF THE UPPER CERVICAL SPINE DURING MOTOR VEHICLE COLLISION: BIOMECHANICS AND IMPLICATIONS FOR OCCUPANT PROTECTION

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ABSTRACT

Unlike the thoracic and lumbar areas, the cervical spine is much more vulnerable to injury during vehicle collision whether frontal, side, rear-end, or roll-over. At the time of vehicle collision, forces are transmitted to the restrained or unrestrained occupant. The head can be loaded by direct impact with surfaces in the occupant space or can exert inertia while being whipped around by various forces. The only structures stabilizing the neck are the muscles, the intervertebral disc and the configuration of the posterior apophyseal joints and their supporting ligaments. The most common modes of cervical spine injury are flexion, rotation, axial loading, shearing and extension.

Fracture dislocation of the cervical spine involves a high risk of injury to the spinal cord that can result in partial or complete quadriplegia. Cervical spine fracture at the highest level (C1-C2) with cord trauma is usually fatal.

Our accident research team has investigated various motor vehicle collisions in which occupants have sustained these potentially serious upper cervical spine fracture/dislocations. We discuss the reconstructed injury mechanisms, biomechanics and the implications for occupant protection.

INTRODUCTION

The cervical spine protects the spinal cord and allows a significant range of motion and at the same time support for the head. The extensive range of motion is possible because of the many articulations between the cervical vertebrae. The upper cervical spine consists of the occipital condyles and the first and second and cervical vertebrae (the atlas and axis, respectively). The atlas and axis are not typical cervical vertebrae. They are profoundly modified structurally to follow the movements of the superadjacent skull.

The atlas has no body, but consists of a bony ring with an anterior and posterior arch and with large lateral masses that bear the superior and inferior articular surfaces or facets. The superior facets are for articulation with the occiput and are oval and concave; the inferior articular facets are slightly convex and oval and are directed inferiorly and medially.

The atlas operates as a unit with the occiput and rotation of the skull in the horizontal plane is permitted mainly by movement between C1 and C2.

The body of the axis overlaps the forepart of C3, the ondontoid process arising from its upper surface. The joints of this occipital-atlanto-axial complex (skull and C1 and C2) confer much of the range of mobility of the head while also serving to transmit the weight of the cranium to the unmodified portion of the cervical spine which begins at the third cervical vertebra. The strategic position and mobility of the upper cervical spine renders it vulnerable to impact forces seen in motor vehicle collisions, especially with intrusion into the occupant space or inadequate restraint of the occupant. The following cases are representative of motor vehicle crashes we have investigated in which injuries to the upper cervical spine of vehicle occupants were documented. Analyses of these injury modes anticipate planning for improved occupant protection.

CASE 1

The case vehicle, a 1985 Dodge van, was travelling westbound on a median divided freeway at an estimated speed of 100 kilometres per hour in the right lane. The van came up behind a westbound International transport tractor and trailer which had slowed to 30 kilometres per hour in heavy traffic. The van collided with the rear of the trailer, the van bumper and engine block underiding the rear trailer structures. The rear of the trailer penetrated into the van driver's occupant space, displacing rearward the posterior hood, instrument panel and steering column. The 39-year-old fully belted female driver made head contact with the intruding hood and sustained separation of the atlantooccipital junction with brainstem contusion, subarachnoid hemorrhage, and instant death. The only other significant injury was a mid-shaft fracture of her right femur.

CASE 2

This traffic victim, a 16-year-old male pedestrian, 175 cm tall and weighing 66 kg, was struck by a 1975 Mercury four-door sedan travelling at an estimated speed of 60 kilometres per hour. The vehicle struck the pedestrian in the left rear standing position with right bumper and right anterior hood contact. This direct impact resulted in fractures of left tibia and fibula, left pelvis, and fracture dislocation of vertebra T11, with large soft tissue contusions over trunk, chest and arms. There was a subgaleal hematoma over the entire scalp with no epidural or subdural hematoma. There was a complete ligamentous disruption at the level of the atlas and the occipital bone. The cervical spine was otherwise intact. He died instantly from transection of the spinal cord at the cervical-medullary junction.

