

Whiplash Injury Determination With Conventional Spine Imaging and Cryomicrotomy

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Study Design. Soft tissue–related injuries to the cervical spine structures were produced by use of intact entire human cadavers undergoing rear-end impacts. Radiography, computed tomography, and cryomicrotomy techniques were used to evaluate the injury.

Objectives. To replicate soft tissue injuries resulting from single input of whiplash acceleration to whole human cadavers simulating vehicular rear impacts, and to assess the ability of different modes of imaging to visualize soft tissue cervical lesions.

Summary of Background Data. Whiplash-associated disorders such as headache and neck pain are implicated with soft tissue abnormalities to structures of the cervical spine. To the authors' best knowledge, no previous studies have been conducted to determine whether single cycle whiplash acceleration input to intact entire human cadavers can result in these soft tissue alterations. There is also a scarcity of data on the efficacy of radiography and computed tomography in assessing these injuries.

Methods. Four intact entire human cadavers underwent single whiplash acceleration (3.3g or 4.5g) loading by use of a whole-body sled. Pretest and posttest radiographs, computed tomography images, and sequential anatomic sections using a cryomicrotome were obtained to determine the extent of trauma to the cervical spine structures.

Results. Routine radiography identified the least number of lesions (one lesion in two specimens). Although computed tomography was more effective (three lesions in two specimens), trauma was not readily apparent to all soft tissues of the cervical spine. Cryomicrotome sections identified structural alterations in all four specimens to lower cervical spine components that included stretch and tear of the ligamentum flavum, annulus disruption, anterior longitudinal ligament rupture, and zygapophysial joint compromise with tear of the capsular ligaments.

Conclusions. These results clearly indicate that a single application of whiplash acceleration pulse can induce soft tissue–related and ligament-related alterations to cervical spine structures. The pathologic changes identified in this study support previous observations from human volunteers observations with regard to the location of whiplash injury and may assist in the explanation of pain arising from this injury. Although computed tomography is a better imaging modality than radiography, subtle but clinically relevant injuries may be left undiagnosed with this technique. The cryomicrotome technique offers a

unique procedure to understand and compare soft tissue–related injuries to the cervical anatomy caused by whiplash loading. Recognition of these injuries may advance the general knowledge of the whiplash disorder. [Key words: whiplash acceleration, computed tomography, cryomicrotomy, soft tissue injury, zygapophysial joint] **Spine 2001;26:2443–2448**

There has been renewed interest in the scientific community to investigate the mechanism of whiplash-associated disorders because of the steadily increasing motor vehicle use secondary to migration of the population to more urban areas, particularly in the United States. In addition, the disorder is reported to occur predominately in rear-end vehicular crashes.^{21,25} Whiplash injuries have a significant impact in terms of economic burden to society and dysfunction to the involved patient. For example, the incidence of injury is 4 per 100,000 in the United States, and the annual estimated cost is \$10 billion. In the United Kingdom, the cost exceeds £2.5 billion; in Germany the estimate is DM2 billion; in Canada it is \$250 million Canadian; and in Australia the cost is estimated at \$540 million Australian.^{10,12,13}

From a mechanical perspective, whiplash injury is mainly an acceleration-induced phenomenon. Typically, the occupant sustains posteroanterior acceleration to the torso, neck, and head structures secondary to rear-end impact from a vehicle or a fixed object. The neck-head structures respond with extension followed by flexion mechanism without the head impacting any interior object within the vehicle. The injury of the head-neck complex belongs to the noncontact acceleration type; this is termed inertial loading. Often the severity of impact, as measured by the imparted acceleration, is considered to be of low magnitude and does not induce any bony damage in the form of acute fractures and subluxations. Spine radiographs of whiplash-injured patients are routinely assessed to be normal for the specific age group. Thus, the injury does not lend itself to objective identification in traditional imaging methods. However, certain types of treatments for this disorder are being used by clinicians to alleviate pain. For example, the Bogduk group has shown that percutaneous radiofrequency neurotomy is effective to relieve zygapophysial joint-induced neck pain in whiplash patients.^{1–4,14} This is based on the paradigm that the spinal zygapophysial (facet) joints that are replete with pain-sensitive structures are mechanically damaged secondary to single-impact rear-end acceleration input to the human occupant.¹⁶ Although this

