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# ANALYSIS OF EJECTION INJURY OF SPINE IN AVIATORS

Neurosurgery

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## ABSTRACT

Aviators present a unique subgroup of population who are subject to abnormal and complex biodynamic forces and loads which are super-added to the normal physiological loads on the spine. These complex biodynamic forces are more pronounced, when an aviator ejects from an aircraft. Successful management of these cases requires proper understanding of the complex physiology that the vertebral column of the fighter pilots is subjected to. This paper brings out the data of ejection spinal injuries and correlates the injuries with the known spinal biodynamics with ejection forces. The paper also discusses the implications of spinal biodynamics on determining the fighter pilot's flying fitness in future.

## KEYWORDS

Aviator, ejection, spine

## INTRODUCTION

Flying is an unnatural activity for human beings who have evolved terrestrially. An aviator places tremendous stress and strain on his spine while flying an aircraft, subjecting his spine to high speeds and simultaneous pull of gravity magnified several times due to various complex aerial manoeuvres undertaken by the aviator. While ejecting from an aircraft he puts a sudden tremendous load on his spine as he accelerates off from an already accelerating aircraft often in an awkward posture resulting in spinal fractures in many cases. To understand the various mechanisms, etiological factors and thereby apply the knowledge for prevention, it is important to understand the biomechanics, anatomy, ergonomics and effect of posture and vibration and forces of ejection on the back.

### Load Bearing and Transmission

Knowledge about load bearing and weight transmission of the spine is largely due to observation during experimental spinal biomechanics by Henzel et al [1] who determined the breaking strength of the vertebra under axial compression. They also determined the vertebral body force transmission during acceleration, body weight supported by the vertebra at various levels. This is reproduced in Table 1.

There is a relatively constant - approximately 3% - increase in percentage body weight supported by successive vertebrae from T8 to L5. The head and neck has been taken at being 9% of body weight. The weight of the upper half of the trunk is partly borne by and transmitted to the lower dorsal region transmitted by the sacrum to the lower limbs through a well-marked thickening of the bone in the Ilium in the roof of the acetabulum. From this they calculated probability of damage/ risk curves for various vertebrae. Correction factors were applied to derive age specific risk of fracture probabilities. The literature on ejection spinal injuries indicates that T11 to L2 vertebra are most prone to fractures during ejection from a fighter aircraft [2][3][4].This fact is substantiated by the breaking load in G brought out by Henzel et al [1] which for these vertebrae is the lowest (22.7 to 24.1)

**Table 1: Breaking strength of vertebrae. Reproduced from Table V in** *Gierke H, Henzel J, Mohr G. Reappraisal of Biodynamic Implications of Human Ejections. Aerosp Med. 1968;39(3):231–40*

| Vertebra | % body weight carried | Weight carried in lbs of a 160lb man | Breaking strength in lbs | Breaking load in G |
|---|---|---|---|---|
| T1 | 9 | 14.4 | 360 | 25 |
| T2 | 12 | 19.2 | 480 | 25 |
| T3 | 15 | 24 | 690 | 25 |
| T4 | 18 | 28.8 | 720 | 25 |
| T5 | 21 | 33.6 | 840 | 25 |
| T6 | 25 | 40 | 1000 | 25 |
| T7 | 29 | 46.4 | 1160 | 25 |
| T8 | 33 | 52.8 | 1315 | 25 |
| T9 | 37 | 59.2 | 1493 | 24.9 |
| T10 | 40 | 64 | 1632 | 25.2 |
| T11 | 44 | 70 | 1700 | 24.2 |
| T12 | 47 | 75.2 | 1757 | 23.4 |
| L1 | 50 | 80 | 1790 | 22.4 |
| L2 | 53 | 84.8 | 1925 | 22.7 |
| L3 | 56 | 89.6 | 2160 | 24.1 |
| L4 | 58 | 92.8 | 2168 | 23.4 |
| L5 | 60 | 96 | 2366 | 24.6 |

### Spine Architecture

In order to understand the changes that occur in the vertebral body and its end plate after a pilot ejects from aircraft, it is essential to understand the vertebral body architecture since this has bearing on method and means to manage these patients. Vertebral bone is composed of mineral apatite, *which has high compressive strength*, dispersed in protein collagen matrix *which provides stiffness*.