CASE 3

This traffic victim was a 21-year-old male cyclist who was travelling southbound on a rural two-lane highway at night when he was struck from behind by a 1976 Oldsmobile Cutlass travelling southbound at an estimated speed of 65 to 70 kilometres per hour. His injuries were extensive and severe involving massive crushing of chest, fracture of both humeri and massive crushing of right leg with amputation of right foot. There was complete ligamentous disruption at the level of the atlas on the occipital bone with no other injury to the cervical spine. He died instantly from transection of the spinal cord as in Case 2 above.

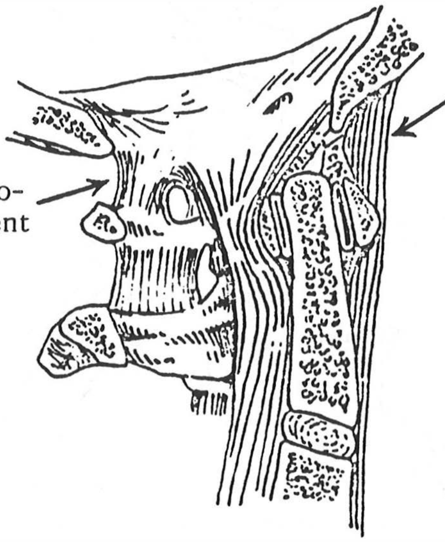


Figure 1 - Median section through occipital skull and upper cervical spine.

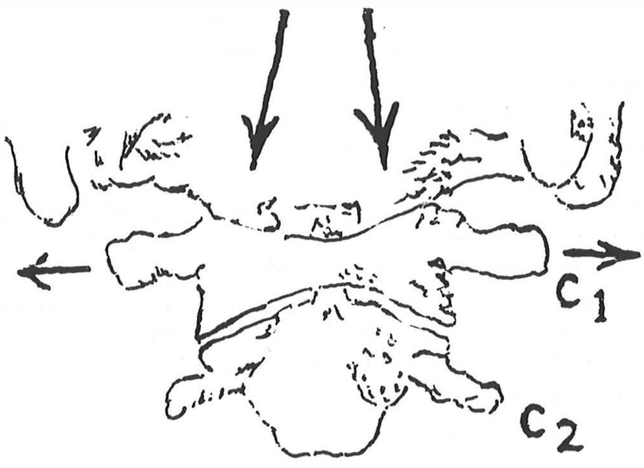
DISCUSSION

The majority of biomechanical studies and review papers dealing with injury to the cervical spine give little attention the ligamentous disruption injury at the level of skull on the atlas. The ligamentous junction here is a very tough and durable bonding, lacking the elastic properties of most of the ligamentous bonding seen throughout the cervical spine below this junction (Figure 1). The mechanism of injury seen in all three of the above cases is a high intensity extension and shearing force applied between the human head and body. In Case 1 above, the victim's body continued moving forward with respect to the rapidly decelerating vehicle. Her head impacted the intruding hood and was driven backward creating neck extension and a shearing force of high intensity. This relatively inelastic fibrous bonding at the atlanto-occipital junction appears to be selectively vulnerable to the shearing force, and rupture occurs at this junction with sparing of the more elastic and supple structures in the cervical spine below. In Cases 2 and 3 above, similar forces of hyperextension and shearing are applied to the neck of the pedestrian and cyclist. In these two cases there is a sudden high acceleration force applied to the legs and torso (Figure 2). The inertia of the head, approximately 5 kg multiplied by the 'g' force of the collision, leads to ligamentous disruption at the atlanto-occipital junction by a similar mechanism as described for Case 1.

Figure 2 - Pedestrian lower body impact inducing acceleration forces that transmit a high energy shearing force to the cervical spine in extension.

CASE 4

The case vehicle, a 1976 Chevrolet two-door sedan, was travelling southbound on a two-lane gravel road at an estimated speed of 50 kilometres per hour. The driver lost control and the vehicle egressed onto the right shoulder and roadside while executing a counter-clockwise yaw. The vehicle was sliding sideways, right side forward, when it impacted and broke off a roadside hydro-pole with the right front quarter-panel and wheel-well area. There were seven unbelted occupants in this car, four in the rear seat. The case victim was the right rear passenger, a 58-year-old male, who impacted the right door with his torso and the right upper door sill and roof with his head. On admission to hospital he was conscious and alert with no neurologic deficit. He incurred fractured right ribs, clavicle and pelvis with laceration of his urinary bladder. Chest trauma resulted in contusions to lungs and heart. The injury of interest was fracture of the atlas C1, identified by x-ray and tomograms. The atlas was fractured through the right anterior and posterior arches with 5 mm separation of the right segment. The fracture was clinically stable and was managed conservatively with no neurologic injury present or developing later.