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Table 1. Radiologic, Computed Tomography, and Cryomicrotome Findings

Patient	Radiology	Computed Tomography	Cryomicrotome
A1	None	None	Anterior anulus tear at C5–C6, anterior longitudinal ligament, disruption at C5–C6, separation of C6–C7 ligamentum flavum at the superior level of the lamina with anterior displacement into the spinal canal
B3	None	None	Diastasis of the C5–C6 zygapophysial joint with tear in the joint capsular ligament in the ventral and dorsal regions on the right side; C6–C7 ligamentum flavum separated from the C7 superior lamina with associated hematoma
C4	C5–C6 disc distraction without body fracture	C5–C6 intervertebral disc distraction without bony fracture, C5–C6 zygapophysial joint distraction on the right side	Anterior longitudinal ligament rupture at C5–C6 interspace with disc disruption extending to the level of the posterior longitudinal ligament; stretch associated with mild tear of the ligamentum flavum at C5–C6; zygapophysial joint capsule stretch and tear at the C5–C6 ventral and dorsal regions on the right; diastasis of the C4–C5 zygapophysial joint on the left without tear of the capsular ligament at this level
D5	Mild avulsion of anterior–inferior C5 body	Mild avulsion of anterior–inferior C5 vertebral body	Diastasis and hematoma in the right C5–C6 zygapophysial joint with joint capsular ligament tear in the ventral region and right atlantoaxial joint with hematoma in the dorsal aspect of the joint with tear of the ligament in this region; C5 vertebral body anterior–inferior avulsion associated with anterior longitudinal ligament tear at the distal vertebral body level

method has served as an indirect validation of zygapophysial joint abnormality and has provided a means to treat whiplash patients, to the best of the authors' knowledge, biomechanical studies have not been reported in literature that document soft tissue–related injuries to the human secondary to single-event rear-end acceleration input. Consequently, there is a need to demonstrate that these types of clinically relevant structural alterations occur to the head-neck complex in a controlled laboratory environment. Thus, the purpose of the present study was to use an appropriate experimental model to induce accelerations to the human surrogate and to identify and differentiate soft tissue injuries using conventional spine radiographs and cryomicrotomy. Another objective is to assess the ability of different modes of imaging to visualize soft tissue cervical lesions.

■ Materials and Methods

One male (aged 58 years) and three female (aged 65, 89, and 76 years) intact entire human cadavers were used in the study. All subjects were screened before selection for human immunodeficiency virus and hepatitis A, B, and C. In addition, they were radiographically screened for any pre-existing spinal abnormalities such as fracture, subluxation, or metastatic disease. Radiographs of the head-neck, chest, and extremities were obtained before testing. The specimens were clothed in leotards and placed on a custom-designed bench seat without a headrest. The height of the backrest was 583 mm for female and 700 mm for male specimens. These heights fully supported the entire dorsal column of the specimen. The seat was rigid, *i.e.*, no yielding or deformation of the seat occurred during whiplash acceleration. A cushion material, representative of vehicular padding, was used to support the specimen back to the seat. The specimens were belted with lap and shoulder belts. The torso was restrained by the shoulder harness, and the lap belt was tight, *ie*, no initial slack was permitted between the specimen and the belt. This was accomplished by attaching a cinch

