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Fracture of the Odontoid Process

An experimental and clinical study

by
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FRACTURE OF THE ODONTOID PROCESS. An experimental and clinical study

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ABSTRACT. Fractures of the odontoid process have a bad reputation because of their tendency for non-union. The cause has been considered to be insufficient arterial blood supply and/or inadequate fixation of the fracture. The fracture mechanism has not been elucidated.

In this study, the theories on hyperflexion, hyperextension, and horizontal shear as the cause of odontoid fractures were tested by experiments on cadaver specimens. However, no odontoid fracture could be produced by violent hyperflexion, hyperextension or horizontal shear; instead injuries occurred below the axis. Violent vertical compression also failed to produce odontoid fractures; instead such an impact resulted in fractures of the atlas. But, when an impact was used that combined horizontal shear and vertical compression, odontoid fractures could be produced, and they were similar to those seen in patients. The experimental and clinical odontoid fractures were classified into four types, A, B, C, and D, depending on their level; type A passing through the isthmus of the odontoid process and the others passing progressively at lower levels. All types were observed in the clinical study and all but type C were produced in the experimental study. When a combined type of impact (horizontal shear and vertical compression) was directed straight in the sagittal plane through the axis (anterior or posterior impact), type D odontoid fractures were produced; when such an impact was directed 45° to the sagittal plane (anterolateral impact), type B odontoid fractures were produced, and when it was directed 90° to the sagittal plane (lateral impact), type A odontoid fractures were produced.

The influence of different odontoid fractures on the arterial supply to the odontoid process was studied experimentally using cadaver specimens whose arteries were filled with contrast medium either before or after the production of the fracture. The arterial sources to the odontoid process are paired anterior and posterior ascending arteries, paired inferior and superior anterior horizontal arteries, and paired posterior horizontal arteries. Arteries entering the odontoid process at the base anastomose inside the bone with arteries entering at the apex. In some instances when the experimental fracture involved a part of the body of the axis, injuries to the ascending arteries were observed. In all instances, thus irrespective of the level of the fractures, arteries within the odontoid process were filled with contrast medium. When the fracture was situated in the isthmus, this filling was mediated by arteries entering at the apex of the odontoid process.

The medical records and radiographs of 78 patients with odontoid fracture were studied. Most fractures were caused by a high velocity force. Three patients died as a consequence of the odontoid fracture. Eighteen patients had neurologic symptoms on admission to the hospital. In most of them these symptoms were minor, but 1 had tetraplegia.

Forty-eight patients were examined with radiography at a follow-up investigation. Twenty-four had bone union. One had been operated on early with posterior fusion and 4 had undergone such an operation late (because of non-union). All fusions had healed, but the state of the fracture could not be determined on the radiographs. Nineteen patients had non-union, 1 of them with a spontaneous anterior fusion between the axis and the atlas. The rate of bone union was significantly ($p < 0.05$) increased the more the fracture involved the body of the axis, when comparing the fracture types; it was significantly ($p < 0.05$) increased in fractures displaced anteriorly compared to those displaced posteriorly, and it was significantly ($p < 0.05$) increased after skull traction > six weeks compared to treatment in a collar or Minerva jacket.

Key words: arterial supply, cervical spine, experimental fracture, follow-up study, fracture mechanism, odontoid process.

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INTRODUCTION

Fractures of the odontoid process account for 7 – 13 % of all fractures of the cervical spine and 1 – 2 % of all vertebral fractures. Fractures of the odontoid process have acquired a bad reputation because of their tendency for non-union. In conservatively treated materials a rate of non-union is reported between 0 – 80 %. Various reasons explain this wide percentage distribution: in some materials there has been a selection of patients for strict conservative treatment or early fusion; in some investigations a radiographic examination has not been carried out at follow-up of all patients; finally, in some materials no difference has been made between bone union and fibrous union.

The opinions differ regarding the cause of non-union. A distinction can be made between two major non-related causes:

1) The arterial supply of the odontoid process and
2) The fixation of an odontoid process fracture.

1. The arterial supply is considered to be influenced by the age of the patient as the rate of arterio-sclerosis increases with increasing age. Moreover, the arterial supply may be influenced by the level of the fracture and by the displacement of the same.

2. Fixation of the fracture is influenced by the level of the fracture, the displacement of the fracture, the associated ligament injuries, the delay in treatment, and finally the type of treatment.

There are several opinions on the fracture mechanism in fractures of the odontoid process. Theories have been presented on hyperflexion, hyperextension, rotation, horizontal shear and vertical compression. Most theories are based on the observations in clinical and autopsy materials. Few experiments have been carried out.

For this reason it was thought to be of some interest to pose some questions on the nature of odontoid process fractures both experimentally and clinically.

Questions

Fracture mechanism

1. Can the present theories on the odontoid process fractures be substantiated by experimental tests?
2. Can fractures of the odontoid process be experimentally produced at different levels?
3. Is it possible to find any connection experimentally between the impact causing the fracture and the appearance of the fracture, the level of the fracture, and the associated ligament injuries?

Arterial supply

4. What is the influence of an experimental odontoid fracture on the arterial supply of the odontoid process?

Clinical

5. What is the course for patients with a fracture of the odontoid process treated conservatively in different ways?
6. Is it possible to find any early signs which may predict bone union or non-union?

Anatomy (Figures 1 and 2)

The odontoid process is important for the stability of the articulation between the atlas and the axis. The position of the odontoid process in relation to the posterior facet of the anterior arch of the atlas is secured by the transverse ligament running posterior to the odontoid. This ligament is the strong transverse part of the cruciate ligament, the more slender longitudinal part connects the axis to the skull. The accessory ligaments arise from the massae laterales of the atlas and insert into the lateral aspects of the base of the odontoid process. The small apical ligament arises from the tip of the odontoid and inserts into the anterior rim of the foramen magnum. The strong alar ligaments arise from the posterolateral aspects of the odontoid and insert into the occipital condyles.

The anterior atlanto-occipital membrane runs from the anterior arch of the atlas to the base of the skull. The anterior longitudinal ligament runs partly as a prolongation of the anterior atlanto-occipital membrane and partly from the anterior arch of the atlas down on the anterior aspect of the vertebral bodies.

The tectorial membrane runs from the skull down into the spinal canal on the posterior aspect of the odontoid and the transverse ligament. It then continues on the posterior aspect of the vertebral bodies as the posterior longitudinal ligament.

The slender portion of the odontoid process just above the base is called the isthmus.

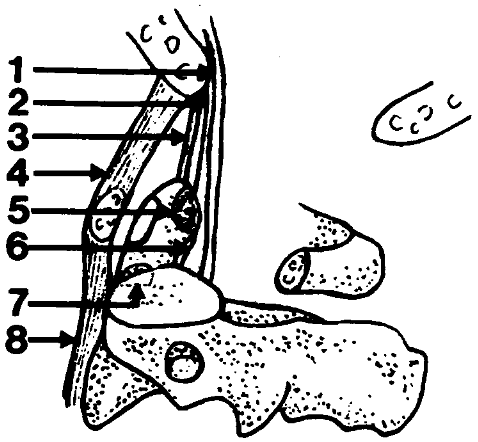

Figure 1. *Lateral view. Ligaments around the odontoid process.*

1 = Tectorial membrane
2 = Longitudinal part of cruciate ligament
3 = Apical ligament
4 = Anterior atlanto-occipital membrane
5 = Insertion of alar ligament
6 = Transverse ligament (transverse part of the cruciate ligament)
7 = Insertion of accessory ligament
8 = Anterior longitudinal ligament

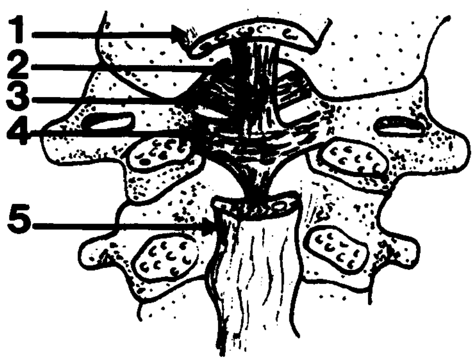

Figure 2. Posterior view. Ligaments around the odontoid process

1 = Tectorial membrane
2 = Longitudinal part of cruciate ligament
3 = Alar ligament
4 = Transverse ligament (transverse part of the cruciate ligament)
5 = Posterior longitudinal ligament

Definitions

Earlier classifications

Schatzker et al. (1971) classified fractures of the odontoid process into two types:

Low fractures: The fracture is either at the level or below the level of the attachment of the accessory ligaments.

High fractures: The fracture is, on one or both sides, above the attachment of the accessory ligaments.

Anderson & D'Alonzo (1974) have classified fractures of the odontoid process into three types:

Type I: An oblique fracture through the upper part of the odontoid process.

Type II: Fracture at the junction of the odontoid process with the body of the axis.

Type III: Fracture extending down into the cancellous portion of the body of the axis.

In practice, it may be difficult to classify the odontoid fractures according to these definitions as there are no distinct border lines between the types.

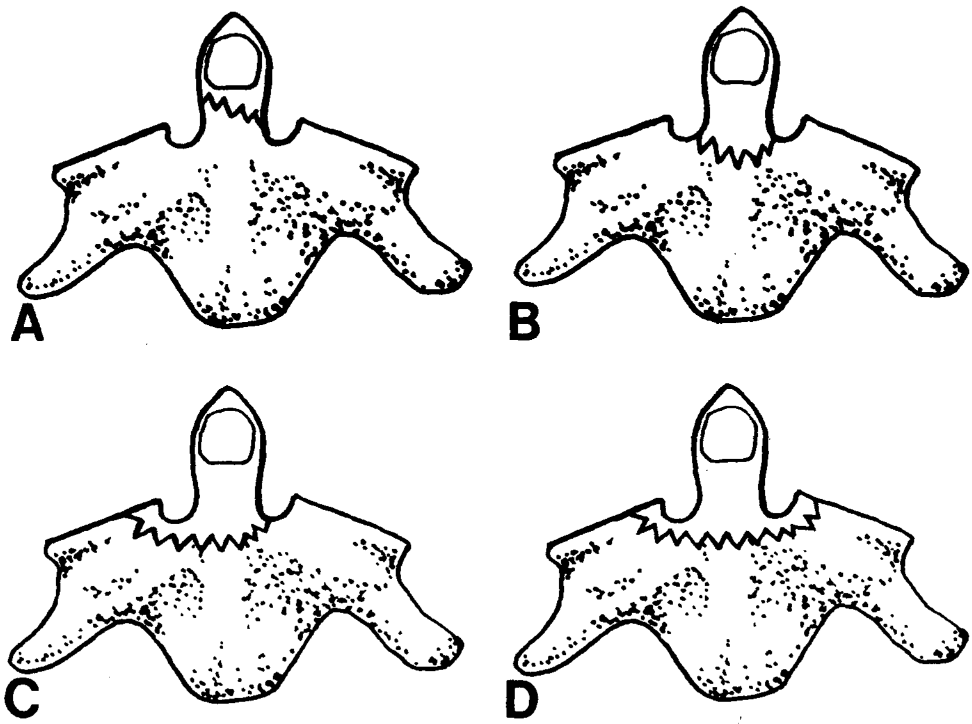

Figure 3. New Classification of fractures of the odontoid process.

A: Type A fracture. The fracture passes through the isthmus of the odontoid process.

B: Type B fracture. The fracture passes down into the most superior part of the body of the axis.

C: Type C fracture. The fracture passes through the superior part of the body of the axis and involves the medial part of one of the superior articular facets of the axis.

D: Type D fracture. The fracture passes through the superior part of the body of the axis and involves the medial part of both the superior articular facets of the axis.

New classification

For the above reasons a new classification is proposed. It was elaborated for a better interpretation of the experimental work in this investigation in relation to the anatomy of the region. The analysis of the radiographs in the present clinical study further justify the new classification and it will be presented already here to avoid any misunderstanding of the reader in interpreting the results of this investigation.

Type A (Figure 3 A): Fracture through the isthmus of the odontoid process. On the lateral radiograph it does not pass any further down than to the inferior border of the transverse ligament.

Type B (Figure 3 B): Fracture passing down into the most superior part of the body of the axis but not involving the superior articular facets of the axis.

Type C (Figure 3 C): Fracture through the superior part of the body of the axis involving the medial part of one of the superior articular facets of the axis.

Type D (Figure 3 D): Fracture through the superior part of the body of the axis involving the medial part of both the superior articular facets of the axis.

EXPERIMENTAL FRACTURE OF THE ODONTOID PROCESS OF THE AXIS

by

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INTRODUCTION

The knowledge of fracture mechanisms is of importance in understanding and treating orthopaedic injuries. This is in particular true of lower cervical spine fractures and dislocations, which are discussed in terms of hyperflexion and hyperextension injuries. Besides information on the fracture the mode of injury can also suggest the possibility of associated ligament lesions and consequently instability at the fracture site. The fracture mechanism in fractures of the odontoid process has as yet not been satisfactory analysed. Most theories on the fracture mechanism are derived from calculations based on clinical and/or autopsy materials. Few experimental fractures have been produced.

This study was carried out:

1. To analyse the existing theories regarding the fracture mechanism in fractures of the odontoid process and, based on these theories, attempt experimentally to produce odontoid fractures.
2. To attempt experimentally to produce fractures at different levels of the odontoid process and further to study the associated ligament injuries.

REVIEW OF THE LITERATURE

Relation between anatomy and fracture site

Bardeen (1910) (cited by Blockey and Purser) described a rudimentary island of cartilage in the superior part of the body of the axis. The cartilage separates the odontoid process from the axis in childhood. With increasing age it disappears in most individuals. However, between 30 and 50 years of age a rudimentary island of cartilage was retained in 23.5 % in a material presented by Plaut (1938). It has been suggested that this island of cartilage may determine the site and type of fractures through the odontoid process (Plaut 1938, Sköld 1978).

Relation between movement of C II and fracture site

Wackenheim and Lopez (1969) studied the axes of movement in flexion and extension of C II on radiographs in relation to the foramen magnum. They found that the axes were not the same. The flexion axis was situated in the corpodental region and they postulated that flexion could account for basal fractures of the odontoid. The extension axis was situated near the transverse ligament and they postulated that extension could account for apical fractures or lesions of the transverse ligament.

Earlier investigations on experimental fractures

Reports on experimental fractures are very few and until 1978 only two have been found. In 1978 Mouradian et al. published a report on 23 fractures and Voigt et al. described 1 fracture.