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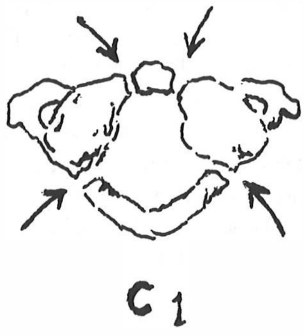

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Figure 3 - Representation of forces to produce the Jefferson fracture. An axial load to the vertex of the skull is transmitted to the occipital condyles and articulations of C1 (a). This causes explosion of the arch with lateral propulsion of one or both lateral masses. Four possible fracture sites are seen in (b).

DISCUSSION

The atlas is a thin narrow ring of bone. The weakest portion of the atlas and the part most often fractured is the posterior arch (Figure 3b). The biomechanical specificity of this fracture mode seems to be based on the differences in the resolution of forces between the occipital condyles, the axis and the lower cervical spine. When a sudden direct load is applied to the head, the occipital condyles are forced downward and progressively outward in a wedge-like fashion within the shallow recesses of the atlas (Figure 3a). The type of injury sustained depends on the angle of inclination of the occipital condyles relative to the atlas and on the characteristics of the driving force. The most common etiology of the atlas fracture is a direct blow to the vertex of the skull. The fracture pattern may be unilateral or bilateral, depending on the initial position of the head and neck with respect to the driving force. In Case 4 above, the victim had a laceration and bruising to his right upper forehead and scalp, evidencing his point of contact with the upper door sill. His body was moving upwards, forwards, and to the right when he impacted the roof sill. The downward thrust from head impact would have selectively loaded the right side more than the left resulting in this unilateral Jefferson fracture. The driving force of this impact would be accentuated by the loading of his body from the other unbelted rear seat occupants. It is typical of this fracture that neurologic symptoms are absent or minor. The usual displacement of fragments results in enlargement of the spinal canal rather than compression.

CASE 5

The case vehicle, a 1980 Lincoln Continental two-door sedan, was travelling westbound on a median divided freeway at an estimated speed of 100 kilometres per hour in the right lane. The case vehicle made a brushing side contact with a vehicle to its left, lost control and egressed onto the right shoulder where it struck a stiff barrier system with its right front corner, creating a Delta-V force of about 30 kilometres per hour before the vehicle rotated clockwise beyond this impact point. The occupant of interest in the case vehicle is the right front passenger, a 34-year-old unrestrained female, 136 cm tall and weighing 58 kg, who made head contact with the upper windscreen and sunvisor. She sustained bruising to her forehead and left knee. At hospital x-rays revealed an asymptomatic hangman's fracture of the lateral pedicles of C2 with minor forward displacement of the body of C2 on C3. The fracture was treated conservatively with partial immobilization in a cervical collar and she made an uneventful recovery, the fracture healing and stabilizing without any neurologic symptoms.

CASE 6

The case vehicle, a 1978 Ford van, was travelling eastbound on a two-lane paved highway at an estimated speed of 80 kilometres per hour. The driver lost control and the vehicle egressed to its right onto the south shoulder and made right frontal impact with the south bank of the roadside ditch after which the vehicle rolled over twice coming to rest on its wheels. The occupant of interest is the unbelted right front passenger, a 62-year-old male, 170 cm tall and weighing 80 kg. He sustained a closed head injury with diffuse brain damage that left him deeply comatose. Neurosurgical intervention included bilateral temporal burr holes and maintenance on a respirator. Coma continued, sepsis ensued and he died one month after collision. X-rays at the time of admission to hospital revealed a hangman's fracture through the pedicles of C2 with anterior displacement of the body of C2 on the body of C3. Examination of the spinal cord at autopsy revealed no evidence of cord damage in the region of this upper cervical fracture.