plate to the lap portion of the belt at the anchor location. The specimens were prepared as follows. Accelerometers and targets were placed on the head and the spinous process of T1. They were aligned in such a manner that the Frankfort plane, *i.e.*, the line joining the external auditory meatus and the inferior region of the orbit, was horizontal. Pretest radiographs of head-neck complexes were obtained to document the alignment. Other positioning details consisted of the following. The lower extremities were extended to simulate a normal driving position. The torso of the specimen was restrained with a three-point lap and shoulder harness belt. The specimens were tested at single rear-impact, mean acceleration levels of 3.3g or 4.5g by use of full-body sled equipment. The change in velocity was 4.4 m/sec or 6.8 m/sec with a pulse duration of 137 msec or 154 msec. This level of acceleration pulse was chosen on the basis of published reports indicating that 75–90% of whiplash injuries occur at speeds less than 6.9 m/sec.^{8,9,12} Each subject was tested only once with the specified whiplash acceleration level. Radiographs of the head-neck were obtained after the simulated impact. In addition, computed tomography scans were obtained at 1.0-mm intervals. Furthermore, cryomicrotomy was done according to accepted procedures.¹⁹ The specimens underwent cryosectioning at 15- to 30- μ m intervals with a heavy-duty cryomicrotome device (LKB 2250, Leica, Inc., Deerfield, IL) in the sagittal plane. Photographs of the tissue were taken to parallel the sequential computed tomography scans, and a correlation was made between the imaging methods to identify in detail the structural alterations sustained by cervical spine tissues. Injuries were identified in a blinded fashion by a team of clinicians from the neuroradiology, neurosurgery, and orthopedic surgery departments.

■ Results

Three human cadaver specimens were tested at a mean acceleration level of 4.5g, and one subject (B3) was tested at a slightly lower acceleration of 3.3g. Except for subject C4, all were female. Peak head angular accelerations ranged from 590 to 1200 rad/sec/sec in these specimens.



Figure 1. Parasagittal computed tomography (A) and cryomicrotome (B) images demonstrating the diastasis (arrow) of the right C5–C6 zygapophysial joint of specimen C4.

Peak head inferior to superior displacements ranged from 0.01 to 0.02 m. Peak head anteroposterior displacements ranged from 0.08 to 0.10 m. Bony fractures did not occur in any test. However, one specimen (D5) sustained a mild avulsion of the anterior-inferior tip of the fifth cervical vertebral body. This injury was identified on plain radiographs, midsagittal computed tomography scans, and cryomicrotome images. Cryomicrotomy revealed additional abnormalities, including the stretch of the anterior longitudinal ligament at the C5–C6 disc space at the distal body and diastasis of the right C5–C6 zygapophysial and atlantoaxial joints with associated capsular tears. In another specimen (C4), radiography and computed tomography revealed the distraction of the C5–C6 disc space. Cryomicrotomy also identified this abnormality. Although the diastasis of the C5–C6 zygapophysial joint was revealed by parasagittal

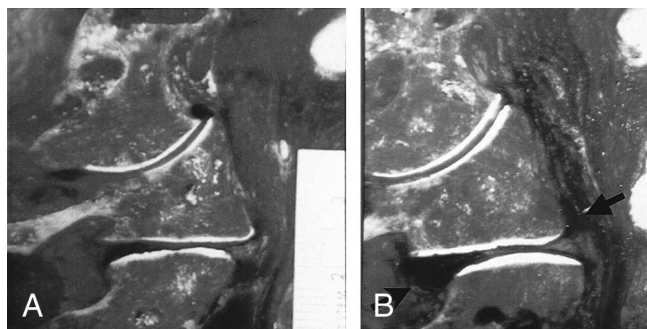


Figure 2. A, cryomicrotome anatomic image of OC–C1–C2 complex indicating the normal anatomy of the left C1–C2 joint of specimen D5. B, zygapophysial joint on the right side indicates hematoma surrounding the joint.