In 1848 Orfila (cited by Fritsche 1913) succeeded in fracturing the odontoid process in 1 of his 20 cadaver experiments in which he tried to imitate judicial hanging. From this experiment it could be assumed that the fracture was the result of a distraction of the head from the upper cervical spine with a subsequent avulsion of the odontoid process by the alar ligaments.

Blockey and Purser (1956) were not successful in their attempts to produce fractures of the odontoid process by flexion, extension, or rotation.

Selecki and Williams (1970) studied the effect of compression loads on cervical spine specimens. In 22 experiments they described 1 fracture of the odontoid process when a compressive force was applied to a specimen held in flexion. In addition, fractures of other parts of the upper cervical spine were produced.

Mouradian et al. (1978) described a series of experiments on 45 cadaver specimens. Eleven were used in preliminary tests. They presented the results in 34 specimens in which the direction of force was flexion in 16, lateral in 11, extension in 4, and rotation-extension in 3.

The axis was fixed with epoxy in a cell leaving the atlas and the occiput free. In 5 of the lateral experiments the axis was held stationary while the load was applied laterally through a steel braid placed around the atlas. In the other experiments the skull base was amounted with epoxy in an aluminium container. This container was then attached to the loading apparatus through a stainless steel turn-backle which allowed the application of the 23 k.p.s. preload. Loading was applied by a pneumatically operated materials testing machine. The loading capacity of the machine was 500 k.p.s. within approximately 0.1 sec.

The effect of *flexion* force was tested in 16 specimens (Table 1). Ten fractures of the odontoid process were produced. In 1 experiment, in which the load was applied to the dens, 1 odontoid fracture was produced (Type III according to Andersson and D'Alonzo 1974). In 9 experiments, in which the load was applied to the skull base, 9 fractures were produced (1 type II and 8 type III fractures). The effect of *lateral* force was tested in 11 specimens. In 5 experiments, in which the load was applied to the atlas, 5 odontoid fractures were produced (4 Type II and 1 Type III fractures). In 6 experiments in which the load was applied to the skull base, 6 odontoid fractures were produced (6 Type II fractures). The effect of *extension* force was tested in 4 specimens. No odontoid fracture was produced. The effect of *rotation-extension* force was tested in 3 specimens. In 2 experiments, in which the load was applied to the atlas, 1 odontoid fracture was produced (Type III). In 1 experiment, in which the load was applied to the skull base, 1 odontoid fracture was produced (Type III).

The result in the 11 preliminary tests was not reported.

Table 1. Experimental work on odontoid fractures by Mouradian et al. (1978). Reported odontoid fractures classified according to Anderson and D'Alonzo (1974).

Reported experiments	Direction of loading force	Site of application of load	Odontoid fractures Type II	Type III
16	Flexion	Dens		1
		Skull base	1	8
11	Lateral	Atlas	4	1
		Skull base	6	
4	Extension	Skull base		
3	Rotation	Atlas		1
	Extension	Skull base		1

Mouradian et al. concluded that their model was not reliable for production of odontoid fractures by applying a flexion force since forward loading produced fracture only in half of the experiments. Extension as a mechanism of fracture was not demonstrated experimentally although clinical evidence suggested such a mechanism. In lateral loading apparently the massa lateralis of atlas acted as a bony hammer striking the odontoid process and applying the necessary shearing and bending force to produce the fracture of the odontoid process. "Unfortunately the clinical correlate, if any, of the lateral injury produced in the laboratory was not immediately apparent". According to the authors a pure lateral blow probably did not occur in any patient in their clinical series.

Voigt et al. (1978) reported fractures of the axis in 2 of their experiments with cadavers on an acceleration track. The purpose of these experiments was to design an instrument panel which in head-on-collision would offer the car occupant optimal protection. In 1 experiment there was a fracture of the odontoid process and in the other bilateral fracture of the arch of the axis (hangman's fracture). They concluded that the odontoid fracture was the result of a violent flexion which could be demonstrated on a high speed film.

Theories based on clinical and autopsy materials

Various theories like e.g. avulsion, shear, compression, and lateral bending have been advanced on the mechanism of odontoid fracture and a summary of these will be presented.

Avulsion

Many authors (Jefferson 1920, Wüsthoff 1923, Osgood and Lund 1928, Amyes and Anderson 1956, Blockey and Purser 1956, J. Böhler 1965, Kattan 1975, Sköld 1978) maintain that hyperflexion, hyperextension, or forced rotation will cause a fracture of the odontoid process, which becomes avulsed by stretching of the alar ligaments. In hyperextension the posterior arch of the atlas may also be fractured as a result of being crushed between the occiput and the axis. A fracture of the posterior arch of the atlas was thus considered to indicate a hyperextension of the head without any shearing effect.

Shear

Forces other than those of movement in normal directions have been postulated to be responsible for fractures of the odontoid process (Plaut 1938, Howorth and Petrie 1965). Kolisko (1916) and Wüsthoff (1923) found in cadaver specimens that the alar ligaments were not tight but relaxed when the head was extended and they postulated that the anterior arch of the atlas would attain major importance in fracturing the odontoid process.

A shear horizontally in a sagittal plane may displace the atlas on the axis and cause an odontoid fracture. With the force acting in an anteroposterior direction the anterior arch of the atlas shears off the odontoid process; with the force acting in a postero-anterior direction the transverse ligament produces the fracture. No experiments support this theory. In a report of 20 experiments

Fielding et al. (1974) described the result of a postero-anterior force applied to the atlas. In all experiments the transverse ligament was torn and there was no fracture of the odontoid process. They also applied a force directed to the odontoid process in 15 specimens and found that in no specimen the force required to fracture the odontoid process was significantly less than that to rupture the transverse ligament.

This observation had been made already in 1872 by Smith (cited by Wüsthoff 1923) who concluded by his experimental work that the odontoid process was stronger than both the anterior arch of the atlas and the transverse ligament.

Compression

Sir Ludwig Guttmann (1976) maintained that a fracture of the odontoid process was produced by forces acting in a vertical or vertical-posterior direction. When the fracture resulted from flexion or extension Sköld (1978) in reconstructing the fracture mechanism concluded that a simultaneous vertical compression of the neck was of importance.

A pure compressive force acting in the upper cervical spine is considered mainly to cause fractures of the arches of the atlas. This was concluded in 1920 by Jefferson on describing the fracture of the atlas which nowadays carries his name. This conclusion was based on his clinical works and experiments made by Braquehaie and Laubie (1900) (cited by Jefferson).

Lateral bending

The fact that some clinical odontoid fractures are angulated or slightly dislocated to the side has been pointed out by Hipp et al. (1963) and J. Böhler (1971). Therefore, a lateral bending could be involved in the fracture mechanism.

Combination of forces

Schatzker et al. (1971) came to the conclusion after reviewing the literature that the fracture of the odontoid process was not the result of a simple avulsion or shear but a combination of these forces and that the displacement was the result of the shearing force.

OWN INVESTIGATION

Material

Forty-one human cadaver specimens were used (Table 2). The specimens were from patients who had died from non-skeletal disease. At radiography during the experiments the cervical spine appeared normal in the atlanto-axial joints. The age distribution of the individuals was 23 – 94 years. It was not possible to establish the duration of the bedrest from the medical records. The specimens consisted of 6 – 7 cervical spine vertebrae and 2 – 5 cm of the skull base surrounding the foramen magnum. The specimens had all their ligaments left intact. The specimens were stored in a deep freeze (–20°C) until they were to be used and then thawed in 37 – 39°C water for half an hour.

Table 2. Cervical spine specimens (F = female, M = male)

Experiment	Age	Sex	Cause of death
1	60	F	Myocardial infarction
2	65	M	Cancer of the lung
3	54	F	Tumor of the brain
4			
5	47	M	Myocardial infarction
6	80	M	Pulmonary oedema
7	81	F	Circulatory insufficiency
8	57	M	Aortic aneurysm
9			
10	86	F	Cancer of the breast
11	63	F	Cerebral haemorrhage
12	30	F	Cancer of the breast
13	70	M	Myocardial infarction
14	88	M	Duodenal ulcer. Haemorrhage
15	64	F	Leucaemia
16	66	M	Malignant melanoma
17	61	F	Circulatory insufficiency
18	67	F	Leucaemia
19	82	F	Cancer of the colon
20	74	M	Cancer of the liver
21			
22	70	F	Myocardial infarction
23	36	M	Tumor of the brain
24	78	M	Cancer of the lung
25			
26	61	M	Malignant melanoma
27	33	F	Cancer of the uterus
28			
29	45	M	Liver insufficiency
30	94	M	Myocardial infarction
31	55	M	Pulmonary embolus
32	73	M	Myocardial infarction
33	46	M	Liver insufficiency
34	65	M	Myocardial infarction
35	64	M	Myocardial infarction
36	23	F	Circulatory insufficiency
37	50	F	Uraemia
38	23	F	Cerebral haemorrhage. Hypertension
39	61	M	Myocardial infarction
40	77	F	Cerebral haemorrhage
41	65	M	Cancer of the pancreas

Method

After thawing, the specimens were fixed in a metal box with epoxyresin (Plastic Padding®) leaving the axis and atlas free. The metal box was screwed onto a stand which was adjustable. A wooden block (W in Figure 4) was fixed with epoxyresin to the skull base. This block, simulating the skull and hence called the skull below, was subjected to an impact by a pendulum (Figure 5) with a radius of 225 cm and a weight of 35 kg. A 3 mm thick steel plate (S in Figure 5) was attached to the superior surface of the pendulum. This steel plate protruded anteriorly for 8 cm. The anterior edge of the steel plate transferred the impact to the skull. In order to secure the impact to reach the skull at a predetermined place, a block of oak tree (O, in Figure 4) was attached so that it formed a corner with the skull. The impact was directed into this corner (Figure 5). The height of the pendulum varied from 25 – 120 cm which gave the impact a maximal energy of 85 – 410 Nm.

One aim was to transmit the force of the pendulum through the skull to the upper cervical spine. Another aim was to define the direction of the force in each individual test. To achieve this, adjustments of the position of the specimen had to be made and the exactness was determined by radiography of the specimen set-up in 2 perpendicular planes for each experiment. This was found to be of fundamental importance in the production of previous experimental fractures (Peterson et al. 1976, Lansinger and Romanus 1977).

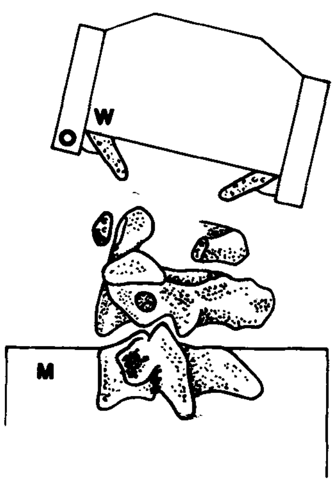

Figure 4. Fixation of the specimen. The specimen is fixed in a metal box (M) with epoxyresin. A wooden block (W) is fixed to the skull. A block of oak tree (O) is attached to the skull.

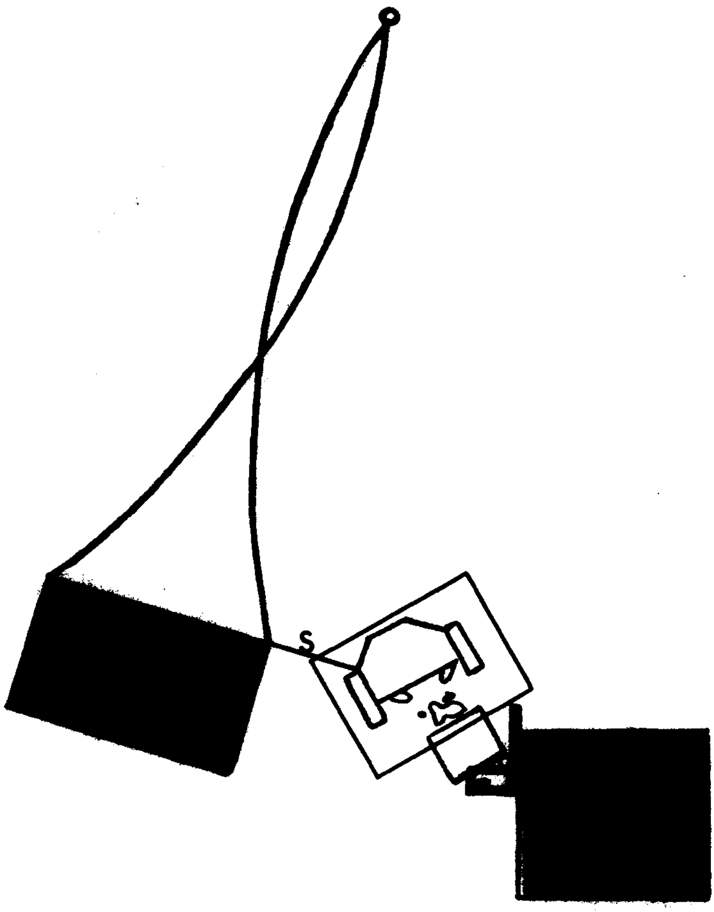

Figure 5. Experimental set-up. The details in Figure 4 are within the frame. A steel plate (S) is attached to the pendulum.

Radiographic measurements

A line (a in Figure 6) was drawn on the radiograph of the specimen along the vertical axis of the odontoid process. A second line (b in Figure 6) was drawn to indicate the direction of the impact by the pendulum. The angle (α in Figure 6) between the two lines was measured (odontoid-impact angle). A third line (c in Figure 6) was drawn from the base of the odontoid process (point A in Figure 6) perpendicular to the line b. The reference point A was chosen for comparison of the base of the odontoid process on the radiograph in all projections. The point was situated on the vertical line through the odontoid process 1 mm below the most superior parts of the superior articular facets of the axis.

