

Biomechanical Study of C2 (Axis) Fracture: Effect of Restraint

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Abstract

Introduction: In human, the cervical spine region is very susceptible to impact injury. The complex structures of C1 and C2 serve to transmit the weight of the cranium to the greatly similar structural cervical spine from C3 caudally. Application of sudden disruption forces will detach the junction of the cervico-cranium with the pars interarticularis of the neural arch of C2 from the lower cervical spine by fracturing, as in a “hangman’s fracture”. Severe falls or blows to the head from heavy objects will cause the fracture of the odontoid process of C2. Many biomechanical studies were conducted based on full restraint of the inferior aspects of isolated C2 to produce odontoid fracture. In this study, two different restraining conditions of C2 were adopted experimentally to determine the absolute fracture load and the corresponding fracture patterns that are common to C2. **Materials and Methods:** Nine C2 vertebrae obtained from cadaver spines, ranging from 51 to 80 years, were used. Two specified restraint conditions were employed: (1) fully constrain the posterior element postero-anteriorly up to one-quarter of the inferior facet; and (2) fixing of C2 by a specially-designed rig whereby the body of C2 embedded in the pivoted cup and its inferior facets positioned on top of two lateral plates. Antero-posterior shear force was applied on the anterior articulating facet of the dens until failure. **Results:** These specified restraint conditions had resulted in specific fracture of C2. Antero-posterior shear force ranges from 840 to 1220 N was required to cause fracture across the pars interarticularis under restraint condition 1. Failure load of between 900 and 1500 N was found to cause odontoid fracture under restraint condition 2. These values are in agreement with published data. **Conclusions:** The biomechanical response of C2 was specific to the mode of restraint conditions of C2. In reality, depending on the force vector applied to the head, precise posture at the time of trauma, spinal geometry, and physical properties, different types of C2 fracture patterns may happen. These findings are of potentials for the biomechanical correlation and validation study of C2 vertebra using analytical approaches, and in the surgical anterior screw fixation of odontoid fracture.

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Introduction

In human, the occipito-atlanto-axial (C0-C1-C2) joint complex is an important region of the spine and often susceptible to impact injury in trauma. Traffic accidents frequently produce a distinct variety of fracture (or fracture-dislocation) of the upper cervical spine, characterised by a bilateral avulsion-fracture through the neural arch of C2 without injury to the odontoid process and with or without fracture-dislocation of the 2nd cervical vertebral body upon the 3rd. The term “hangman’s fracture” is used to describe this injury of traumatic spondylolisthesis of C2 based on superficial similarity to the injury seen after judicial hanging.¹

The fracture of the odontoid process of the axis is another type of commonly found fractures. Severe falls or blows to the head from heavy objects mainly caused this type of fracture.² There are three distinct types of fracture based on the anatomical location of the fracture line, and they are classified as Types I, II and III of odontoid fracture.³

Fracture of C2 accounted for approximately 20% of cervical spine fractures, of which odontoid fractures are the most common, accounting for 59%.⁴ There are vast amount of published documents detailing the epidemiology and management of C2 fractures.⁴⁻¹⁸ Only a few studies, however, have been conducted to determine the magnitude of anterior failure load and fracture patterns of C2 under

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different constraint conditions.^{1,2,7,8,19}

In this report, an experimental study was conducted to determine the magnitude of antero-posterior failure load under two different restraining conditions of C2 that yield distinct type of failure patterns commonly found in C2. Accordingly, in one restrain condition, a specially-designed jig was fabricated for the rigid fixation of C2 to simulate the articulation between C2 and C3 *in vivo*.

Materials and Methods

Nine specimens from elderly subjects (age range 51 to 80 years) who died of various diseases were used for the study. The C2 vertebrae, with all the musculature, soft tissues and ligaments and capsule dissected, were removed from 9 human cadavers at the time of autopsy and sealed in double plastic bags, and frozen at -20°C for later use. Table I lists the known data, such as sex, age, weight, height and cause of death of the donor of the nine specimens.