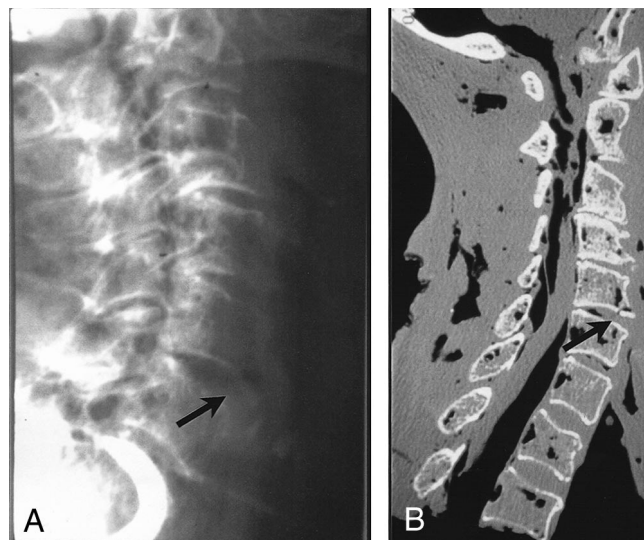


Figure 3. Radiograph (A) and sagittal computed tomography image (B) of specimen D5 illustrating the avulsion abnormality fracture of the C5 body (arrow).

computed tomography on this subject, radiography did not identify the existence of such an abnormality. Cryomicrotomy confirmed the diastasis and discovered additional soft tissue–related pathologic changes, including abnormalities in the anterior and posterior columns at the lower cervical level (Table 1). In all specimens, cryomicrotome sections identified structural alterations to midlower cervical spine components that included stretch and tear of the ligamentum flavum, disc anulus disruption, anterior longitudinal ligament rupture, and zygapophysial joint compromise with tear of the capsular ligaments. These anatomic observations on a specimen-by-specimen basis comparing radiography, computed tomography, and cryomicrotome techniques are included in Table 1. Figures 1 through 4 illustrate structural alterations sustained by the test specimens secondary to single application of whiplash acceleration.



Figure 4. Sagittal cryomicrotome image demonstrating the separation of the ligamentum flavum (arrow) from the inferior lamina in specimen C4.

■ Discussion

Impact biomechanical studies simulating crashes are done with human cadavers.²⁶ Isolated ligamentous column^{11,18} and head-neck complexes have been used in studies of whiplash.^{23,24} For example, Cusick et al⁶ and Yoganandan et al²⁴ applied whiplash acceleration to intact head-neck complexes and determined their localized and overall kinematics. Data were also obtained on the transient nonphysiologic S curve during the initial stages of acceleration and facet joint sliding kinematics.^{6,25} An intact entire human cadaver was used here to meet the study's objectives (production of soft tissue injuries and assessment of the ability of different modes of imaging to visualize soft tissue lesions in whiplash). The rationale for using intact entire human cadavers was that isolated head-neck complexes require fixed boundary conditions to apply acceleration, discounting the interaction of the distal column.^{23,27} Human volunteer studies indicate that the thoracic spine straightens during rear-end impact,¹⁵ imparting motions to the neck and head. These effects are automatically incorporated in an entire cadaver model. Whiplash loading was limited to one cycle to more closely mimic clinical situations in which the majority of persons sustain a single rear-end crash, and to insure that post-test observations were attributable to a single injury.²¹ Although it was possible to test the specimen by repeated accelerations, the effects of cumulative loading on injury limit the applicability of the study to *in vivo* situations. Gross dissection of the head-neck complex, done while the specimen is not frozen, causes soft tissues to become infiltrated with bodily fluids. The cryomicrotomy technique preserves the anatomic features of the spine *in situ* and facilitates the obtaining of sequential images of hard and soft tissue structures that parallel computed tomography scans. Consequently, cryomicrotomy was used to determine the injuries and compared with other clinical methods.

Despite these significant merits in terms of the experimental model (intact entire cadaver), loading paradigm (single whiplash), and injury determination and comparison (radiograph, computed tomography, cryomicrotomy), it should be emphasized that the model included only full passive musculature. Subsequent effects of the muscle tone were not present. Although this may appear to be a limitation, electromyographic studies using human volunteers in rear-end impacts have concluded that the initial physiologic condition of the subject, *i.e.*, tensed or relaxed nature of neck muscles before impact, do not influence spinal motions.¹⁷ Furthermore, laboratory studies using animal models have demonstrated the time to develop muscle forces to be approximately 200 msec.²² Tennyson et al remarked that the reaction time of the experimental animal is shorter than that of the human. It has also been shown that the joints of the cervical spine undergo maximum deformation during the early part of whiplash acceleration wherein

the muscle tone activations are minimal or absent.⁷ Consequently, it can be concluded that the present intact cadaver model is appropriate to produce and compare injuries caused by whiplash loading.