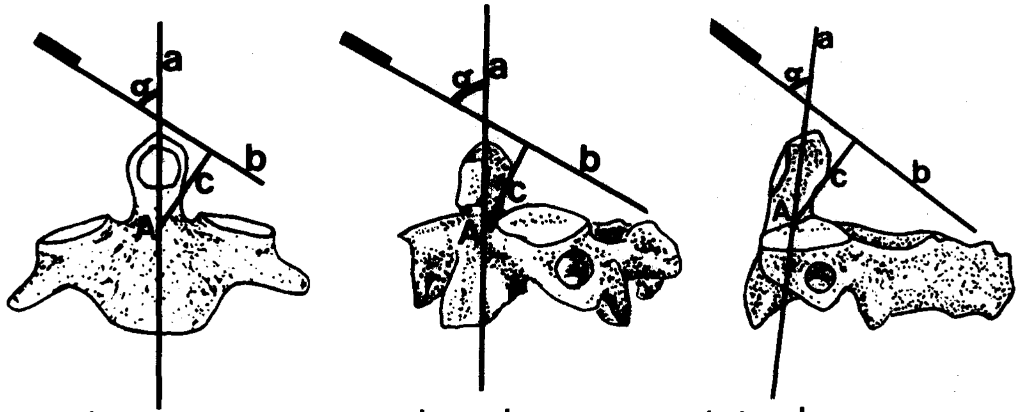

Figure 6. Frontal, anterolateral, and lateral views illustrating radiographic measurements of the axis.

a = central line through the odontoid process

b = line in the elongation of the inferior surface of the steel plate of the pendulum

c = the perpendicular from the base of the odontoid process to the line b, α = odontoid-impact angle, A = a point at the base of the odontoid process on the central line.

Theoretical calculations

The angle α indicates the direction of the impact (line b in Figure 6) in relation to the axis of the odontoid (line a in figure 6). The perpendicular distance (line c in Figure 6) indicates to which point on the line a the impact is directed. When the angle α is 0 the force is acting in axial compression of the odontoid process. With increasing angle α the compression force is decreasing. When the perpendicular is 0 and the angle α is restricted to a sector indicated ± α in Figure 7

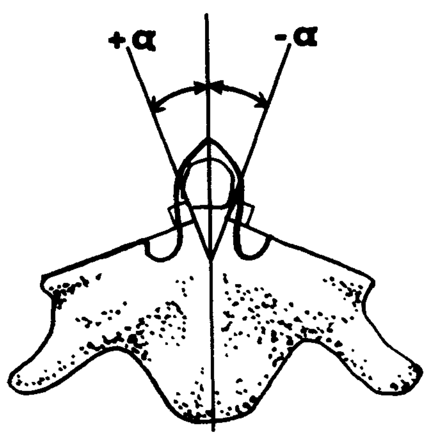

Figure 7. Frontal drawing of the axis illustrating the sector in which no significant bending force would be acting. The lines bordering the angles +α and −α (corresponding to line b in Figure 6) are perpendicular to the elongation of the superior articular facets of the axis.

there is no significant bending force acting at the base of the odontoid process; within this sector the impact is directed at a minimum of 90° to the articular facets of the axis. With increasing value of the perpendicular there is a proportional increase in the bending force, if the energy and the angle α are unaltered. In this investigation the angle α, the perpendicular, and the energy varied in the different experiments. These factors interact and it is reasonable to assume that their relative size has an influence on the result of the experiments.

Graphic design for determining the site of the blow to the head

Radiographs of a normal skull and upper cervical spine taken in the same projections as those used in the experiments were placed on the specimen radiographs in such a way that the two C II:s covered each other (Figure 8). The line b on the specimen radiograph was drawn out to the surface of the normal skull. The point in which the line b reached this skeletal point was approximated to be the place in which the blow would have struck the head. In this way the angle α and the perpendicular were the same in a drawing of the radiographed head and in the experiments. The data and the results of the experiments are summarized in Table 3.

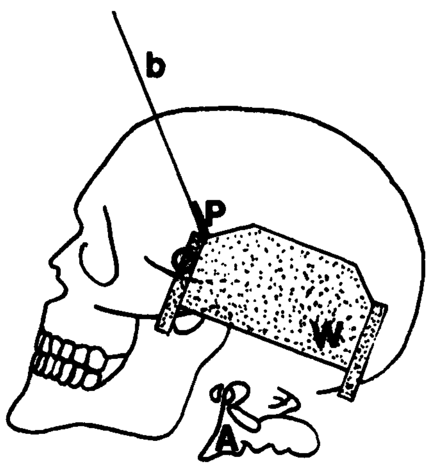

Figure 8. Graphic design for determining the site of the blow on the head.
P = steel plate on the pendulum
W = wooden block
O = block of oak tree
A = axis
b = line to the surface of the skull in the elongation of the inferior surface of the steel plate.

Table 3. Data relating to experiments on odontoid fractures

Experiment	α°	Perpendicular mm	Energy Nm	Position of the skull	Position of the impact	Result
1	74	77	70	Flexion	Posterior	Rupture of the interspinous ligaments and the apophyseal joint capsules C II – C III.
2	80	35	105	Flexion	Posterior	Rupture of the interspinous ligaments and the apophyseal joint capsules C II – C III.
3	80	52	120	Flexion	Posterior	Rupture of the interspinous ligaments, the apophyseal joint capsules, the posterior longitudinal ligament, and the posterior part of the disc C II – C III.
4	109	35	85	Extension	Anterior	Rupture of the anterior and posterior longitudinal ligaments and the disc C II – C III.
5	56	57	135	Flexion	Posterior	Rupture of the interspinous ligaments, the apophyseal joint capsules, the posterior longitudinal ligament, and the disc C II – C III.
6	21	12	135	Flexion	Posterior	Rupture of the interspinous ligaments, the apophyseal joint capsules, the posterior longitudinal ligament and the disc C II – C III.
7	18	1	135	Extension	Anterior	Jefferson fracture. Fracture of the arch of the axis.
8	34	24	105	Extension	Anterior	Jefferson fracture.
9	39	56	105	Extension	Anterior	Jefferson fracture. Rupture of the anterior atlanto-occipital membrane and the apical and alar ligaments.
10	44	14	105	Extension	Anterior	Odontoid fracture type D. Anterior longitudinal ligament seemed elongated. Posterior longitudinal ligament torn from the body of axis.
11	63	80	170	Neutral	Lateral	Decapitation between the occiput and the atlas.
12	56	137	135	Extension	Anterior	Rupture of the anterior and posterior longitudinal ligaments and the disc C II – C III. Partial rupture of the apophyseal joint capsules at the same level.
13	4	6	135	Flexion	Posterior	Bilateral fracture of the posterior arch of the atlas.
14	29	34	135	Flexion	Posterior	Jefferson fracture. Rupture of the transverse ligament at its right insertion.
15	25	29	170	Flexion	Posterior	Rupture of the apical, alar, and transverse ligaments and the tectorial membrane.

Table 3 cont. Data relating to experiments on odontoid fractures

Experiment	α°	Perpendicular mm	Energy Nm	Position of the skull	Position of the impact	Result
16	35	36	135	Flexion	Posterior	Odontoid fracture type D. Anterior longitudinal ligament torn from the body of the axis. Posterior longitudinal ligament seemed elongated.
17	65	28	135	Flexion	Anterior	Jefferson fracture. Rupture of the anterior atlanto-occipital membrane, the alar and the apical ligaments and the tectorial membrane.
18	52	17	135	Flexion	Anterior	Odontoid fracture type D. Anterior longitudinal ligament ruptured. Posterior longitudinal ligament torn from the body of the axis. Partial rupture of the posterior atlanto-occipital membrane.
19	36	9	105	Flexion	Posterior	Odontoid fracture type D. Anterior longitudinal ligament torn from the body of the axis. Posterior longitudinal ligament seemed elongated.
20	36	76	135	Extension	Anterior	Odontoid fracture type D. Rupture of the anterior longitudinal ligament. Posterior longitudinal ligament torn from the body of the axis.
21	43	26	135	Extension	Anterior	Partial rupture of the anterior atlanto-membrane and the alar ligaments.
22	55	12	135	Flexion	Anterior	Odontoid fracture type D. Anterior longitudinal seemed elongated. Posterior longitudinal ligament torn from the body of the axis.
23	60	68	410	Neutral	Antero-lateral	Decapitation between the occiput and the atlas. Rupture of the anterior longitudinal ligament and the anterior part of the disc C II – C III.
24	58	23	170	Flexion	Antero-lateral	Partial rupture of the anterior atlanto-occipital membrane. Rupture of one of the alar ligaments (contralateral to the impact).
25	14	11	205	Neutral	Postero-lateral	Rupture of the transverse ligament.
26	35	13	170	Flexion	Antero-lateral	Odontoid fracture type B. Anterior longitudinal ligament seemed elongated. Posterior longitudinal ligament torn from the body of the axis.
27	40	17	205	Flexion	Lateral	Small fracture at the lateral border of the inferior articular facet of the atlas on the impact side.

Table 3 cont. Data relating to experiments on odontoid fractures

Experiment	α^{o}	Perpendicular mm	Energy Nm	Position of the skull	Position of the impact	Result
28	50	47	205	Flexion	Lateral	Compression fracture of the superior articular facet of the axis on the impact side.
29	40	6	170	Flexion	Lateral	Oblique fracture through the body and posterior arch of the axis.
30	27	21	240	Neutral	Antero-lateral	Jefferson fracture.
31	50	40	275	Neutral	Lateral	Hangman's fracture.
32	58	52	240	Flexion	Lateral	Odontoid fracture type A. Compression fracture on the anteromedial side of the occipital condyle (ipsilateral to the impact).
33	58	53	275	Neutral	Lateral	Odontoid fracture type A.
34	36	65	240	Neutral	Anterior	Jefferson fracture. Rupture of the anterior atlanto-occipital membrane, the alar, apical, and transverse ligaments.
35	64	63	260	Flexion	Lateral	Odontoid fracture type A.
36	72	61	310	Flexion	Lateral	Odontoid fracture type A. Jefferson fracture. Compression fracture on the anteromedial side of the occipital condyle (ipsilateral to the impact).
37	51	53	240	Neutral	Anterior	Odontoid fracture type D. Total separation of the specimen (all ligaments ruptured at the level of the fracture).
38	62	48	225	Neutral	Anterior	Odontoid fracture type D. Bilateral fracture of the posterior arch of the atlas. Total separation of the specimen (all ligaments ruptured at the level of the fracture).
39	54	44	240	Neutral	Antero-lateral	Odontoid fracture type B. Anterior longitudinal ligament seemed elongated. Posterior longitudinal ligament torn from the body of the axis.
40	60	26	310	Neutral	Antero-lateral	Fracture of the skull base at the insertion of the anterior atlanto-occipital membrane (Osteoporosis).
41	44	30	240	Flexion	Antero-lateral	Odontoid fracture type B. Anterior longitudinal ligament seemed elongated. Posterior longitudinal ligament torn from the body of the axis.

PRELIMINARY STUDY I

The aim of this study was to test a) earlier presented theories on the fracture mechanism of odontoid fractures and, hopefully, b) to produce fracture of the odontoid process. A preliminary study of 16 experiments was performed with an impact mainly in anterior or posterior direction.

Set-up of the specimen

In 15 experiments the specimen was placed so that the impact from the pendulum acted in the sagittal plane through the skull, atlas and axis. In 1 experiment the impact acted perpendicular to this plane. In 6 experiments the impact was anterior, in 9 posterior. The skull was held in maximum extension when it was anterior, in maximum flexion when it was posterior.

Results of the preliminary study I

Experiments 1, 2 and 3: These experiments were performed in order to test the theories, previously cited, by Plaut (1938), and Howorth and Petrie (1964). An attempt was made to direct the impact as nearly horizontal as possible in the sagittal plane. The angle α was 74, 80 and 80°, the perpendicular 77, 35 and 52 mm, and the energy 70, 105 and 120 Nm respectively. The skull was held in flexion. The impact corresponded to a blow on the posterior part of the head (Figure 9). The result was a hyperflexion injury (Figure 10). Ruptures occurred in the interspinous ligaments and the joint capsules of the apophyseal joints; in Experiment 3, also in the posterior longitudinal ligament and the posterior part of the disc between the axis and C III.

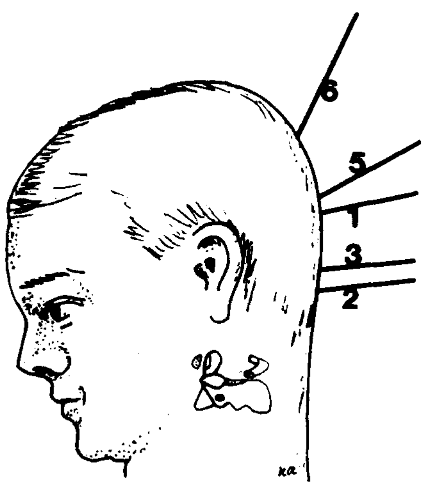

Figure 9. Drawing illustrating the direction of the impact in Experiments 1, 2, 3, 5, and 6.

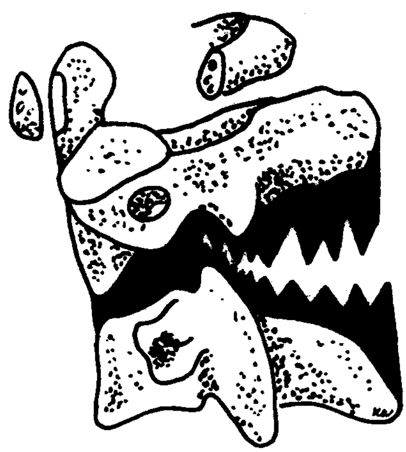

Figure 10. Drawing illustrating the hyperflexion injury (rupture of the interspinous ligaments) in Experiments 1, 2, 3, 5, and 6.

Experiment 4: This experiment was performed in order to test the influence of a horizontal shear applied to the anterior part of the skull. The angle α was 109°, the perpendicular 35 mm, and the energy 85 Nm. The skull was held in extension. The impact corresponded to a blow on the chin (Figure 11). The result was a hyperextension injury between the axis and C III with rupture of the anterior longitudinal ligament, the disc and the posterior longitudinal ligament (Figure 12).

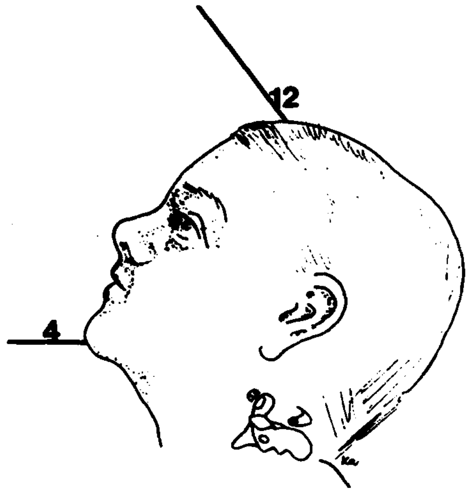

Figure 11. Drawing illustrating the direction of the impact in Experiments 4 and 12.