TABLE I: PHYSIOLOGICAL DATA OF THE SPECIMEN USED FOR THE STUDY

Specimen no.	Sex	Age (yr)	Weight (kg)	Height (m)	Cause of death
3	M	73	37.8	1.68	Bronchopneumonia
5	M	64	69.5	1.62	Liver cirrhosis
7	M	51	40.4	1.70	Bronchopneumonia
1	F	76	52.8	—	Ischaemic heart disease
2	M	73	39.6	1.52	Ischaemic heart disease
4	F	80	30.5	1.50	Acute myocardial infarction
6	M	54	34.0	1.57	Ischaemic heart disease
8	M	70	56.2	1.65	Chronic renal disease
9	M	70	53.6	1.60	Congestive heart disease

Morphometric dimensions of the harvested C2 were measured using ruler and calipers. Figure 1 shows the dimensions measured on the vertebrae and odontoid process. Table II gives the data measured on the 7 vertebral specimens.

Before being tested, the specimens were fully thawed at room temperature. With the limited number of specimens available, for obvious reasons, the 9 specimens were distributed into 2 groups: 3 specimens were used for testing using restraint condition 1 and 6 specimens were used in restraint condition 2. Two out of the 6 specimens used in restraint condition 2 were used in a preliminary study to investigate the fixation requirement in restraint condition 2. The preliminary study also investigated the rate of loading in restraint condition 2.

For all the tests, the specimens were loaded to failure with the displacement-controlled electric actuator (Instron 1195, England). The time histories of both the actuator motion and the reaction force under the specimen were recorded with the Instron integral chart recorder to determine:

1. The failure load, which is the maximum of the load-displacement compressive curve, and
2. The total cross-head displacement at the point where the failure load occurred.

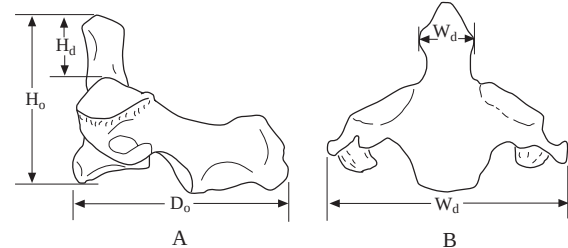


Fig. 1. (A) Lateral and (B) anterior views of C2 showing the overall vertebral and odontoid process measurements.

TABLE II: OVERALL DIMENSIONS OF C2 USED FOR THE STUDY (in mm)

Specimen no.	H _o	D _o	W _o	H _d	D _d	W _d	D _c	W _c	D _b	W _b
1	31	46	45.5	15	7.1	7.5	19	23	16.5	19.5
2	32	46.5	45	15	8.5	8.5	20	27	15.5	19.5
3	33	52.5	44.5	14.5	11	10.5	21	24	19.0	20.5
4	32	42.5	44.5	13	10.5	9.5	17	22	15	17.5
5	32	48.5	44.0	16.5	7.2	8.5	20.0	23.5	15	17.5
6	31.5	47.5	42.2	13.5	10.5	9.2	19.5	23	16	18.5
7	36	47.5	44.0	15	11.5	9.5	20.5	25.5	17	19
Mean	32.42	47.29	44.24	14.64	9.47	9.03	19.6	24.0	16.29	18.86
Ratio	H _o /D _o		W _o /D _o	H _d /H _o		W _d /D _d		W _c /D _c		W _b /D _b
**	0.686		0.936	0.452		0.954		1.22		1.16

H: height (sup-inf); D: depth (antero-posterior); W: width (L-R); o: overall dimension; d: odontoid process (dens); c: spinal canal; b: base of body

** Mean ratio

Restraint Condition 1

For this set of tests, the posterior element of each specimen (three for this case) was potted postero-anteriorly up to a level about one-quarter of the inferior articulating facets using the cement material ISOPON P40 (David & Son, Northants, England). The pot together with the cemented vertebra was left in open air in the room for about an hour for the cement material to harden. The pot was then mounted on to the moving cross-head of the testing machine. An antero-posterior shear load was applied at the articulating surface of the dens via the load plunger attached to the superior platen of the stationary cross-beam which was fixed to a 50 kN load cell. A cross-head moving at 1 mm/min was selected. Figure 2 shows the overall schematic setup of the experimental apparatus, and specimen with load application location on the midway of the anterior articulating facet of the dens.