The architecture of the vertebral body comprises of highly porous trabecular bone, and a fairly dense and solid shell. The shell is very thin throughout, on average only 0.35–0.5 mm. The trabecular bone bears the majority of the vertical compressive loads, while the outer shell forms a reinforced structure, which additionally resists torsion and shear. The cortex and trabecular core share compressive loading in an interdependent manner. The predominant orientation of individual trabeculae is vertical, in line with the principal loading direction, while adjoining horizontal trabeculae stabilize the vertical trabecular columns. The increase in vertebral strength caudally is mostly due to the increased vertebral body size, as bone density is fairly constant between individual vertebral levels. Bone loss associated with aging can lead to a loss of these horizontal tie elements, which increases the effective length of the vertical structures and can facilitate the failure of individual trabeculae by buckling [5].

The vertebral endplate forms a structural boundary between the intervertebral disc and the cancellous core of the vertebral body. Comprising a thin layer of semi-porous subchondral bone, approximately 0.5 mm thick, the principal functions of the end plate are to prevent extrusion of the disc into the porous vertebral body, and to evenly distribute load to the vertebral body. With its dense cartilage layer, the endplate also serves as a semi-permeable membrane, which allows the transfer of water and solutes but prevents the loss of large proteoglycan molecules from the disc. The vertebral endplate and underlying trabecular bone together form a non-rigid system which demonstrates a significant deflection under compressive loading of up to 0.5 mm. High compressive loads lead to endplate failure due to pressurization of the nucleus pulposus. Nuclear material is often extruded into the adjacent vertebral body following fracture

(Schmorl's nodes), thereby establishing a possible source of pain from increased intra-osseous pressure[6]. It is important to note that end plate fractures also occur at load levels which are significantly below those required to produce vertebral body fractures.

Load sharing in the facet joints can be measured directly [6] or calculated with mechanical models [7]. In an upright standing position, 10–20% of the compressive load is carried by the facets. In hyperextension, approximately 30% of the load is transmitted through the facets. During torsion, the contralateral facet is heavily loaded. Both these events happen when a pilot while being seated; bends, turns and reaches for various controls during flying the aircraft. Facet joint pressure is also influenced by disc height: a 1-mm decrease in disc height results in a 36% increase in facet pressure; a 4-mm decrease in disc height a 61% increase in facet joint pressure. Due to the innervation of the facet capsules, there is therefore the potential for disc degeneration to cause facet joint pain.

The spine is an elastic column, with enhanced stability due to the complex curvature of the spine (kyphosis and lordosis), the support of the longitudinal ligaments, the elasticity of the ligamentum flavum, and most importantly the active muscle forces, the extrinsic support provided by trunk muscles stabilizes and redistributes loading on the spine and allows the spine to withstand loads of several times body weight.

Employing a mathematical relationship between applied spinal compressive loading and disc pressure established in carefully controlled in vitro experiments, Nachemson et al [8] have published extensive data on spinal loading (Table 2)

**Table 2. Typical spinal loads**.

| Activity | Load on L3 disc (N) |
|---|---|
| Supine, awake | 250 |
| Supine, traction | 0 |
| Supine, arm exercises | 500 |
| Upright sitting without support | 700 |
| Sitting with lumbar support, 110° incline | 400 |
| Standing at ease | 500 |
| Coughing | 600 |
| Forward bend 20° | 600 |
| Forward bend 40° | 1000 |
| Forward bend 20° with 20 kg | 1200 |
| Forward bend, 20° and rotated 20° with 10 kg | 2100 |
| Sit up exercises | 1200 |
| Lifting 10 kg, back straight, knees bent | 1700 |
| Lifting 10 kg, back bent | 1900 |
| Holding 5 kg, arms extended | 1900 |

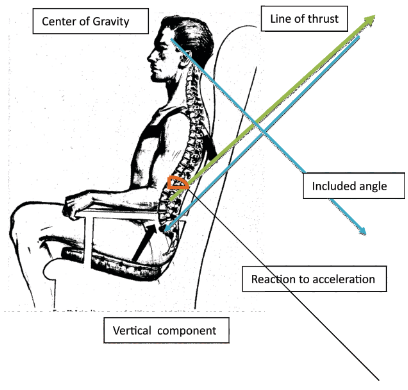
### Ejection and Back Ache

When a pilot is forced to eject vertically out of his aircraft, he quickly acquires two motions: (a) a rigid-body motion having a trajectory which will clear him from the aircraft and (b) a 'wave' travels from the seat upward toward the head. Clinical observations on the condition of the spine of 55 Swedish pilots, who had to eject by catapult from their aircraft, were reported by Hirsch and Nachemson [9]. Thirteen, or about one fourth of the subjects were found to have incurred vertebral fractures. The injuries were invariably compression fractures of the vertebral bodies, especially the endplates. The overall incidence of spinal fractures in survived ejections is variously reported as 20-30% in many Indian as well as .across the Air Forces in India as well as abroad. [2,4,10–14]