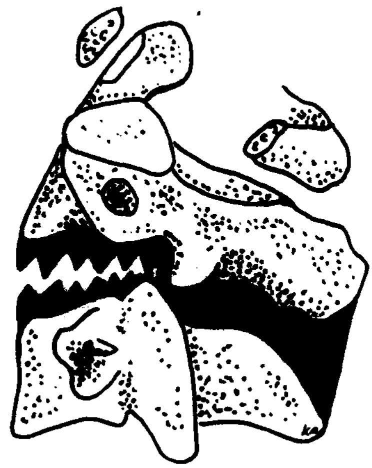

Figure 12. Drawing illustrating the hyperextension injury (rupture of the disc and anterior and posterior longitudinal ligaments) in Experiments 4 and 12.

Experiments 5 and 6: The object of these experiments was to test the influence of an increasing flexion force between the occiput and the cervical spine. It was postulated that this could be achieved by changing the direction, point of application and energy of the impact. The angle α was 56 and 21°, the perpendicular 57 and 12 mm, and the energy 135 and 135 Nm respectively. The skull was held in flexion. The impact corresponded to a blow on the posterior part of the head (Figure 9). The result was a hyperflexion injury between the axis and C III (Figure 10). Ruptures occurred in the interspinous ligaments, the joint capsules of the apophyseal joints, the posterior longitudinal ligament and the disc between the axis and C III.

Comment: In these 6 experiments no odontoid fracture was produced. It was concluded that the resultant force in the upper cervical spine was a distraction force. This force was larger than the strength in the ligaments between the axis and C III.

Question: Would a compressive force added to the impact change the pattern of injury?

Experiment 7: The object of this experiment was to test an impact in almost vertical compression. The angle α was 18°, the perpendicular 1 mm and the energy 135 Nm. The skull was held in extension. The impact corresponded to a blow on the vertex of the head (Figure 13). This resulted in fractures involving both the anterior and posterior arches of the atlas (Jefferson fracture, Figure 14). In addition, there were also fractures of the arch of the axis.

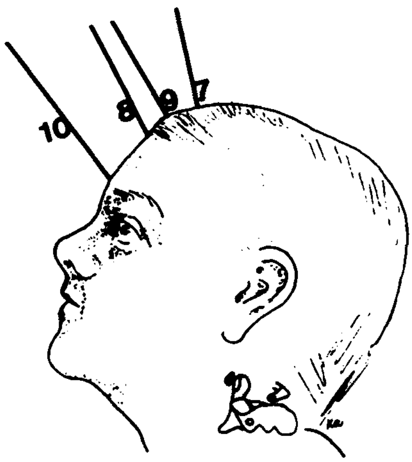

Figure 13. Drawing illustrating the direction of the impact in Experiments 7, 8, 9, and 10.

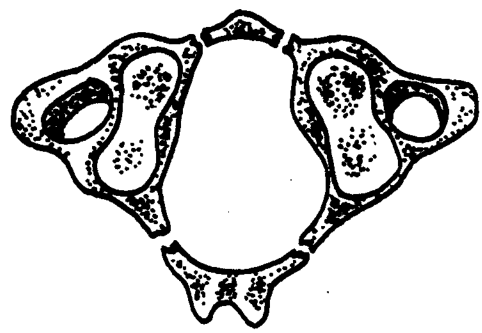

Figure 14. Schematic superior view of a Jefferson fracture of the atlas which was the result in Experiments 7, 8, and 9.

Experiments 8 and 9: The object of these experiments was to decrease the compressive force. The angle α was 34 and 39°, the perpendicular 24 and 56 mm, and the energy 105 and 105 Nm respectively. The skull was held in extension. The impact corresponded to a blow high on the forehead (Figure 13). These experiments also resulted in Jefferson fractures (Figure 14). In addition, in Experiment 9, the anterior atlanto-occipital membrane and the apical and alar ligaments were ruptured.

Experiment 10: The object of this experiment was to further decrease the compressive force. The angle α was 44°, the perpendicular 14 mm, and the energy 105 Nm. The head was held in extension. The impact corresponded to a blow low on the forehead (Figure 13). In this experiment the first fracture of the odontoid process was obtained (Figures 15 and 16). The fracture passed through the superior part of the body of the axis and the medial part of the superior articular facets (type D fracture). The anterior longitudinal ligament seemed elongated and the posterior longitudinal ligament was torn from the body of axis.

Experiment 11: The object of this experiment was to observe the influence of a lateral bending force. The angle α was 63°, the perpendicular 80 mm, and the energy 170 Nm. The skull was held in neutral position. The impact corresponded to a blow very high on the lateral side of the head

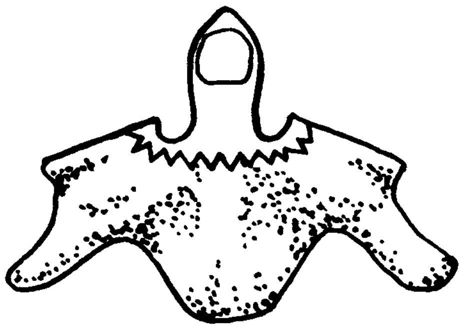

Figure 15. Schematic anterior view of the type D odontoid fracture which occurred in Experiments 10, 16, 18, 19, 20, 22, 37, and 38.

Figure 16. The axis in Experiment 10. Type D fracture.

(Figure 17). This experiment resulted in decapitation with ruptures of all ligaments and soft tissues between the occiput and the cervical spine.

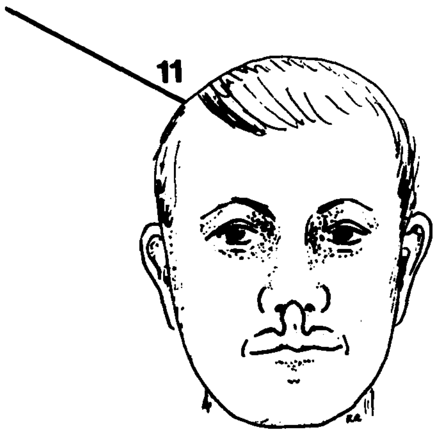

Figure 17. Drawing illustrating the direction of the impact in Experiment 11.

Experiment 12: The object of this experiment was to increase the extension force compared to Experiment 10 in which a fracture of the odontoid process was obtained. It was postulated that this could be achieved by increasing the angle α, the perpendicular and the energy. The angle α was 56°, the perpendicular 137 mm and the energy 135 Nm. The skull was held in extension. The impact corresponded to a blow between the forehead and the vertex (Figure 11). A hyperextension injury (Figure 12) occurred between axis and C III with rupture of the anterior longitudinal ligament, the disc and the posterior longitudinal ligament. The joint capsules of the apophyseal joints were partially ruptured.

Experiments 13 and 14: The object of these experiments was to test a decreasing vertical compression applied to the posterior part of the skull. The angle α was 4 and 29°, the perpendicular 6 and 34 mm, and the energy 135 and 135 Nm respectively. The skull was held in flexion. The impact corresponded to a blow on the upper part of the occiput (Figure 18). Experiment 13 resulted in a bilateral fracture of the posterior arch of the atlas, Experiment 14 in a Jefferson fracture (Figure 14). In the latter experiment the transverse ligament was ruptured at the right insertion.

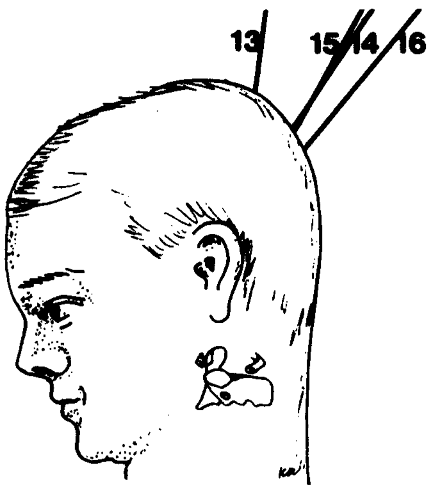

Figure 18. Drawing illustrating the direction of the impact in Experiments 13, 14, 15, and 16.

Experiments 15 and 16: The object of these experiments was to further decrease the compressive component of the impact. The angle α was 25 and 35°, the perpendicular 29 and 36 mm, and the energy 170 and 135 Nm respectively. The skull was held in flexion. The impact corresponded to a blow on the upper part of the occiput (Figure 18). Experiment 15 resulted in rupture of the apical, alar and transverse ligaments; all had ruptured in the substance. The tectorial membrane was avulsed from the base of the skull. Experiment 16 resulted in a type D odontoid fracture (Figure 15). The anterior longitudinal ligament was torn from the body of axis. The posterior longitudinal ligament seemed elongated.

Summary of the preliminary study I

In this preliminary study of 16 experiments, all specimens but one were struck anteriorly or posteriorly. Two odontoid fractures were produced, 1 by an anterior and 1 by a posterior impact. Both fractures were of type D, passing through the superior part of the body of the axis and the medial part of the superior articular facets of the axis. There were 4 Jefferson fractures and 1 bilateral fracture of the posterior arch of the atlas. In 5 experiments there was a hyperflexion and in 2 a hyperextension injury to the ligaments between the axis and C III. In 1 specimen the ligaments between the occiput and the upper cervical spine had ruptured. In the single specimen, which was struck from the side, there was a decapitation.

Conclusions of the preliminary study I

This preliminary study demonstrated that a fracture of the odontoid process could not be produced by a simple shear horizontally in the sagittal plane. Neither could such a fracture be produced by a blow forcing the skull into hyperflexion or hyperextension. It seemed as if the odontoid process and the uppermost cervical spine were stronger in their resistance to these type of impact to the skull than the lower part of the cervical spine (in these experiments represented by the junction between the axis and C III, the latter being the level at which the specimens were fixed). The energy escaped from the odontoid process and resulted in movements above the atlas or below the axis.

The odontoid process was fractured in 2 specimens when the skull had been subjected to an impact which was a combination of a horizontal shear and a vertical compression arranged so that it gave minimal movements above the atlas and below the axis.

DEFINITE STUDY I

Set-up of the specimen

In Experiments 17 – 22 the set-up was arranged according to conclusions of the preliminary study. The impact was anterior in 5 experiments, with the skull in flexion in 3 (17, 18, and 22) and in extension in 2 (20 and 21). In Experiment 19 the skull was struck posteriorly in flexion. In all experiments the impact was acting in the sagittal plane. The object of these experiments was to combine a horizontal shear and a vertical compression in order to produce fractures of the odontoid process and to find out if a variation in angle α, perpendicular and energy could influence the level of the odontoid fracture.

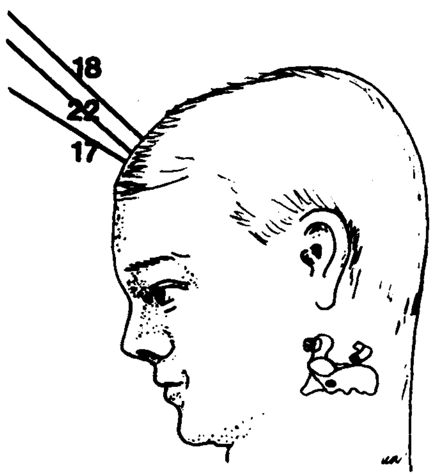

Figure 19. Drawing illustrating the direction of the impact in Experiments 17, 18, and 22.

Results of definite study I

Experiments 17, 18, and 22: The angle α was 65, 52 and 55°, the perpendicular 28, 17 and 12 mm, and the energy 135, 135 and 135 Nm respectively. The skull was held in flexion. The impact corresponded to a blow between the forehead and the vertex (Figure 19). Experiment 17 resulted in a Jefferson fracture (Figure 14) and rupture of the anterior atlanto-occipital membrane, the apical and alar ligaments, and the tectorial membrane. Experiments 18 and 22 resulted in a type D odontoid fracture (Figure 15). The anterior longitudinal ligament was ruptured in Experiment 18 and seemed elongated in Experiment 22; in these 2 experiments the posterior longitudinal ligament was torn from the body of axis.

Experiments 20 and 21: The angle α was 36 and 43°, the perpendicular 76 and 26 mm, and the energy 135 and 135 Nm respectively. The skull was held in extension. The impact corresponded to a blow between the forehead and the vertex in Experiment 20 and on the forehead in Experiment 21 (Figure 20). Experiment 20 resulted in a type D odontoid fracture (Figure 15). The anterior longitudinal ligament was ruptured while the posterior longitudinal ligament was torn from the body of axis. Experiment 21 resulted in a partial rupture in the substance of the anterior atlanto-occipital membrane and the alar ligaments.

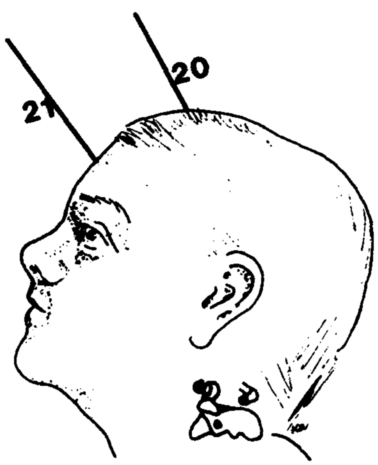

Figure 20. Drawing illustrating the direction of the impact in Experiments 20 and 21.

Experiment 19: The angle α was 36°, the perpendicular 9 mm, and the energy 105 Nm. The skull was held in flexion. The impact corresponded to a blow on the mid-portion of the occiput (Figure 21). The result was a type D odontoid fracture (Figures 15 and 22). The anterior longitudinal ligament was torn from the body of axis. The posterior longitudinal ligament seemed elongated.

Comments to preliminary study I and definite study I

In the 22 experiments performed, 6 odontoid fractures were produced. The energy, the direction of the impact, the degree of compression and the position of the skull (flexion-extension) were changed. When a fracture of the odontoid process was obtained it was always of type D, involving the superior part of the body of the axis and the medial part of the superior articular facets (Figure 15). In order to get higher fractures in the odontoid process two new set-ups were tested in a second preliminary study.