Computed tomography was not done before testing because of cost and logistic constraints. All four subjects were free of observable lesions before testing on the basis of radiographic evaluation. Normal lordosis was preserved in all specimens. All cervical spines were considered normal for the age of the cadaver. Because these specimens were from the elderly population, some amount of degeneration might have existed that could not be completely assessed by radiographic techniques. The cryomicrotome results, however, were very clear in depicting injuries sustained because of whiplash loading. Similar to traditional pathologic analyses, pre-existing injuries in cadaver specimens would be identified with some scar tissue, which were not identified as injuries secondary to loading. As can be seen from Figures 2 and 4, soft tissue lesions were often associated with rupture of local capillaries in the area. In addition, trauma was not the cause of death in any cadaver. It is acknowledged that the elderly group of cadavers used in the present study might have been more susceptible to injury than a robust young adult. However, the authors consider that the results of this study offer a conservative assessment of whiplash injury. These findings attain a higher level of recognition when one considers that the mean driving age of the population in this country is on the rise. Indeed, it has been reported that by 2020 the number of drivers aged 70 years or more is expected to increase 60% to approximately 31 million.

The present study was conducted at impact severities of 4.4 or 6.8 m/sec (input change in velocities). As indicated earlier, this level of severity was chosen on the basis of published reports that 75% to 90% of whiplash-related injuries leading to chronic symptoms occur at changes in velocities less than 6.9 m/sec. The level of dynamic input used in the present study is higher than those used in published human volunteer studies, which adopted changes in velocities of less than 2.8 m/sec. Structural alterations to the cervical spine were not reported in these human volunteer studies, although some subjects described having pain after the rear-impact test.⁵ Factors such as impact severity and age differences (cadavers were from an elderly population, whereas volunteers were relatively younger) may account for the differences.

Trauma stemming from a single application of whiplash pulse was a principal focus of this study. As indicated, whiplash patients are predominantly from vehicular crashes, and the injury (manifested as headache or neck pain) is confined to the soft tissues of the head-neck complex. The radiography and computed tomography used in this study parallel *in vivo* investigations with the clear acknowledgment that computed tomography may not be routinely ordered for every patient. Additionally, the use of a cadaver model made it possible to obtain

sequential anatomic sections with the cryomicrotome. This method was effective in documenting the post-test anatomy of the hard and soft tissue structures and also served as a standard for the comparison of findings from the two radiography-based techniques (study's objectives, stated in the introduction).

In all cases, additional abnormalities were observed on cryomicrotome images (Table 1). Routine radiography identified the least number of lesions. Although computed tomography was more effective, trauma was not readily apparent to the soft tissue structures. In fact, the results of computed tomography were unremarkable in all cases (except for No. C4). All specimens showed abnormalities to the anterior and posterior columns on the cryomicrotome images. The injuries were frequently confined to the lower spine in all cases (Figure 5). Anterior column abnormalities at C5–C6 were attributed to the extension injury mechanism. Posterior column abnormalities consisted primarily of zygapophysial joint diastasis, attributed to the localized extension of the lower spine during the initial whiplash acceleration. The anteroposterior sliding of the zygapophysial joint associated with pinching in the dorsal region and capsular strains may be responsible for the compromise in the joint integrity.^{7,25} This can lead to pain because this component is reported to be rich in nociceptor structures, which could undergo excitation by motions exceeding physiologic limits.^{2,4} This study has shown documentary evidence for the potential onset of neck pain secondary to abnormal motions in these soft tissues. As illustrated in the cryomicrotome images, hematoma in the joint sec-

ondary to the compromise of the capsular soft tissue anatomy may also elicit pain.