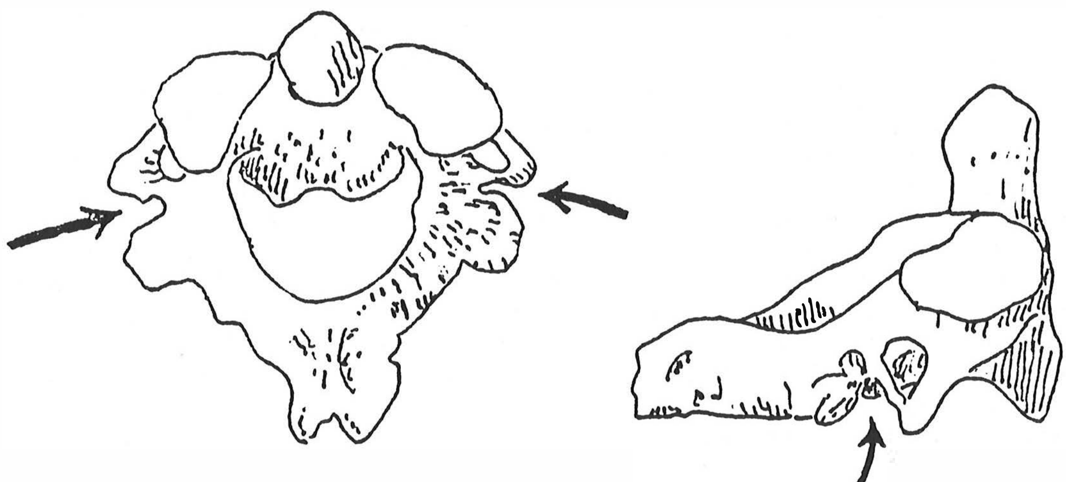

Figure 4 - Drawings of a superior and lateral view of the isolates axis showing the narrowing of the pedicles (arrows), the stout spinous process and the wide circular spinal canal.

DISCUSSION

The above two cases are typical of other cases in our files and in the scientific literature where the mode of injury has been C2 fracture caused by neck extension and compression. Extension of the upper cervical spine with axial compression may be produced by a simple forward fall with the face, forehead, or vertex striking an obstacle while the after coming body exerts inertial force. A similar situation occurs when the unrestrained motor vehicle occupant is either projected forward to forcefully encounter the interior of his occupant space with his head, or where he incurs similar collision forces on ejection from the vehicle. After injury the subject may complain of no symptoms, usually holds his head slightly flexed, in which position the fracture is stable although the anterior ligament and intervertebral disc below the axis may be disrupted. Neurological injury is rare, presumably because the spinal canal is sufficiently wide at this level (Figure 4) to accommodate some movement of the fragments, which in any case tend to separate and widen the canal. Associated mid-cervical injuries and fractures of the spinous processes are also sometimes seen and suggest that compression has occurred. The above two cases are examples of impact to the anterior head with axial loading in neck extension, axis pedicle fracture with no injury to the spinal cord at that level (Figure 6a).

CASE 7

The case vehicle, a 1983 Dodge Aries four-door sedan, was travelling eastbound along a median divided freeway at an estimated speed of 90 kilometres per hour. The driver of a 1979 Mack truck tractor hauling an unloaded 1980 trailmobile dump semitrailer, turned the vehicle into a crossover link in the roadway median and brought the vehicle to a halt intending to make a U-turn. The vehicle's trailer was totally blocking the eastbound travel lane of the roadway. As the case vehicle approached the stationary tractor-trailer, the driver of the case vehicle applied the brakes. The case vehicle entered into a clockwise rotation, and the left side of the vehicle impacted the rear of the semi-trailer. The case vehicle sustained a broad crush across the front left and centre left side to a maximum penetration of 35 cm. The Delta-V for this impact was approximately 35 km/hr.

The occupant of interest in the case vehicle is the right front passenger, a 36-year-old female, 170 cm tall and weighing approximately 66 kg. She was wearing the available lap and torso seat belt restraint system. She sustained a hangman's fracture dislocation of cervical vertebrae C2 on C3 with trauma to the cervical cord; a fracture to the distal end of the right femur; and a contusion above her right breast. Death was instantaneous. Alignment of the restraint system tongue and D-ring loading marks on the seat belt webbing indicated that the system, as worn by the right front occupant contained approximately 20 cm of slack. This occupant made forceful contact of her chin with the upper instrument panel. The degree of forward excursion executed by this occupant suggests that the shoulder harness had either slipped off her shoulder or had been placed in her axilla for reason of comfort and convenience. Chin impact with the upper instrument panel resulted in sudden forceful head extension and extraction of the upper cervical spine.