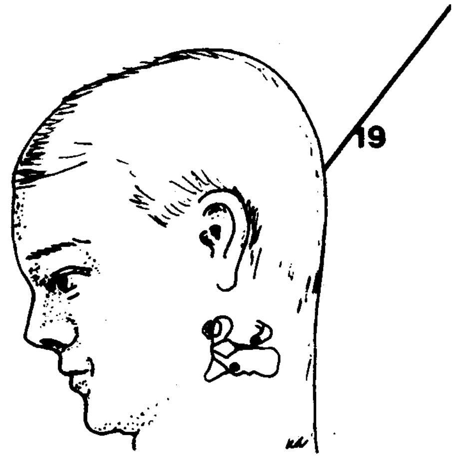

Figure 21. Drawing illustrating the direction of the impact in Experiment 19.

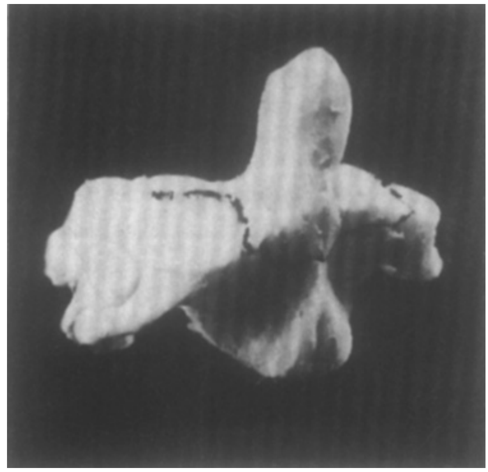

Figure 22. The axis in Experiment 19. Type D fracture.

PRELIMINARY STUDY II

The object of this study was to test a new hypothesis. Could it be possible to produce fractures of the odontoid process at higher levels by changing the direction of the impact in the horizontal plane? Ten specimens were used. In 5, the impact was directed at 45° to the sagittal plane (anterolateral impact in 4 and posterolateral in 1); in another 5 experiments, the impact was directed at 90° to the sagittal plane (lateral impact).

Anterolateral and posterolateral impact

Experiments 23, 24 and 26: The angle α was 60, 58 and 35°, the perpendicular 68, 23 and 13 mm, and the energy 410, 170 and 170 Nm respectively. The skull was held in neutral position in Experiment 23 and in flexion in Experiments 24 and 26. The impact corresponded to a blow on the lateral side on the forehead (Figures 23 and 24). Experiment 23, in which the energy was largest, resulted in a decapitation with rupture of all ligaments between the occiput and the cervical spine. In addition, there was a rupture of the anterior longitudinal ligament and the anterior part of the disc between the axis and C III. Experiment 24 resulted in a partial rupture of the anterior atlanto-occipital membrane and a complete rupture of the alar ligament (contralateral to the impact). Experiment 26, in which the compression seemed to be largest, resulted in a type B odontoid fracture (Figures 25 and 26) with the fracture line passing through the upper-most part of the body of the axis but not entering into the superior articular facets. The anterior longitudinal ligament seemed elongated. The posterior longitudinal ligament was torn from the body of axis.

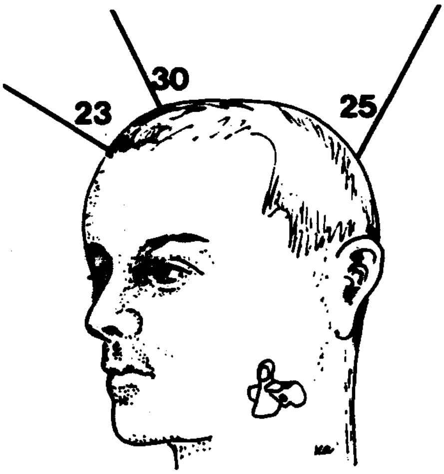

Figure 23. Drawing illustrating the direction of the impact in Experiments 23, 25, and 30.

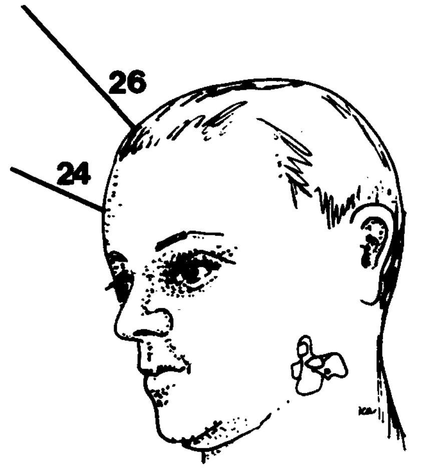

Figure 24. Drawing illustrating the direction of the impact in Experiments 24 and 26.

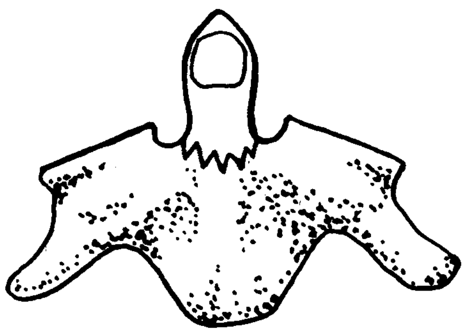

Figure 25. Schematic anterior view of the type B odontoid fracture which occurred in Experiments 26, 39, and 41.

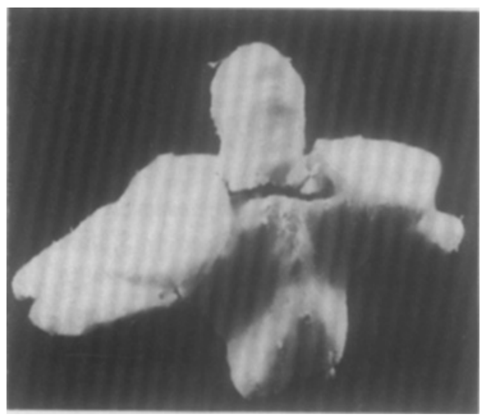

Figure 26. The axis in Experiment 26. Type B fracture.

Experiment 30: The object was to further increase the compressive effect of the impact. The angle α was 27°, the perpendicular 21 mm and the energy 240 Nm. The skull was held in neutral position. The impact corresponded to a blow on the lateral side of the head between the forehead and the vertex (Figure 23). This experiment resulted in a Jefferson fracture (Figure 14).

Experiment 25: The object was to direct the impact to the posterolateral side of the skull when combining a horizontal shear and a vertical compression. The angle α was 14°, the perpendicular 11 mm and the energy 205 Nm. The skull was held in neutral position. The impact corresponded to a blow high on the posterolateral side of the occiput (Figure 23). This resulted in a rupture of the transverse ligament in its substance. The alar ligaments were unaffected. The atlas could be subluxated anteriorly when the head was flexed. Measured on the radiographs the subluxation was 5 mm between the anterior arch of the atlas and the odontoid process.

Lateral impact

From Experiment 11 it was learnt that a blow too high on the skull, as indicated by a large perpendicular (80 mm), resulted in a decapitation. It was decided to subject the specimen to an impact which would correspond to a blow on the lateral side of the skull some centimetres over the ear (Figures 27 and 28). In 5 experiments, the degree of compression was varied as indicated by the angle α and the perpendicular.

The object of these experiments was to produce a fracture of the odontoid process at a higher level than earlier.

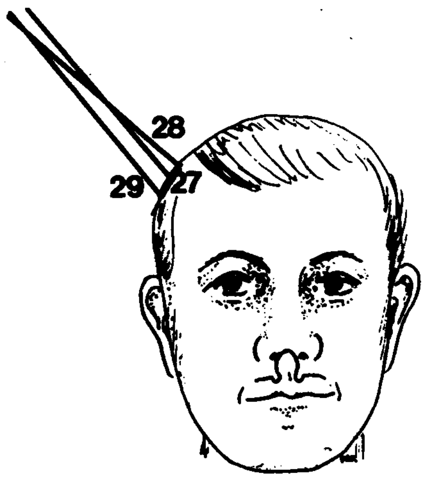

Figure 27. Drawing illustrating the direction of the impact in Experiments 27, 28, and 29.

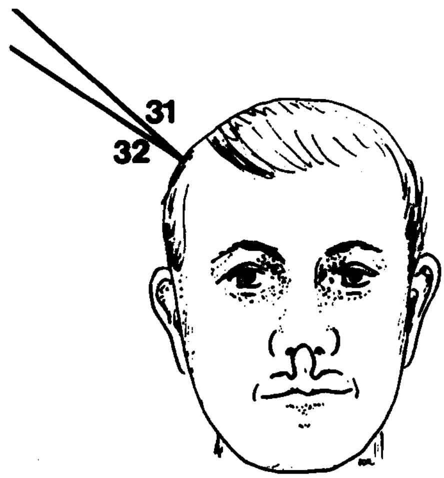

Figure 28. Drawing illustrating the direction of the impact in Experiments 31 and 32.

Experiment 27: The angle α was 40°, the perpendicular 17 mm, and the energy 205 Nm. The skull was held in flexion. A small fracture occurred through the lateral border of the inferior articular facet of the atlas, ipsilateral to the impact.

Experiment 28: The object of this experiment was to decrease the compressive effect of the impact. The angle α was 50°, the perpendicular 47 mm, and the energy 205 Nm. The skull was held in flexion. The result was a compression fracture of the superior articular facet of the axis, ipsilateral to the impact.

Experiment 29: The object of this experiment was to direct the impact towards the base of the odontoid process. The angle α was 40° (the same as in Experiment 27), the perpendicular 6 mm, and the energy 170 Nm. The skull was held in flexion. The result was a fracture of axis passing from the odontoid base, ipsilateral to the impact, down obliquely through the body to the contralateral side (Figure 29). In addition, the posterior arch of the axis was fractured ipsilateral to the impact (Figure 29 B).

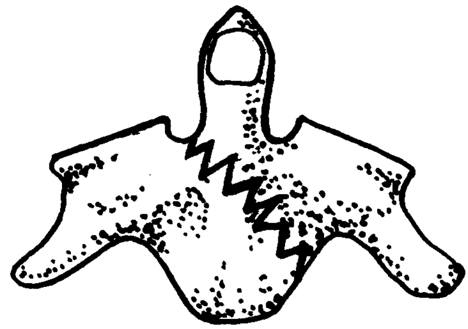

Figure 29. A: Schematic frontal view of the fracture which occurred in Experiment 29.

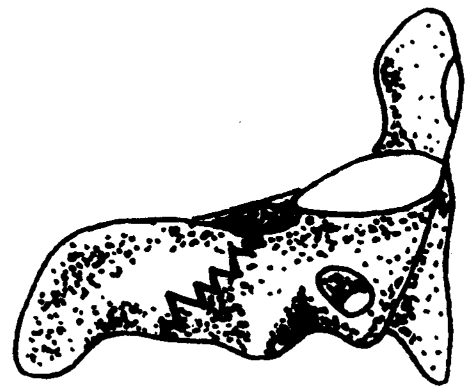

Figure 29. B: Schematic lateral view of the fracture which occurred in Experiment 29.

Experiment 31: The object of this experiment was to decrease the compressive effect of the impact compared to Experiment 29. The angle α was 50°, the perpendicular 40 mm, and the energy 275 Nm. The skull was held in neutral position. This resulted in bilateral fracture of the arch of the axis behind the superior and in front of the inferior articular facets (Figure 30); in addition, the anterior longitudinal ligament, the disc between axis and C III, and the posterior longitudinal ligament were ruptured (so called hangman's fracture).

Figure 30. Drawing of the fracture that occurred in Experiment 31 (hangman's fracture).

Experiment 32: The object of this experiment was to further decrease the compressive effect of the impact. The angle α was 58°, the perpendicular 52 mm, and the energy 240 Nm. The skull was held in flexion. The result was a type A odontoid fracture (Figures 31 and 32). The fracture line passed through the isthmus of the odontoid process above the insertion of the accessory ligaments. In addition, there was a small compression fracture on the anteromedial side of the occipital condyle ipsilateral to the impact.

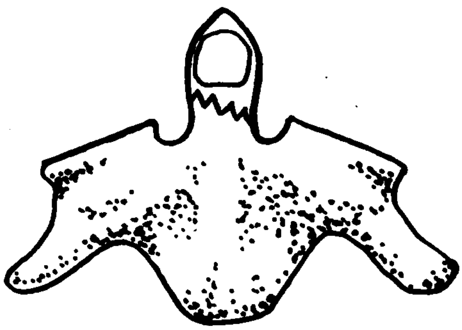

Figure 31. Schematic anterior view of the type A odontoid fracture which occurred in Experiments 32, 33, 35, and 36.

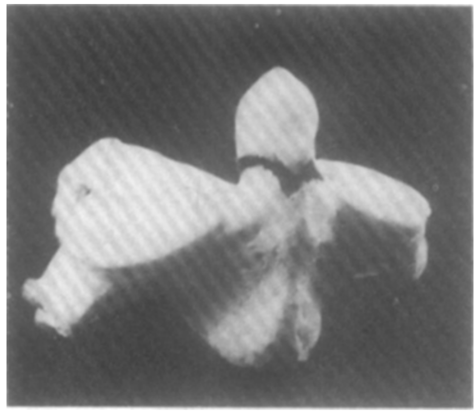

Figure 32. The axis in Experiment 32. Type A fracture.

Conclusions of the preliminary study II

It seemed possible to produce fractures at a higher level through the odontoid process by changing the direction of the impact in the horizontal plane. The distraction and compression forces in the specimens had to be balanced so that only minor movement occurred in flexion, extension and lateral bending. The impact had further to be applied in such a way that the atlas could escape without being caught between the occiput and the axis.

DEFINITE STUDY II

Anterior impact

Experiments 34, 37, and 38: The object was to produce type D odontoid fractures (Figure 15) with the skull held in neutral position. The influence of a larger energy than had been used in the previous experiments with an anterior impact was also tested. The angle α was 36, 51, and 62°, the perpendicular 65, 53, and 48 mm, and the energy 240, 240, and 225 Nm respectively. The skull was held in neutral position. In Experiment 34, in which the impact corresponded to a blow near the vertex (Figure 33), the result was a Jefferson fracture (Figure 14) and rupture of the anterior atlanto-occipital membrane, the alar, apical and transverse ligaments. In Experiments 37 and 38, in which the impact corresponded to a blow more anteriorly (Figure 33), resulted in type D odontoid fractures. In the 2 experiments in which an odontoid fracture was produced all ligamentous structures between the atlas and the axis had ruptured at the level of the fracture. Moreover, in Experiment 38, there was a bilateral fracture of the posterior arch of the atlas.