The diagnosis and management of overt cervical spine fractures and subluxations are well established in the clinical literature. However, the more occult whiplash-associated injuries are less understood. The lack of objective radiographic findings in whiplash-associated injuries has often led to the dismissal of patients' symptoms. Acknowledgments in the past few years that the complex of whiplash-associated injuries does occur have led to the acceptance of patients' pain, but pain generators are still unclear. The present study has clearly shown that structural alterations occur to the head-neck complex as a result of whiplash injury and furthermore that these alterations do not completely lend themselves to identification by routine spine radiographs and computed tomography. These findings begin to define the injuries and potential sources of pain (caused by the delineated structural abnormalities) that can be experienced by a whiplash patient secondary to single-cycle rear-impact acceleration. A better understanding of these injuries will allow better treatment of these patients and perhaps the eventual development of an efficacious treatment algorithm. This research is a first step in the process.

The predominant structural pathoanatomic changes noted in this study relate to potential apophyseal joint injury, especially the midlower facets of the cervical spine, which may serve as the secondary effect of the "pinching" mechanism (anteroposterior shear associated with axial motions of the capsule) in the facets during the whiplash phenomenon.⁶ The facet joint injuries demonstrated in certain cryomicrotome sections could possibly serve as the potential source of cervical pain. Recently, radiofrequency thermal denervation has been proposed as a treatment of facet pain that has not responded to noninterventional therapies.¹⁴ Sapir and Gorup reported significant reduction in symptoms in 46 patients and did not demonstrate that the potential for secondary gain influenced the response to treatment.²⁰ Careful evaluation of severe posterior cervical pain after whiplash for a potential facet arthropathy is therefore a reasonable consideration. Such findings may lead to consideration of interventional techniques such as radiofrequency thermal denervation lesions. Certainly, the consequences of the decoupling mechanism during the whiplash phenomenon may place adverse stresses on upper cervical structures, including the musculature and the C2 neural complex. The present findings do not show consistent reproducible injury patterns in the upper cervical region, but certain findings of unilateral C1–C2 facet changes in the current study suggest that adverse forces and motions could be acting on these structures. Although speculative, the potential response to diagnostic neural blockade and the consideration of peripheral-nerve stimulation techniques deserve future evaluation in selective cases of occipital neuralgia-type syndromes.

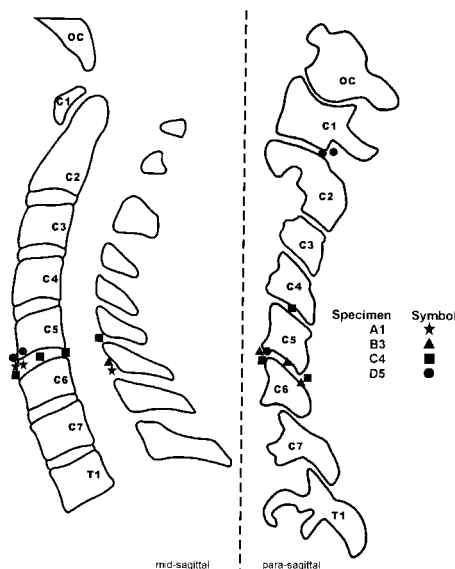


Figure 5. Schematic representation of injury location on a specimen-by-specimen basis. Right, zygapophysial joint injuries in the parasagittal section. Left, other injuries in the midsagittal section. Note the concentration of injuries at C5–C6. See Table 1 for details.

■ Key Points

- The intact entire human cadaver is an appropriate experimental model to determine whiplash injury.
- This study verifies the production of soft tissue injuries to the cervical spine resulting from single whiplash acceleration to intact human cadavers. In particular, the lower cervical spine is identified as the region of abnormality.
- Although computed tomography is a better imaging modality than routine radiography, all injuries are not assessable by this technique.
- Recognition of these injuries may advance the general knowledge of the whiplash disorder.

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