The aircraft ejection seats have undergone tremendous change in technology from earlier spring loaded ejection seats to gas initiated, Cartridge activated and to current rocket assisted / rocket pack seats in all new generation aircraft. The acceleration profile of most present day upward catapult seats averages 200-300 G/sec onset, 22 G max, 70 - 10 ft/sec terminal velocity and 10-80 milliseconds of peak G exposure.[15]

The escapee is required to sit straight in the seat during ejection so as to prevent spinal injuries which are commonest in the lower thoracic and upper lumbar vertebrae. The forces acting on the spine during ejection are as depicted in Fig 1

**Fig 1 – Forces acting on the Spine during ejection: Reproduced from Fig 20 in [15]**




The included angle which exists between the seat line of thrust and the longitudinal axis of spine is usually kept at a maximum of 18o in the conventional seats. This determines the flexion force which acts on the upper part of the torso and this for an upward thrust of 6G is 20G, and for 8G is 25G respectively. During ejection, maintenance of the four normal spinal curves results in symmetrical load distribution and enhanced safe loading capability. The importance of this simple, biomechanical fact cannot be overemphasized when considering seat-to-head spinal stress in which unsymmetrical vertebra-disc load distribution and transmission may cause early structural failure. During the initial phase of ejection acceleration there is a forceful tendency for cervical and dorso-lumbar flexion to the degree that an individual who is unrestrained or poorly restrained will experience spinal bending. If such spinal flexion is sufficient, the major portion of an acceleration force vector may be concentrated along the anterior superior and inferior margins of a few vertebrae[15]. The various injuries that may occur at various stages of ejection are enumerated in Table 3.

**Table 3: Injuries of the spine pertaining to various ejection phases**

| Forces acting in ejection | Effect on the spine |
|---|---|
| Ejection seat G forces | Spinal compression fractures. |
| Impact with canopy structures | Neck strains and Spinal compression fractures |
| Helmet rotation | Neck Strain |
| Parachute deployment | Cervical Fracture / strain / dislocation |
| Landing | Spinal compression fractures |

Thus, ejection imposes additional accelerative and decelerative stresses on the body especially on the Dorso-Lumbar spine and results in spinal injuries and back ache.

### Retrospective analysis of spinal injury pattern

Digital data base of all ejection injuries available in the archives in India were scrutinised to determine the cases of pilots who had ejected at least once. Ejections in last 10 years were analysed. There were 66 cases of ejection and 24 cases of vertebral fractures. This depicted in the table below [Table 4]. A total of 39 vertebrae were involved in the fractures due to involvement of more than one vertebra in 18 cases. 8 patients had unstable fractures, two with cord injury, who underwent spinal fusion. Rest were managed conservatively. The data acquired, threw up interesting information. As expected, the dorso-lumbar region of D12 –L1 was most commonly involved in fractures. However, there were fractures in almost all the dorsal vertebra. This indicated that the forces of ejection had affected these vertebra, probably because of abnormal posture of the pilots at the time of ejection. This possible cause of fractures occurring all long the dorsal vertebra is depicted in Fig 2 below.

**Fig 2: Impact of ejection forces on the dorsal vertebra according to the posture at the time of ejection.**

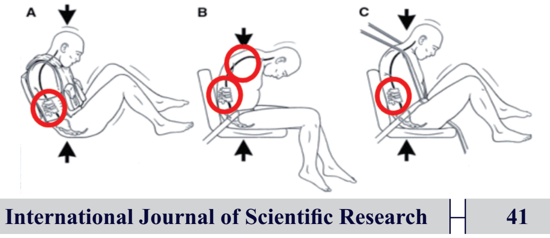


**Table 4: Distribution of injuries sustained**

| Injuries sustained | Total Number | Multiple Level | Single Level |
|---|---|---|---|
| No Fracture | 42 | | |
| Vertebral Fractures | 24 | 18 | 6 |
| Head Injuries | 3 | | |
| Limb Fractures | 5 | | |