Restraint Condition 2

Six of the cadaver second cervical vertebrae (specimens no. 1, 2, 4, 6, 8 and 9) of Table I were studied. Cups were machined from a rectangular aluminium bar and milled to form a cell of inner dimensions 22 x 22 x 17 mm in depth, width and height, respectively. These dimensions allow the anterior, posterior and inferior bony surfaces of C2 vertebral body to be embedded with ISOPON P40 within the cell. A special jig was fabricated to hold the cup potted with C2 and the two adjustable lateral metal plates in position. These adjustable lateral plates allowed the resting of the inferior articulating facets according to the inclination of the facets. To fill the gap, a thin layer of ISOPON P40 was sandwiched between the inferior articular facets and the two adjustable lateral metal plates. This arrangement simulates the structural articular supports of the vertebra *in vivo* by C3 below. Figure 3 shows the unassembled components and the assembled apparatus set up for testing.

Due to the unique fixation of C2 under this restraint condition, two preliminary trials were conducted on two specimens (nos. 8 and 9) to investigate the proper rigid articulation of C2 within the rig at slow loading rate. Accordingly, an application of antero-posterior load at a cross-head displacement of 1 mm/min had failed to produce any fracture of the odontoid. The cell was unable to provide suitable fixation of the anterior surface of the vertebral body in the cementing preparation, the specimen slowly slipped off the cell tearing bone along the anterior base of the body. In order to ensure the rigid fixation of the vertebral body within the cup, 3 nails of 1 mm diameter by 13 mm length were inserted, spaced laterally, into the anterior body in the regions relatively distant from the areas described for odontoid Type III fracture. About 2 to 3 mm of the nails was exposed to enhance the better bonding

between the body and the ISOPON. The bonding between the ISOPON and the cell produced no problem.

With experience in the cementing of the vertebral body in the cup, assembling and mounting of the rig in the loading apparatus, 4 samples of the specimen were tested and loaded to failure as described in restraint condition 1, but with cross-head displacement of 10 mm/min. Similarly, the failure load and the total cross-head displacement for each specimen were determined.

Results

Restraint Condition 1

The load-deformation curves for specimens tested showed sigmoidal response. The curves exhibit non-linearity (convex towards the abscissa) at low loads of up to approximately 450 N, followed by another non-linearity which is convex towards the ordinate until failure. Specimen 3 clearly exhibited “saw-tooth-like” load-displacement patterns distinguished by a relatively constant load under continuous deformation after failure (the maximum load prior to the abrupt change in the slope of the load-displacement curve). The maximum load for this specimen occurred when the cross-head moved 2.7 mm. Failure load of 1030, 1220 and 840 N at deformation of 2.7, 6.7 and 5.5 mm for specimens 3, 5 and 7, respectively, were determined and summarised in Table III.

Fractures occurred mainly through the pars interarticularis junction between the superior facet and the inferior facet, and also across the latero-posterior base of the body. Fractures were non-bilateral and no odontoid fracture of any type was observed.

Restraint Condition 2

All the specimens tested produced odontoid fractures of specified type, and the fracture was abrupt with an audible noise. Two specimens produced Type III odontoid fractures, i.e. fracture laterally below the junction of the dens across the anterior body of the axis. Specimen 4 fractured in a Type I odontoid fracture through the superior portion of the

TABLE III: FRACTURE MAGNITUDE AND TYPE OF FAILURE

Specimen no.	Restraint condition	Type of fracture	Failure ^a	
			Load	Deformation
3	1	Across pars	1030	2.7
5	1	Across pars	1220	6.7
7	1	Across pars	840	5.5
1	2	Type III	1170	3.2
2	2	Type III	1500	10.0
4	2	Type I	900	6.8
6	2	Across the body	1190	9.0