CASE 8

The case vehicle, a 1984 Honda Accord two-door sedan, was travelling eastbound on a two lane paved highway at an estimated speed of 80 kilometres per hour. The vehicle egressed onto the right shoulder entering a shallow ditch and making frontal impact with a culvert structure associated with a private driveway. The vehicle was partially arrested in its forward progress and underwent a violent pitch and yaw, becoming airborne. The vehicle vaulted a distance of about 9 metres, coming to rest on its roof in the private driveway, pointing in a southwesterly direction. There was a broad area of crush across the left front of the vehicle. The Delta-V for this frontal impact was approximately 30 km/hr.

The occupant of interest in the case vehicle is the right front passenger a 34-year-old female, 160 cm tall and weighing 54 kg. She was wearing the available lap and torso restraint system with the bucket seat in the fully reclined position. After the crash she was found tangled in her seat belt webbing, suspended above the underlying vehicle roof. She had a brief loss of consciousness and then complained of neck and shoulder pain with numbness and tingling in both shoulders. Her legs felt numb and she had lost power in them. She was transported to hospital where examination and x-ray studies revealed a C2 hangman's fracture with fracture of the lateral pedicle of C2 and fracture of superior and inferior articular facets of C2, C3 on the right side. Within a few days she recovered the function in her legs, but continued to complain of numbness and weakness in both hands. The neck fracture was treated by immobilization in halo traction. Weakness and paresthesiaes persisted in her right arm and hand for an extended period of months.

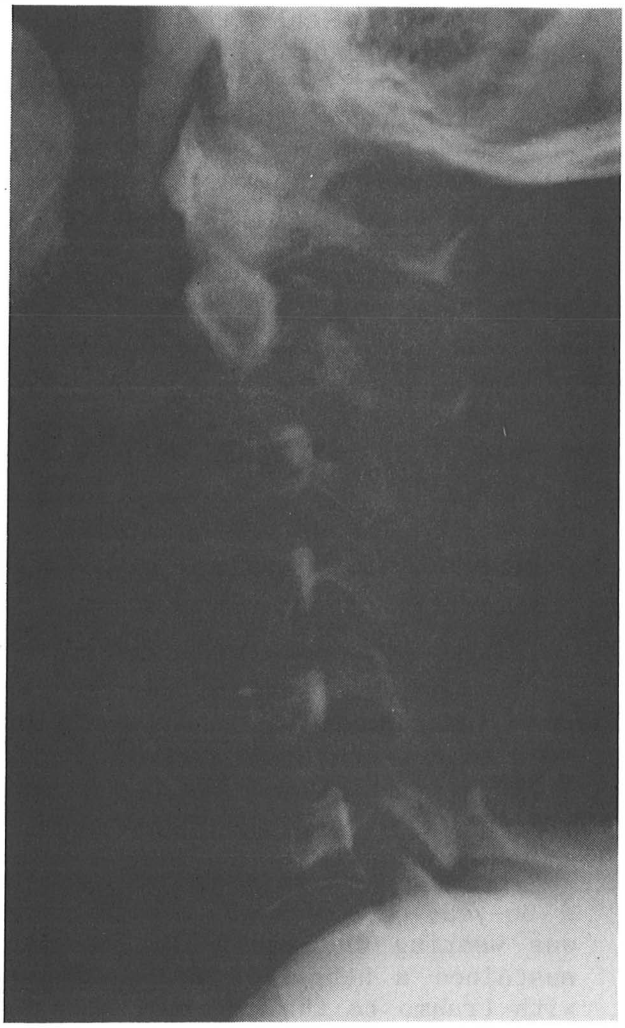

Figure 5 - X-ray of cervical spine in Case 8 showing fracture of lateral pedicles of axis.

DISCUSSION

In contradistinction to the usual mechanism of hangman's fracture seen in motor vehicle collisions where reconstruction of occupant kinematics reveals an extension and compression mode, the above two cases of fracture were caused by extension and distraction. Distraction of the upper cervical spine follows violent extension when the rapidly moving body is sudddenly restrained under the chin or upper neck. This is the aim of judicial hanging by a submental knot and "long drop" (which varies inversely with the victim's weight and is usually about two metres). Distraction results in more violent tissue injury than compression and is usually accompanied by a greater likelihood of neurologic sequellae from direct injury to the spine cord (Figure 6b).