**Table 5: Distribution of fractures as per vertebra**

| Vertebra involved | Number of cases with fracture |
|---|---|
| D1 | 1 |
| D2 | 1 |
| D3 | 4 |
| D4 | 3 |
| D5 | 0 |
| D6 | 3 |
| D7 | 2 |
| D8 | 1 |
| D9 | 2 |
| D10 | 2 |
| D11 | 2 |
| D12 | 8 |
| L1 | 7 |
| L2 | 1 |
| L3 | 0 |
| L4 | 1 |
| L5 | 0 |
| Sacrum | 1 |

### Management of Ejection Spinal Injuries.

An occupational medicine approach to ejection Spinal injuries suggests the classical levels for prevention and management of any clinical disease entity viz. Primary Prevention, Secondary Prevention, Tertiary Prevention.

Primary prevention of ejection spinal injuries starts with selection process of pilots wherein, radiographic screening is carried out to ensure absence of any spinal disease/ deformity which may affect the bio-dynamics during ejection. Subsequent to selection, training forms an important component in primary prevention. Assumption of proper ejection posture, neck and back exercises to strengthen the supporting musculature to the spine and post ejection actions for pilots to protect a potentially damaged spine are an integral part of training of the pilots.

The Secondary management of ejection spinal injuries starts with the Search and Rescue (SAR) Team which recovers the pilot from the landing. Use of rigid cervical collars, ortho-scoop stretchers and stabilisation using spinal board prior to evacuation go a long way in aggravation of spinal injuries by preventing movement of broken bony fragments of an injured vertebral column. Early detection of spinal injuries is achieved by post ejection radiography using plain radiographs and subsequent MRI scans of the whole spine.

Tertiary prevention by instituting early and appropriate conservative or surgical management as deemed appropriate by the treating surgeon minimises disability due to ejection spinal fractures. Early and proper rehabilitation to get back the pilot into active flying is an integral part of tertiary prevention.

Management of these patients, post ejection, requires a heightened index of suspicion to identify and detect various injuries. The main aim in imaging in the clinical setting of suspected spinal trauma are to depict the vertebral axis rapidly and accurately, and to guide further treatment, specifically a potential surgical decompression.

Plain X-ray films are a quick and easy way to assess the spine, and are readily available in most hospitals. They are the initial modality of screening done in all settings post ejection. Plain radiographs may be helpful in fracture screening, and are mainly used to detect a spinal deformity. Ejection forms an important indication for obtaining "surveillance" radiographs of the whole spine. Plain X-ray films, even with the best possible technique, underestimate the amount of traumatic spine injury, hairline fractures or non-displaced fractures are difficult to detect on conventional radiographs.

Computed tomography or thin-section CT, with reformation in sagittal or coronal planes to evaluate the spine plays a critical role in the rapid assessment of the polytrauma patient, it should include careful review of the soft tissue windows, to gain maximum benefit [16]. The most important limitation of this technique is the inability to provide screening for ligamentous injury. Recent literature data indicate that CT diagnoses thoraco-lumbar spine fractures more accurately than plain X-ray films [17].

MR imaging is the preferred technique for the detection of soft tissue injuries. It is also used to exclude occult vertebral fractures or micro fractures, demonstrated as bone marrow edema of traumatized vertebrae which are unapparent on plain film studies, they appear as T2W hyperintensity. MRI is mainly used to identify spinal cord lesions. MR imaging is the modality of choice for assessing traumatic lesions involving the intervertebral disks and spinal ligaments. All patient post ejection with or without presumed spinal cord injury should undergo a whole spine MR imaging examination as soon as possible and preferably should be repeated after 04 weeks to detect lesions missed on the initial imaging. In patients with spinal cord injury, MR imaging is able to reveal the location and severity of the lesion and, at the same time, to indicate the cause of spinal cord compression

### The questions which need to be answered are:

(a) Is the fracture stable - Successful management of traumatic spine injuries requires understanding of the concepts of spinal stability and instability. Determination of spinal stability is important because treatment strategies rely heavily on this assessment, widely used classification is the **three-column model of the spine**, which was introduced by Denis in 1983 [18].