^a Failure load in N and deformation in mm

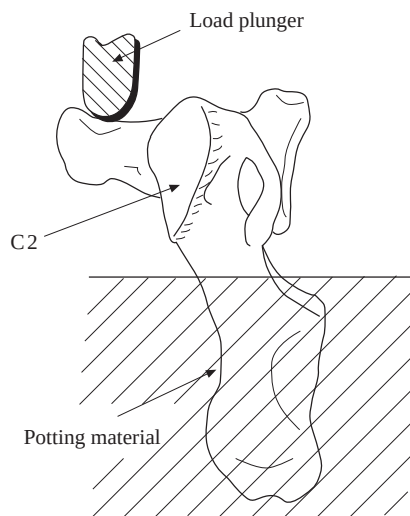


Fig. 2. Schematic setup of the experimental apparatus and specimen.

dens, while specimen 6 had fracture across the inferior region of vertebral body. Figure 4 shows the fractured specimens viewed in the antero-posterior and lateral directions.

The mean shearing force required to break the odontoid was 1190 N. The inconsistent relative displacements of the specimens at the failure force, which ranged from 3.1 to 9.8 mm with a mean of 7.2 mm, were observed.

Table III summarised the magnitude of failure load and the cross-head movement determined from the recorded chart for specimens tested successfully under the two restraint conditions.

Discussion

Direct impact to the vertex of the head due to a fall, head hitting the windscreen or diving, which transmit the force to the contact surface of the axis (C2) with the first cervical vertebra (C1), is common.^{9,19,20} Accordingly, in this study, antero-posterior shear load was applied directly onto the anterior articulating facet of the dens of the restrained C2 until fracture occurred under the two different restraint conditions of the vertebral element.

Fig. 3. (A) The unassembled parts and (B) the test setup configuration.

Fig. 4. Fracture patterns of specimens tested under condition 2.

Restraint Condition 1

Under this restraint of posterior element aspect of C2, an antero-posterior shear force of between 840 to 1220 N was required to cause posterior fracture of the C2 tested in dried condition. The application of this antero-posterior load had resulted in bending of the C2 across the unrestrained posterior element and hence the fracture. The load-

deformation curves showed similar mechanical behaviour to that of the vertebral body tested under compression reported by McBroom et al.²¹ However, the magnitude of ultimate loads was lower. It is reasonable to argue that the smaller the size of the cervical vertebrae than the bony structure of other spinal column,²²⁻²⁴ the lesser amount of bony material, coupled with smaller cross-sectional surface areas, to resist deformation may be an acceptable explanation for the lower values obtained. Also the specimens used were aged 51 to 80 years and all died of certain diseases, the natural lower trabecular bone density and strength could have contributed to our lower experimental results.

These experimental results fall within the range of mechanical properties reported by Sonoda.²⁵ In his experimental testing of wet vertebrae of 22 cadavers aged 20 to 79 years, under longitudinal compressive axial loading the average strength of the lower cervical vertebrae was 3150 N. Under posterior shear loading, the strength could be 2/5 of the longitudinal compressive strength was reported. The breaking load in bones from females was about 5/6 of that in the males; and for bones of older age (60 to 79 years) the breaking load was about 1/2 of those in the younger age (20 to 29 years). Sonoda also reported higher magnitude of ultimate load for dried bone.

Restraint Condition 2

Odontoid fractures of different types (I to III) are frequently reported clinically of patients involved in traffic accidents, but the exact mechanism whereby flexion, extension, and rotational injuries due to violence to the head causing such fracture is complex. Shearing or bending forces are assumed primarily to be involved and probably emanate from the transverse ligament, the medial aspect of the lateral masses, or the anterior arch of the atlas (C1). In a traffic accident, a fall or diving into shallow water, the head may strike an obstacle (e.g., windshield) thus transmitting short-duration high magnitude force to the odontoid resulting in its fracture.

Clinical evidence suggests that fracture of the odontoid might result from either a pure extension or hyperextension injury caused by a high-impact blow to the vertex of the skull. The posterior aspect of the ring of the atlas is forced against the dens resulting in shear loading and bending moment at the base of the odontoid.³

In this part of experimental study, the specially-designed rig to restrain the C2 was unique, whereby the specimen was held in conditions which are similar to those that might exist *in vivo*. The pivot of the cup in the rig allowed a slight sagittal rotational movement of C2 under the antero-posterior shear load. The present mechanical test produced the fracture of the odontoid similar to those seen clinically. The results indicated the force required to produce the

fracture under this restraint condition was substantial, over 900 N.