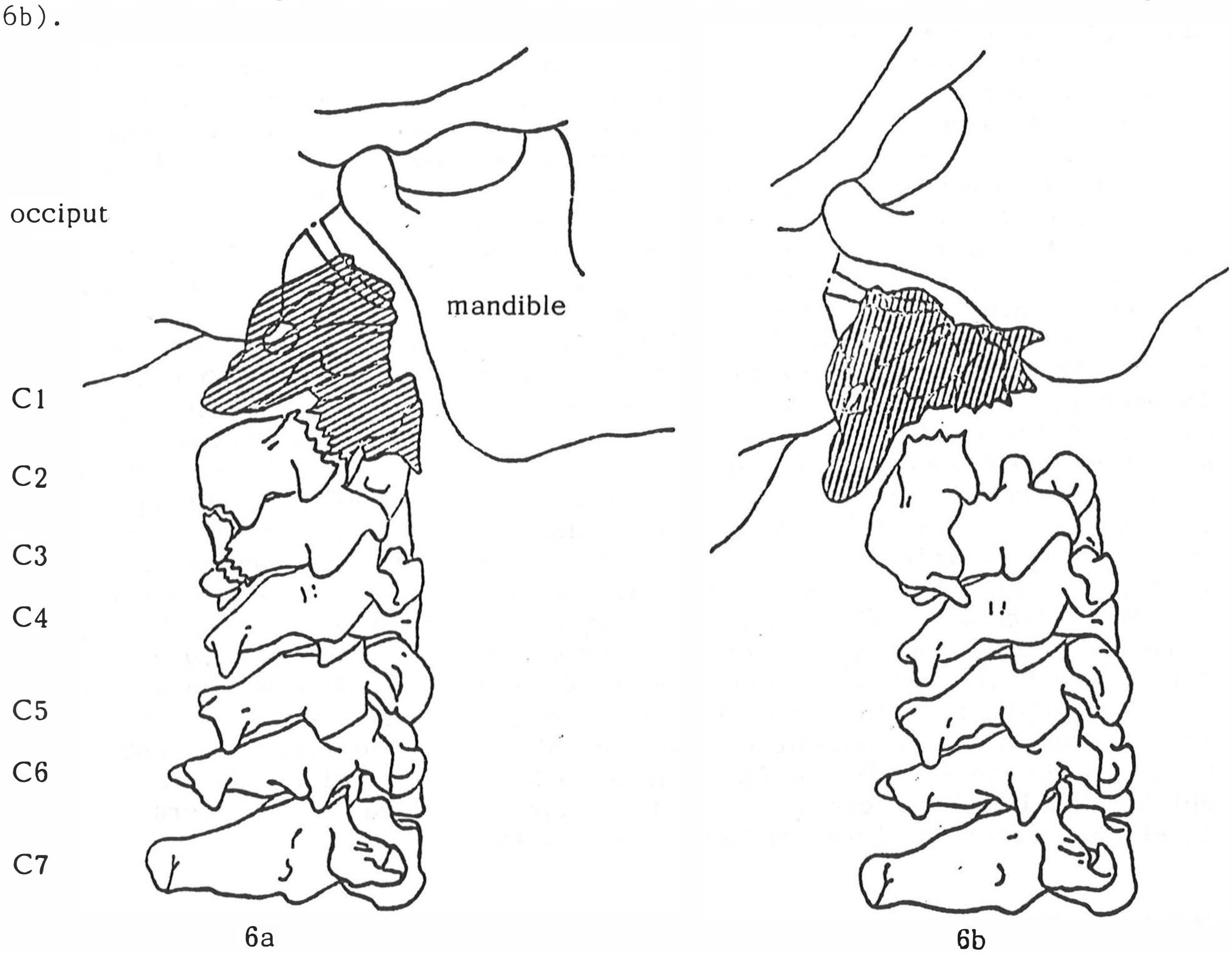

Figure 6 - Drawings of the cervical spine and skull showing fractures through the lateral pedicles of C2 with minimal displacement (a); and with the upper fragment of C2 in the position of extraction compromising the size of the spinal canal.