(b) Is the fracture recent or old - This question is difficult to answer, particularly on conventional X-ray studies. Some indications of recent fractures on imaging studies, are: impaction of bone trabeculae (plain X-ray), bone marrow edema (MR), pre-and paravertebral hemorrhage (MR or CT), epidural hemorrhage (MR or CT), and spinal cord edema (MR). Bone marrow edema on fat-saturated or fat-suppressed MR images is a good indicator of a recent fracture; it decreases gradually over time, but its disappearance is unrelated to relief of pain [19].

Management guidelines of ejection injuries are in no way different than those of injuries due to any other means, all standard practices are adhered to, this should never be biased with the implications on the future prospects of a return to the cockpit. The options in management are

(1) Medical management with analgesics and bed rest.
(2) Surgical decompression, fusion and stabilisation with implants –posterior and / or anterior.
(3) Percutaneous Vertebroplasty / Kyphoplasty

Amongst the three, Percutaneous vertebroplasty or kyphoplasty is a relatively new modality, which is done in the acute setting for pain relief and for early mobilisation. Here the fracture is augmented with bone cement percutaneously. There is level I evidence that vertebroplasty provides superior pain control over medical management in the first 2 weeks, and level II–III evidence that within the first 3 months there are superior outcomes in analgesic use, disability, and general health, and finally level II–III evidence that by 2 years there is a similar level of pain control and physical function with or without vertebroplasty (20).The strength or load-bearing capacity of a single vertebra is significantly increased following augmentation when compared to the intact strength. The effects of vertebroplasty on adjacent structures results in a decrease in the overall segment strength with additional increase in disc pressure resulting in increased loading in the adjacent structures (21). This results in overall, increased risk of fractures in adjacent levels. Adjacent cranial vertebrae are most likely to fracture, whereas thoracic vertebrae were least likely to fracture at the adjacent level. There are no studies on the effect of increased aviation stresses on the vertebra and adjacent vertebra after vertebroplasty. we can only extrapolate the results on ground and this would suggest to adapt a cautious approach in routing these patients back to the cockpit.

### Disposal of Ejection Spinal Injuries.

The Indian guidelines for deciding on the flying fitness of post ejection cases are well laid down. Stable fractures, as determined by the Dennis 3 Column concept, are allowed sufficient period of recovery of upto 24 weeks. Radiographic, clinical and functional evidence of recovery is deemed adequate for re-flighting an ejectee aircrew in to fighter aircraft. They are subjected to Human Engineering evaluation and simulated aviation stresses before deciding upon final fitness to fly. There is evidence to suggest that the stable spinal fracture once healed, can sustain future ejection forces satisfactorily. Pilots who have ejected multiple times did not have the fractures in the same vertebra that were fractured in the first ejection. [14]

In cases of Unstable Fractures, Burst Fractures, and Fracture Dislocations, longer periods of observation on ground is mandated. These cases are more likely to be declared permanently unfit for ejection seat aircraft. Presently, aircrew with Schmorl's nodes detected post ejection are deemed fit for ejection seat aircraft once they are asymptomatic and have achieved functional normality.

### Long Term Implications in aviators

Prolonged sitting in a cramped cockpit, leaning forward and twisting the body in an effort to reach for controls puts a tremendous stress and strain on the aviator's back, which is already loaded due to a wrong sitting posture. Proper education and prevention is the key in successful management of these cases. Changes in vertebral architecture due to degeneration and / or old fractures predispose the aviators to an unstable injury and pain if there is repeated loading at the same site. All the numerical values of the loads on spine are compounded many folds due to effect of pull against gravity – 'G' which the aviators are subjected to during aerobatics and flying. This compounds the multi factorial causes of back pain in aviators.

## CONCLUSIONS

Aviators form a separate subgroup of population who are prone to fractures due to the abnormal forces they experience at the time of ejection and this is further compounded by the abnormal postures they may assume in fractions of seconds in the time they have, after initiating the ejection sequence. The rates of ejection spinal injuries have remained constant through the various generations of ejection seats as seen from the review of literature. This needs to be recognised and understood if post ejection spinal injuries are to be managed correctly.

The widespread availability of MRI in evaluation of post ejection cases has enabled the diagnosis of vertebral body contusions and other soft-tissue injuries which contribute to the causes of back pain in these cases. Diminished vertebral height and reduced inter-vertebral disc spaces leading to facetal arthropathy as a cause of recurrent low back pain in post ejection pilots needs to be given due consideration. Awareness of the peculiarities in a case of post ejection spinal injury for the treating surgeon goes a long way in proper management, rehabilitation and subsequent employability decision of the aviator.

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