The relatively lower force (900 N) which produced the Type I odontoid fracture on the superior surface of the odontoid in specimen 4 was purely due to the tearing off of the cortical shell from the inner connecting trabecular bones as shown in Figure 4. Two specimens (1 and 2) experienced higher forces (1170 N and 1500 N) to produce the shallow Type III fracture, and the specimen which had fracture across the body had failure load of 1190 N. As the odontoid process over which the deforming force is acting is quite short, little more than 15 mm (Table II); a large magnitude of force is thus required to produce the combination of shearing force and bending moment to cause Type II or III fracture of odontoid.²⁶ From simple engineering consideration, the larger depth dimension of the dens measured for specimen 2 (8.5 mm) than that of specimen 1 (7.5 mm), as indicated in Table II, the resulting larger second moment of area of specimen 2 would require larger bending moment, and hence larger posterior shear force. The quantitative effect due to the quality of the bone was not assessed.

The values obtained were comparable to published data. Sasso et al²⁷ had created the Type II odontoid fracture by direct 45° oblique extension loading onto the anterior articular surface of the odontoid process. The body of C2 was potted in denstone and two wires were placed over the medial aspect of the articular surface. The results of the 13 C2 vertebrae, freed of all muscular tissue, showed that a force of 1235 ± 326 N was required to produce a Type II odontoid fracture. No report of the displacement of the specimen at failure was provided.

Doherty et al²⁸ reported on their experimental biomechanical testing of two groups of randomly selected isolated cadaveric C2 vertebrae, with the inferior aspects of the specimens fully constrained. In Group 1, 4 specimens were loaded on the antero-superior aspect of the dens, at the area articulation with the anterior arch of C1. In Group 2, 4 specimens were tested in a similar manner, except the load was 45° from the sagittal plane, orientated in a posterior and lateral direction. Higher failure load of 1736 N for Type III than the 1279 N for Type II fracture for Group 1 and Group 2, respectively, was reported.

In all our tests, the displacement of the specimen was taken to be equal to the relative displacement of the cross-head without taking into consideration any displacement which may occur within the cementing material (ISOPON) and the extension motion of the cup about its pivoting supports. The deformation of the odontoid at failure load taken from the load/deflection graph might include the contribution of deformation from the bonding material and the extension motion of the

cup about its supports. At present, there is no published data for comparison.

In conclusion, the current study carried out under the 2 different restraining conditions of C2 had specifically resulted in either a “hangman” or an “odontoid” fracture of C2 (axis). The magnitude of failure load for either type of fracture was substantial, above 900 N. In reality, depending on factors such as the force vector applied to the head, precise posture at the time of trauma, spinal geometry, and physical properties, different types of the “hangman’s fracture” and “odontoid fracture” patterns of the axis may be produced. The depth and width dimensions of the dens may affect the likely Type II or III fracture. This additional data, we hope, will be useful in the biomechanical study of C2 vertebra using analytical approaches, and in the surgical anterior/posterior fixation using screws.