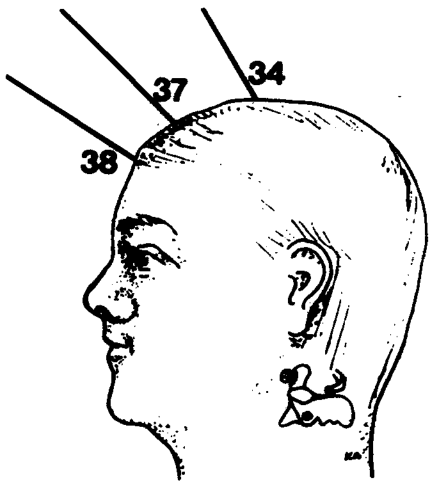

Figure 33. Drawing illustrating the direction of the impact in Experiments 34, 37, and 38.

Anterolateral impact

The impact was directed at 45° to the sagittal plane.

Experiments 39, 40, and 41: The object was to produce type B odontoid fractures (Figure 25) and to test the influence of an increased amount of energy in the impact compared to Experiments 26 in which a type B fracture had been produced. The angle α was 54, 60, and 44°, the perpendicular 44, 26, and 30 mm, and the energy was 240, 310, and 240 Nm respectively. The skull was held in neutral position in Experiments 39 and 40 and in flexion in Experiment 41. The impact corresponded to a blow high on the lateral side of the forehead (Figures 34 and 35) in 2 experiments (39 and 41) and to a blow on the lateral side of the forehead just over the eyebrow (Figure 34) in 1 experiment (40). The experiment with the largest energy (40) resulted in a fracture of the skull base at the insertion of the anterior atlanto-occipital membrane. The bone in this specimen also proved to be soft as in osteoporosis. The other two experiments resulted in type B odontoid fractures. The anterior longitudinal ligament seemed elongated and the posterior longitudinal ligament was torn from the body of the axis.

Lateral impact

The impact was directed at 90° to the sagittal plane.

Experiments 33, 35, and 36: The object was to produce type A odontoid fractures (Figure 31). In Experiment 36 the influence of an increased energy was also tested. The angle α was 58, 64,

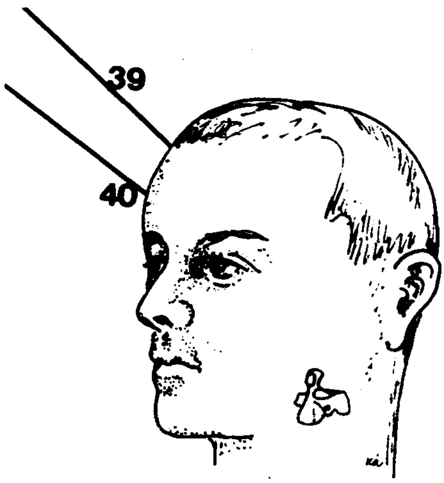

Figure 34. Drawing illustrating the direction of the impact in Experiments 39 and 40.

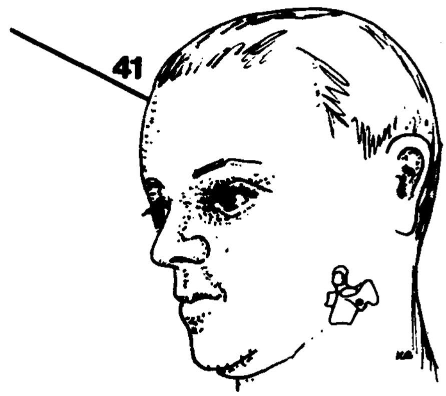

Figure 35. Drawing illustrating the direction of the impact in Experiment 41.

and 72°, the perpendicular 53, 63, and 61 mm, and the energy 275, 260, and 310 Nm respectively. In Experiment 33 the skull was held in neutral position, in the other 2 in flexion. The impact corresponded to a blow on the lateral side of the skull (Figure 36). All experiments resulted in a type A odontoid fracture. In Experiment 36, in which the energy was the largest, a Jefferson fracture (Figure 14) also occurred as well as a small compression fracture on the medial side of the occipital condyle ipsilateral to the impact.

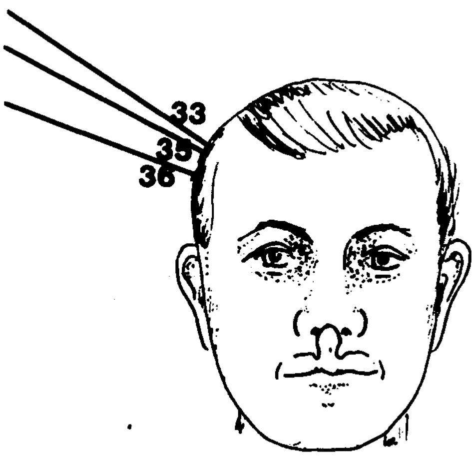

Figure 36. Drawing illustrating the direction of the impact in Experiments 33, 35, and 36.

DEFINITE STUDY III

A study of the arterial supply to the odontoid process in relation to fracture was also of interest (page 51). For this purpose experimental fractures of the odontoid process had to be produced. The set-up was arranged according to the earlier experiments. The previously performed experiments had shown how to produce fractures of the odontoid process, and as the radiographic procedure of the set-up was laborious it was omitted. Before the pendulum was allowed to hit the specimen, the pendulum was pressed against the skull and the movements observed. Adjustment was then made to balance the distraction and compression forces. Attempts were made to prevent flexion, extension, and lateral bending in the specimen and to allow the atlas to be mobile and thus escape from the compression between the occiput and the axis.

In this way it was possible to produce 15 additional fractures of the odontoid process out of 26 experiments (5 type A, 5 type B, and 5 type D fractures). The injuries in these experiments were not studied by dissection as the arterial supply to the odontoid process then would have been destroyed as well as the relation of this supply to the experimental fracture.

The main reason why there were 11 failures of 26 experiments was the difficulty in fixing the specimens. As the purpose in this part of the investigation was to study the arterial supply to the odontoid process these specimens had to have more soft tissues left (muscles and vessels) than was necessary in studying the fracture mechanism. This made a rigid fixation difficult.

DISCUSSION

Testing of earlier hypothesis

Opinions differ as to the fracture mechanism in odontoid process fractures. The most advocated theories imply that a violent movement causes the fracture. Theories on hyperflexion, hyperextension, rotation, and horizontal shear have been discussed (Jefferson 1920, Wüsthoff 1924, Osgood and Lund 1928, Plaut 1938, Amyes and Anderson 1956, Blockey and Purser 1956, Hipp and Keyl 1963, Howorth and Petrie 1964, J. Böhler 1965, Kattan 1975). The influence of a vertical compression force has also been debated (Sir Ludwig Guttmann 1976, Sköld 1978).

Some of these theories were tested. Experiments were made with hyperflexion, hyperextension, and a horizontal shear. These experiments resulted in ligamentous injuries between the axis and C III (the latter fixed). There was no odontoid fracture. Experiments on vertical compression resulted in atlas fractures. There was no odontoid fracture.

Own hypothesis

Apparently a new hypothesis had to be made. Could a combination of a horizontal shearing force and a vertical compression force result in an odontoid fracture? The experiments carried out to test this hypothesis proved its validity.

Analysis of the fracture mechanism

Thirty fractures of the odontoid process were produced. Fifteen of these were produced in the part of the study in which the point of application of the impact and the angle between the impact and the long axis of the odontoid process were carefully calculated and registered. The relation of the direction of the impact to the sagittal plane determined the level of the odontoid fracture that occurred. All 8 odontoid fractures produced by an impact straight in the sagittal plane were of type D, 6 being produced by an anterior and 2 by a posterior impact. All 3 fractures produced by an anterolateral impact, 45° to the sagittal plane, were of type B and all 4 fractures produced by a lateral impact, 90° to the sagittal plane, were of type A. The impact to the specimen corresponded in the type D fractures to a blow on the forehead, between the forehead and the vertex, or on the mid-portion of the occiput (Figures 37 A, B, and C), in the type B fractures, to a blow high on the lateral side of the forehead (Figures 37 D and E), and in the type A fractures, to a blow above the ear (Figure 37 F).

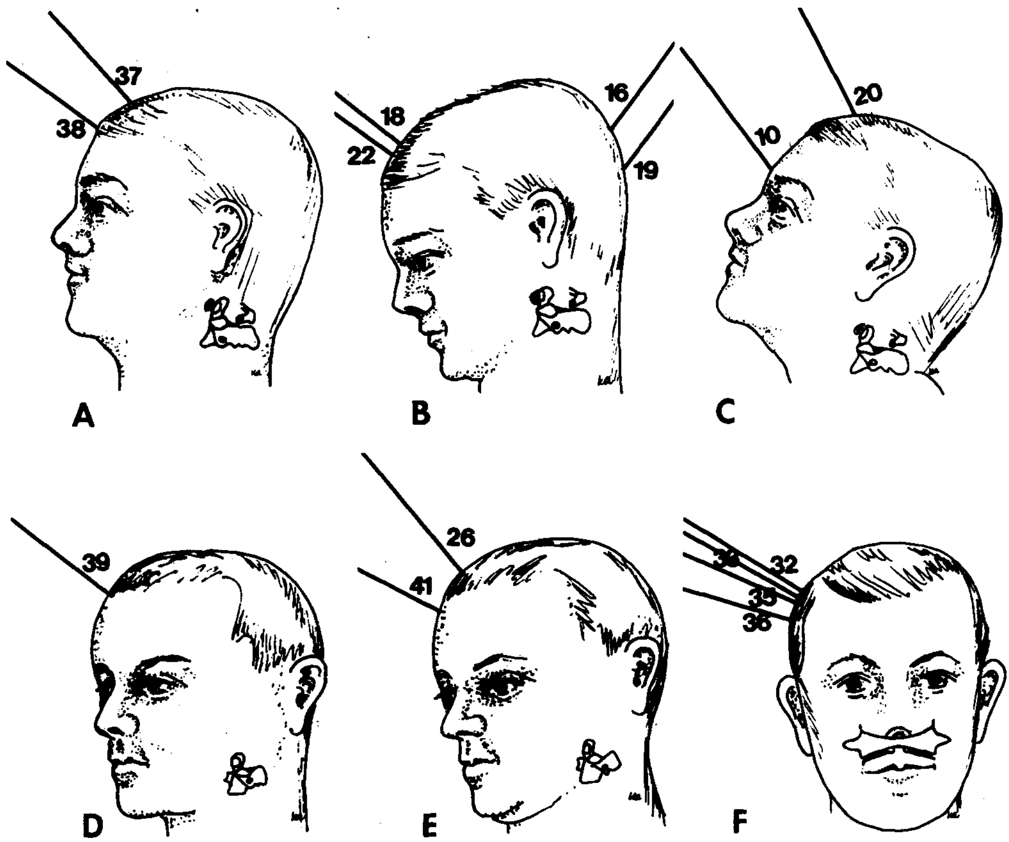

Figure 37. Drawings illustrating the directions of the impact in the experiments in which odontoid fractures were produced. A: Lateral aspect, neutral position. B: Lateral aspect, flexion. C: Lateral aspect, extension. D: Anterolateral aspect, neutral position. E: anterolateral aspect, flexion. F: Frontal aspect.

In the experiments in which odontoid fractures were produced, there was a common denominator, which was the odontoid-impact angle (Tables 4, 5, 6, and 7). This angle was of medium size in almost all of the experiments: some exceptions could be explained by their length of perpendicular. These findings indicate that odontoid fractures are the result of a combination of a horizontal shear and a vertical compression acting on the upper cervical spine. Fractures of the odontoid process were produced only when the direction of the forces were arranged in such a way that no or only minimal flexion, extension, and lateral bending occurred in the atlanto-occipital joints and the upper cervical spine. This contradicts the opinion that odontoid fractures are produced by hyperflexion or hyperextension (Jefferson 1920, Wüsthoff 1923, Amyes and Anderson 1956, Blockey and Purser 1956, J. Böhler 1965, Mouradian et al 1978). The present findings are similar to the observation made in a study on the fracture mechanism of the talus. The talus like the axis is situated in a chain of bones and is fractured indirectly by a blow. It was impossible to fracture the talus when there was any significant movement in the set-up, but a fracture was produced when no or only minor movement occurred (Peterson et al. 1976).

Anatomical structures responsible for transmission of the force

With regard to which structures are responsible for the transmission of the forces to the odontoid process most structures in this region may simultaneously become involved. The same conclusion was made by Schatzker et al. (1971). In a lateral impact the massa lateralis of the atlas may contribute in fracturing the odontoid process. This was also suggested by Mouradian et al. (1978). In lateral impact the direction of the force, when producing odontoid fractures, was approximately parallel to the joint spaces of the ipsilateral atlanto-occipital joint and the contralateral atlanto-axial joint. (Figure 37 F). Also the occipital condyle may act as an impact body. In 2 of the experiments with a lateral impact there was a small compression of the anteromedial side of the occipital condyle ipsilateral to the impact. These small compressions may indicate that the occipital condyles had struck the odontoid process.

Displacement of the fracture

The fracture lines were similar in their sloping in all experiments which resulted in odontoid fractures. The sloping was in the direction of the impact. Excluding 2 experiments in which there was a total separation of the specimen it was found that the fracture could be dislocated or angulated in the direction of the impact, whereas it was stable when the occiput-atlas and odontoid process were moved in the direction against the impact (Figures 38, 39, and 40). This was due to a) the sloping of the fracture and b) the arrangement of the associated ligament injuries. In fractures produced by an anterior impact, the anterior longitudinal ligament appeared elongated and in 2 specimens it was even ruptured. The posterior longitudinal ligament was intact in length but torn from the posterior aspect of the body of the axis. Similarly, in the 2 fractures produced by a posterior impact, the posterior longitudinal ligament appeared elongated whereas the anterior longitudinal ligament seemed to be normal in length but torn from the

Table 4. Experiments for production of odontoid fractures using an anterior impact. Experiments arranged with respect to the odontoid-impact angle (α).