The term hangman's fracture was first used in the literature to describe the characteristic lesion seen in judicial hanging(1). A similar fracture dislocation seen in victims of falls and traffic collisions was later recognized and reported(2),(3). Although the fracture produced by judicial hangings is similar to that observed in motor vehicle accidents and falls, the mechanism of injury has been thought to differ by most authors who have reported cases(2),(4). The judicial hanging fracture is produced by hyperextension and extraction forces applied to the cervical spine. In most reported cases of motor vehicle trauma causing hangman's fracture, the mechanisms have been reported to be hyperextension with axial loading, or occasionally flexion and axial loading. Saldeen presented a case of hangman's fracture with decapitation induced by the use of a diagonal torso belt without a pelvic belt (5). Edgar et al described a motorcyclist who recovered from quadriplegia caused by hangman's fracture sustained when he was caught under the jaw by a rope across the road(6). These latter two motor vehicle cases are undoubtedly due to a hyperextension and extraction forces as seen in judicial hanging. When this fracture occurs, the axis breaks symmetrically across its pedicles or lateral masses and the fracture may extend across the posterior part of the body. Contrary to popular belief the dens always remains intact and does not contribute to spinal cord injury. The pedicles are the thinnest part of the bony ring of the axis, weakened by a foramen transversarium on each side (Figure 4). The lateral masses, bearing the superior articular facets, each straddle the vertebral body and the inferior facet and therefore take a majority of force transmitted through the modified upper two cervical vertebrae to the cervical spine below. The pedicles and lateral masses of the axis are at the point of greatest leverage between the extending upper "cervico-cranium" (the skull, atlas, dens and body of the axis) and the relatively fixed lower cervical spine, to which the neural arch of the axis is anchored by its inferior facets, bifed spinous process and strong nuchal muscles (Figure 1). The junction between C2 and C3 constitutes a site of mechanical weakness in the spine and here the 3rd cervical vertebrae forms a fixed point, firmly anchored to the lower column and also strongly bound to the posterior spine of C2 by the tough interspinous ligament. With the head in the position of extension and the application of an axial loading force, fracturing is most likely at the pivotol point of weakness, the lateral pedicles of C2. With this compression mode of injury, the spinal canal is seldom compromised, often increased in size and neurologic symptoms seldom occur (Figure 6a). When the head is in extension and an extractive force is applied as in judicial hanging or as in Cases 3 and 4 above, there is a disruptive displacement of the body of C2 and the intact Cl posteriorly with respect to C3 (Figure 6b). This markedly compromises the size of the spinal canal during extraction with frequent trauma to the cord at this level and serious or fatal injury often results.

IMPLICATIONS OF THIS ANALYSIS

Fracture to members of the occipito-atlanto-axial complex are almost always the result of head contact, and the differential in the forces applied to the human head in relation to the body. The resulting neck injury is induced by axial loading or compression, tension or extraction, flexion, extension, rotation and shearing, singly or in combination(7). Ligamentous disruption in regions of the cervical spine of a mild to moderate degree is a common event in motor vehicle collisions where head contact may or may not play a role. The life threatening atlanto-occipital ligamentous disruption described in this paper is seen with high intensity shearing forces, often with the neck in extension and may or may not involve head contact in the generation of those injury producing forces.

Prevention of these potentially life threatening injuries to the upper cervical spine will sometimes require prevention of the collision, as in the case of the unprotected pedestrian or cyclist who is impacted by a motor vehicle at speed. To protect vehicle occupants, it is important to minimize intrusion into the occupant space by improvements in the displacement pattern of vehicle frontal structures including the hood, and optimal strength of vehicle doors, pillars and roof structure. Occupant protection against these upper cervical injuries is generally enhanced by the use of a properly fitted lap and shoulder restraint system which limits occupant excursion and modifies or prevents head contact. The special problem of driver head contact with the steering assembly is being addressed by shoulder belt locking and pre-tension devices and steering column airbags. A properly fitted headrest is necessary to prevent injury producing neck hyperextension and shearing forces developing in rear end collision. Case 8 describes a reclining occupant positioning that can lead to submarining under the available belt system and injury producing extension/extraction forces on the neck in the event of frontal collision. Positioning of a vehicle driver in a semi-supine posture is common in the sport of motor racing, where seat belts were the first installed in motor cars. Race officials anticipated the danger of submarining on frontal collision and addressed the problem effectively by including a crotch harness as a component of the restraint system. If vehicle manufacturers are to continue providing fully reclining bucket seats for the right front passenger, they would be wise to caution users of the inherent danger when the vehicle is in motion, and possibly they could supply a crotch harness component in the seat belt system.

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