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REFERENCES

- Schneider R C, Livingston K E, Cave A J E, Hamilton G. Hangman’s fracture of cervical spine. *J Neurosurg* 1965; 22:141-54.
- Osgood R B, Lund C C. Fractures of the odontoid process. *N Engl J Med* 1928; 198:61.
- Anderson L D, D’Alonzo R T. Fractures of odontoid process of the axis. *J Bone Joint Surg Am* 1974; 56:1663-74.
- Greene K A, Dickman C A, Marciano F F, Drabier J B, Hadley M N, Sonntag V K. Acute axis fractures. Analysis of management and outcome in 340 consecutive cases. *Spine* 1997; 22:1843-52.
- Adams V I. Neck injuries: II. Atlantoaxial dislocation—a pathologic study of 14 traffic fatalities. *J Forensic Sci* 1992; 37:565-73.
- Blauth M, Schmidt U, Otte D, Krettek C. Fractures of the odontoid process in small children: biomechanical analysis and report of three cases. *Eur Spine J* 1996; 5:63-70.
- Chiba K, Fujimura Y, Toyama Y, Fujii E, Nakanishi T, Hirabayashi K. Treatment protocol for fractures of the odontoid process. *J Spinal Disord* 1996; 9:267-76.
- Dickman C A, Hadley M N, Browner C, Sonntag V K. Neurosurgical management of acute atlas-axis combination fractures. A review of 25 cases. *J Neurosurg* 1989; 70:45-9.
- Esses S I, Bednar D A. Screw fixation of odontoid fractures and nonunions. *Spine* 1991; 16:S483-5.
- Hadley M N, Dickman C A, Browner C M, Sonntag V K H. Acute axis fractures: a review of 229 cases. *J Neurosurg* 1989; 71:642-47.
- Hadley M N, Sonntag V K, Graham T W, Masferrer R, Browner C. Axis fractures resulting from motor vehicle accidents. The need for occupant restraints. *Spine* 1986; 11:861-4.
- Jeanneret B, Magerl F. Primary posterior fusion C1/2 in odontoid fractures: indications, techniques, and results of transarticular screw fixation. *J Spinal Disord* 1992; 5:464-75.
- Marchesi D G. Management of odontoid fractures. *Orthopedics* 1997; 20:911-6.
- McBride A D, Mukherjee D P, Kruse R N, Albright J A. Anterior screw fixation of type II odontoid fractures. A biomechanical study. *Spine* 1995; 20:1855-60.
- Montesano P X, Anderson P A, Schlehr F, Thalgot J, Lowery G. Odontoid fractures treated by anterior odontoid screw fixation. *Spine* 1991; 16:S33-7.
- Morandi X, Hanna A, Hamlat A, Brassier G. Anterior screw fixation of odontoid fractures. *Surg Neurol* 1999; 51:236-40.
- Schatzker J, Rorabeck C H, Waddell J P. Non-union of the odontoid process. An experimental investigation. *Clin Orthop* 1975; 108:127-37.
- Wang G J, Mabie K N, Whitehill R, Stamp W G. The nonsurgical management of odontoid fractures in adults. *Spine* 1984; 9:229-30.
- Mouradian W H, Fietti V G Jr, Cochran G V B, Fielding J W, Young J. Fractures of the odontoid: a laboratory and clinical study of mechanisms. *Orthop Clin North Am* 1978; 9:985-1001.
- Althoff B. Fracture of odontoid process: An experimental and clinical study. *Acta Orthop Scand Suppl* 1979; 177:1-95.
- McBroom R J, Hayes W C, Edward W T, Goldberg R P, White A A. Prediction of vertebral body compressive fracture using quantitative computed tomography. *J Bone Joint Surg Am* 1985; 67:1206-14.
- Panjabi M M, Duranceau J, Goel V. Cervical human vertebrae—quantitative three-dimensional anatomy of the middle and lower regions. *Spine* 1991; 16:861-9.
- Panjabi M M, Takata K, Goel V. Thoracic human vertebrae—quantitative three-dimensional anatomy. *Spine* 1991; 16:888-900.
- Panjabi M M, Goel V, Oxland T. Human lumbar vertebrae—quantitative three-dimensional anatomy. *Spine* 1992; 17:299-306.
- Sonoda T. Studies on the strength for compression, tension and torsion of the human vertebral column. *J Kyoto Pref Med Univ* 1962; 71:659-702.
- Schaffler M B, Alson M D, Heller J G, Garfin S R. Morphology of the dens. *Spine* 1992; 17:738-43.
- Sasso R, Doherty B J, Crawford M J, Heggeness M H. Biomechanics of odontoid fracture fixation. Comparison of the one- and two-screw technique. *Spine* 1993; 18:1950-3.
- Doherty B J, Heggeness M H, Esses S I. A biomechanical study of odontoid fractures and fracture fixation. *Spine* 1993; 18:178-84.