Experiment	α°	Perpendicular mm	Energy Nm	Result
7	18	1	135	Jefferson fracture. Fracture of the arch of the axis.
8	34	24	105	Jefferson fracture.
34	36	65	240	Jefferson fracture. Rupture of the anterior atlanto-occipital membrane, the alar, apical, and transverse ligaments.
20	36	76	135	Odontoid fracture type D. Rupture of the anterior longitudinal ligament torn from the body of the axis.
9	39	56	105	Jefferson fracture. Rupture of the anterior atlanto-occipital membrane and the apical and alar ligaments.
21	43	26	135	Partial rupture of the anterior atlanto-occipital membrane and the alar ligaments.
10	44	14	105	Odontoid fracture type D. Anterior longitudinal ligament seemed elongated. Posterior longitudinal ligament torn from the body of the axis.
37	51	53	240	Odontoid fracture type D. Total separation of the specimen (all ligaments ruptured at the level of the fracture).
18	52	17	135	Odontoid fracture type D. Anterior longitudinal ligament ruptured. Posterior longitudinal ligament torn from the body of the axis. Partial rupture of the posterior atlanto-occipital membrane.
22	55	12	135	Odontoid fracture type D. Anterior longitudinal ligament seemed elongated. Posterior longitudinal ligament torn from the body of the axis.
12	56	137	135	Rupture of the anterior and posterior longitudinal ligaments and the disc C II – C III. Partial rupture of the apophyseal joint capsules at the same level.
38	62	48	225	Odontoid fracture type D. Bilateral fracture of the posterior arch of the atlas. Total separation of the specimen (all ligaments ruptured at the level of the fracture.
17	65	28	135	Jefferson fracture. Rupture of the anterior atlanto-occipital membrane, the alar and the apical ligaments and the tectorial membrane.
4	109	35	85	Rupture of the anterior and posterior longitudinal ligaments and the disc C II – C III.

Table 5. Experiments for production of odontoid fractures using a posterior impact. Experiments arranged with respect to the odontoid-impact angle (α).

Experiment	α°	Perpendicular mm	Energy Nm	Result
13	4	6	135	Bilateral fracture of the posterior arch of the atlas.
6	21	12	135	Rupture of the interspinous ligaments, the apophyseal joint capsules, the posterior longitudinal ligament, and the disc C II – C III.
15	25	29	170	Rupture of the apical, alar, and transverse ligaments and the tectorial membrane.
14	29	34	135	Jefferson fracture. Rupture of the transverse ligament at its right insertion.
16	35	36	135	Odontoid fracture type D. Anterior longitudinal ligament torn from the body of the axis. Posterior longitudinal ligament seemed elongated.
19	36	9	105	Odontoid fracture type D. Anterior longitudinal ligament torn from the body of the axis. Posterior longitudinal ligament seemed elongated.
5	56	57	135	Rupture of the interspinous ligaments, the apophyseal joint capsules, the posterior longitudinal ligament, and the disc C II – C III.
1	74	77	70	Rupture of the interspinous ligaments and the apophyseal joint capsules C II – C III.
2	80	35	105	Rupture of the interspinous ligaments and apophyseal joint capsules C II – C III.
3	80	52	120	Rupture of the interspinous ligaments, the apophyseal joint capsules, the posterior longitudinal ligament, and the posterior part of the disc C II – C III.

Table 6. Experiments for production of odontoid fractures using an anterolateral impact. Experiments arranged with respect to the odontoid-impact angle (α).

Experiment	α°	Perpendicular mm	Energy Nm	Result
30	27	21	240	Jefferson fracture.
26	35	13	170	Odontoid fracture type B. Anterior longitudinal ligament seemed elongated. Posterior longitudinal ligament torn from the body of the axis.
41	44	30	240	Odontoid fracture type B. Anterior longitudinal ligament seemed elongated. Posterior longitudinal ligament torn from the body of the axis.
39	54	44	240	Odontoid fracture type B. Anterior longitudinal ligament seemed elongated. Posterior longitudinal ligament torn from the body of the axis.
24	58	23	170	Partial rupture of the anterior atlanto-occipital membrane. Rupture of one of the alar ligaments (contralateral to the impact).
40	60	26	310	Fracture of the skull base at the insertion of the anterior atlanto-occipital membrane. (Osteoporosis).
23	60	68	410	Decapitation between the occiput and the atlas. Rupture of the anterior longitudinal ligament and the anterior part of the disc C II – C III.

Table 7. Experiments for production of odontoid fractures with a l a t e r a l impact. Experiments arranged with respect to the odontoid-impact angle (α).

Experiment	α°	Perpendicular mm	Energy Nm	Result
27	40	17	205	Small fracture at the lateral border of the inferior articular facet of the atlas on the impact side.
29	40	6	170	Oblique fracture through the body and posterior arch of the axis.
28	50	47	205	Compression fracture of the superior articular facet of the axis on the impact side.
31	50	40	275	Hangman's fracture.
32	58	52	240	Odontoid fracture type A. Compression fracture on the anteromedial side of the occipital condyle (ipsilateral to the impact).
33	58	53	275	Odontoid fracture type A.
11	63	80	170	Decapitation between the occiput and the atlas.
35	64	63	260	Odontoid fracture type A.
36	72	61	310	Odontoid fracture type A. Jefferson fracture. Compression fracture on the anteromedial side of the occipital condyle (ipsilateral to the impact).

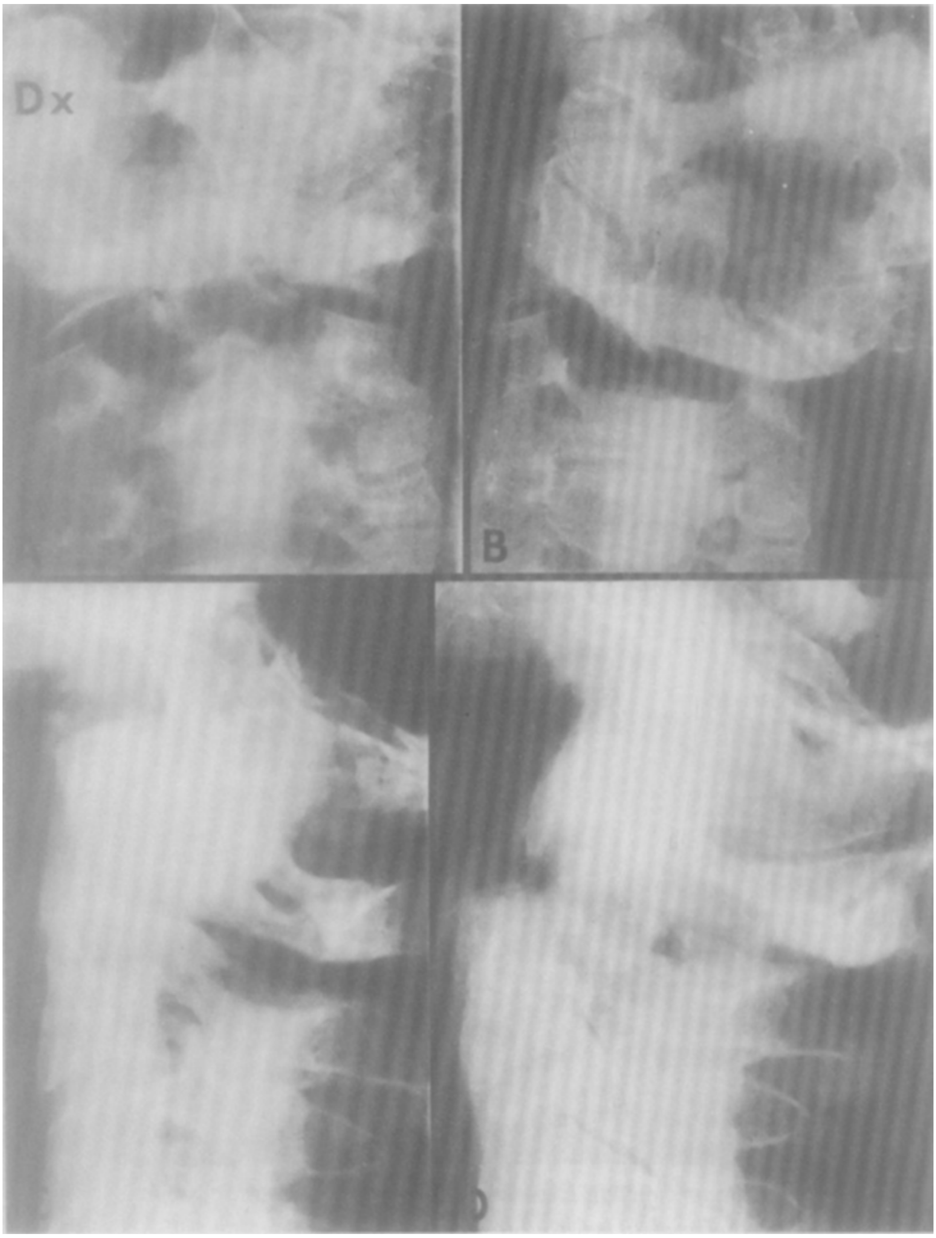

Figure 38. Radiographs of the specimen in Experiment 22. Type D odontoid fracture. A. The skull is forced to the right; the odontoid process is angulated. B: The skull is forced to the left; the odontoid process is angulated. C: The skull is forced anteriorly. D: The skull is forced posteriorly; the odontoid process is displaced backwards.

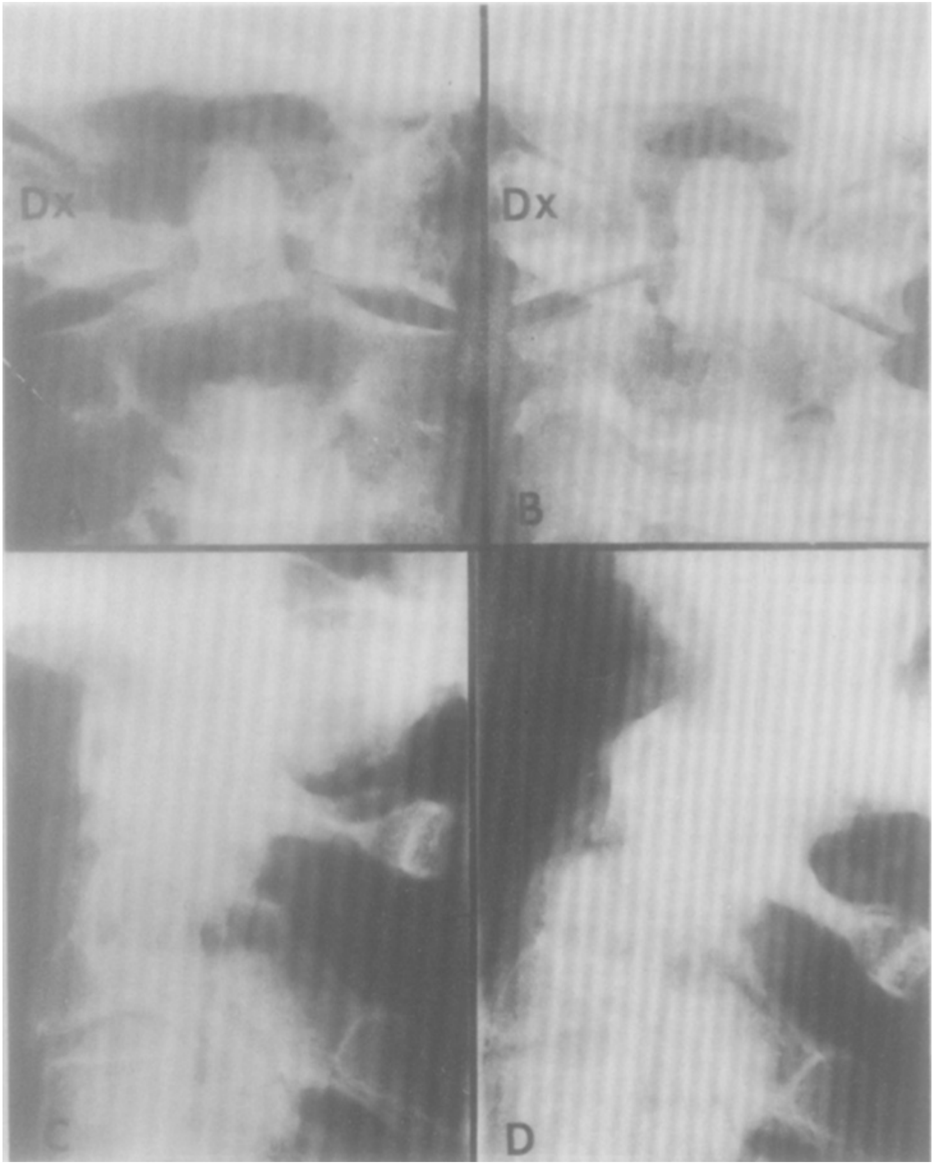

Figure 39. Radiographs of the specimen in Experiment 26. Type B odontoid fracture. A: The skull is forced to the right. B: The skull is forced to the left; there is widening at the fracture site on the right side and angulation of the odontoid process. C: The skull is forced anteriorly. D: The skull is forced posteriorly; the odontoid process is displaced backwards.

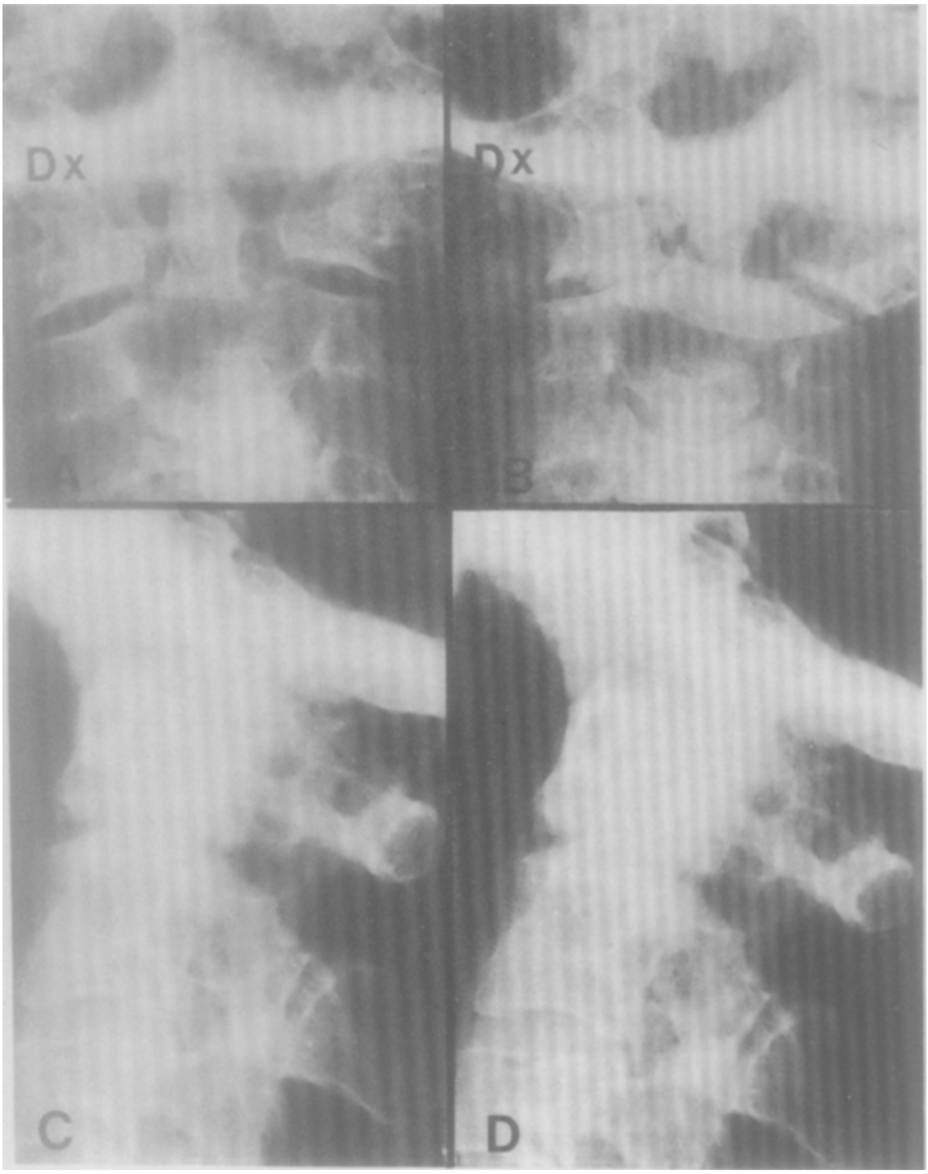

Figure 40. Radiographs of the specimen in Experiment 32. Type A odontoid fracture. A: The skull is forced to the right. B: The skull is forced to the left; there is widening at the fracture site on the right side and angulation of the odontoid process. C: The skull is forced anteriorly. D: The skull is forced posteriorly.

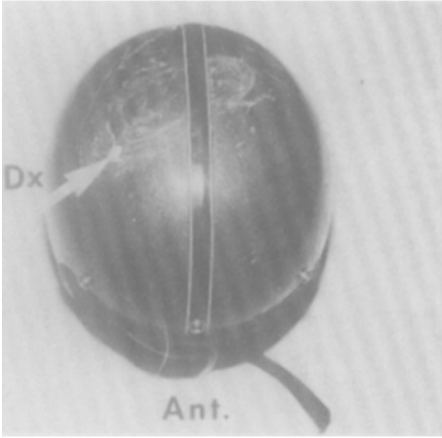

Figure 41. The helmet worn by a patient when fracturing the odontoid process (type A fracture). The helmet is scratched almost transversely in the medial part of the vertex. Its surface is softened on the right side (arrow) indicating the site of the impact.

anterior aspect of the body of the axis. Similar injuries to the longitudinal ligaments were observed by Sköld (1978) in an autopsy material when the fracture involved the superior part of the body of the axis and the medial part of both the superior articular facets of the axis.

With an anterolateral impact there also seemed to be an elongation of the anterior longitudinal ligament. The posterior longitudinal ligament seemed to be normal in length but was torn from the posterior aspect of the body of the axis. In fractures produced by a lateral impact no injury was found in the anterior or posterior longitudinal ligament. It must, however, be pointed out that ligament elongation may be difficult to recognize. It may be speculated that if the fracture mechanism is analysed, information can be obtained concerning the associated ligament injury and hence also the position in which the fracture is stable.

A clinical support to these speculations can be obtained in the following case history of apatient.

A 25-year-old motor-cyclist had an accident and sustained an odontoid fracture. The fracture, situated in the isthmus of the odontoid process, was sloping from the right to the left. His helmet was scratched almost transversely in the middle part of the vertex (Figure 41). Its surface was softened at the right side indicating the site of the impact. Radiographic examination showed that the fracture could be dislocated to the left, but not to the right, nor anteriorly or posteriorly (Figure 42).

Energy

The energy that had to be used for the production of odontoid fractures varied with the type: type D required 105–135 Nm, type B 170–240, and type A 240–275. Despite the high energy being used to produce a type A fracture the result was only a slight tilting of the odontoid process. without any concomitant injury. However, when in 2 experiments a similarly high energy (225–240 Nm) was used to produce a type D fracture, the result was a total separation of the specimen at the level of the fracture. In 1 experiment in which the set-up was arranged for production of a type A fracture 310 Nm was applied. This resulted in both an odontoid fracture and a Jefferson fracture.

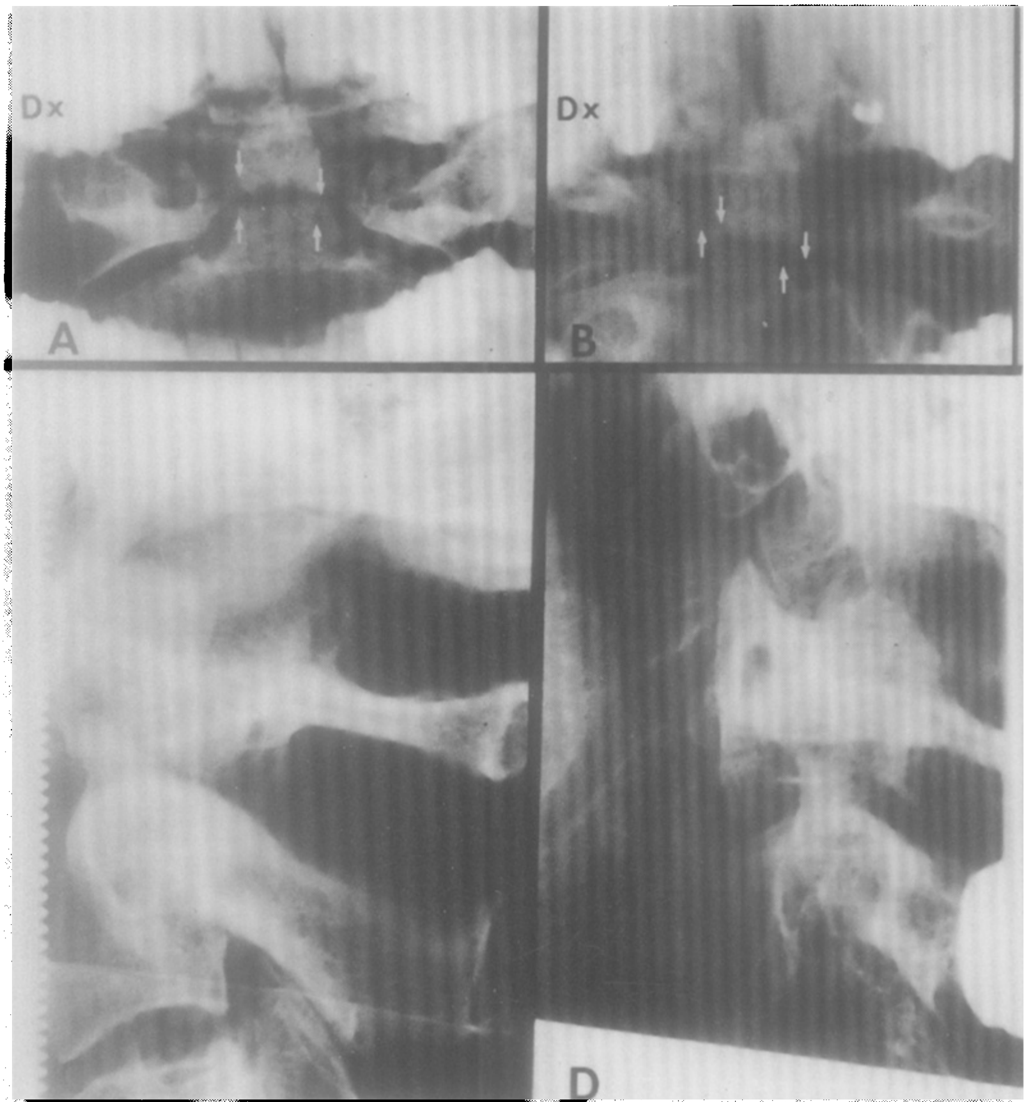

Figure 42. Radiographs of the type A odontoid fracture sustained by the patient whose helmet is shown in Figure 41. The cervical spine was stabilized in a Halo-vest. A: The skull was moved to the right; no displacement. B: The skull was moved to the left; displacement. C: The skull was moved anteriorly; no displacement. D: The skull was moved posteriorly; no displacement.

THE ARTERIAL SUPPLY TO THE ODONTOID PROCESS

A study on the influence of experimental odontoid fractures

by

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INTRODUCTION

The reason for non-union of fractures of the odontoid process has been discussed (Nachemson 1960, Seljeskog et al. 1971, and Schatzker et al. 1971). It has been argued that the vascular supply becomes disturbed to an extent that revascularization does not occur satisfactorily. An impairment in the healing follows. It has also been suggested that in so called low fractures, i.e. fractures through the base of the odontoid process, no vital arteries become injured and consequently healing can be expected to occur (Schatzker et al. 1971, Bailey 1974). In so called high fractures, however, the arteries reaching the odontoid process together with the accessory ligaments are said to become injured and it has been postulated that this may impair circulation to such an extent that non-union of the odontoid fracture ensues. Moreover, the opinion has been advanced that the arterial supply to the odontoid process is so poor in general that odontoid fractures consequently heal badly (Schmorl 1971, Bailey 1974). In an earlier investigation we have studied the arteries surrounding, penetrating into and running within the odontoid process under normal conditions.

The aim of this investigation was to study whether the *extrinsic* and *intrinsic* arterial supply of the odontoid process suffered any damage by the production of different types of odontoid fracture.

REVIEW OF THE LITERATURE

Main arteries in the odontoid region

Adjacent to the upper cervical spine there are two main arteries, the internal carotid artery and the vertebral artery. The internal carotid artery runs anterolaterally in a cephalad direction and enters the skull through the canalis caroticus. The vertebral artery passes through the foramina transversaria of the cervical vertebræ and curves over the posterior arch of the atlas. It then continues into the skull through the foramen magnum.

Close to the internal carotid artery there is the ascending pharangeal artery which is a branch of the external carotid artery. A branch from this artery runs into the skull through the canalis hypoglossi of the occipital condyle.

Arteries to the odontoid process

Only a few publications have been presented on the arterial supply of the odontoid process. Schatzker et al. (1971, 1975) described two main vascular sources. One was derived from so called central arteries which entered the odontoid process at its base and then ran in i cephalad direction inside the odontoid process. The other source was described in a schematic drawing showing arteries from the massa lateralis of the atlas reaching the odontoid process via the accessory ligaments. Moreover, it was suggested that vascular connections exist at the insertion of the alar and apical ligaments. Arteries were demonstrated within the odontoid process but "it was impossible to show with certainity what areas of the dens were supplied by these vessels (through the apical and alar ligaments) or whether anastomoses existed between the vessels which entered the dens through the apical and alar ligaments and the central and peripheral arteries" (Schatzker et al. 1971).

Shiff and Parke (1973), and Parke (1978) demonstrated a regular vascular pattern around the odontoid process. They described three main groups of arteries:

1. Anterior ascending arteries
2. Posterior ascending arteries
3. Cleft perforators (horizontal arteries).

These latter arteries arose from the internal carotid arteries and anastomosed with the anterior ascending arteries at the base of the odontoid process. The paired anterior and posterior ascending arteries arose from the vertebral arteries. The ascending arteries assembled in a vascular arcade on the top of the odontoid process. The anterior ascending arteries gave branches to the anterior aspect of the body of the axis and to the base and anterolateral surfaces of the odontoid process. The posterior ascending arteries gave branches to the posterior aspect of the body of the axis. Shiff and Parke (1973) described small holes in the surface of the odontoid and concluded that these were places of entry for arteries.

No arteries were demonstrated within the odontoid process.

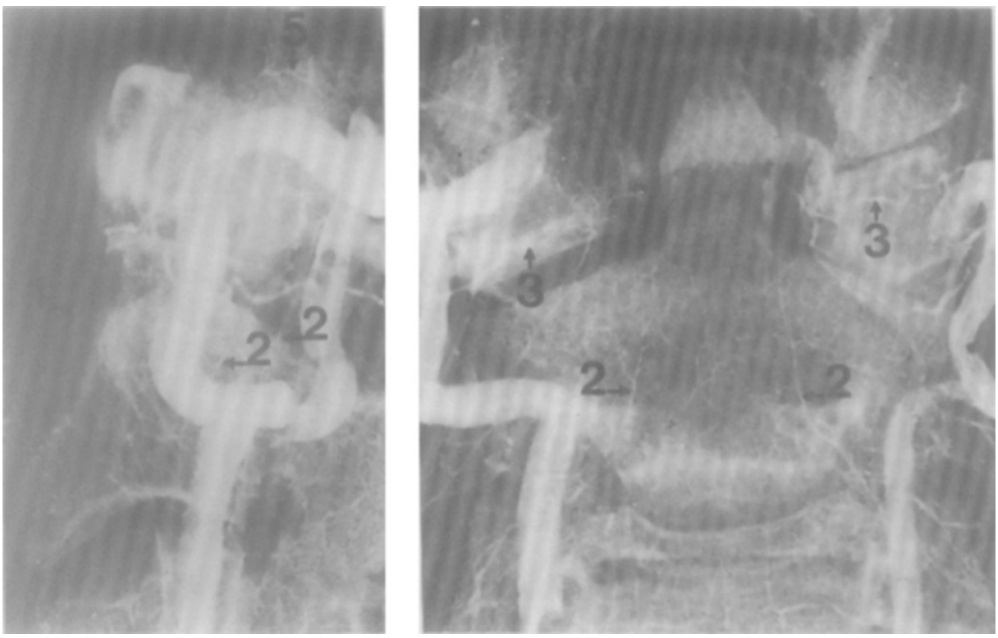

Figure 43. Cadaver specimen. Micropaque® injected into the vertebral arteries. A: Lateral radiograph. B: Anteroposterior radiograph.
1 = Anterior ascending artery. *2 = Posterior ascending artery*
3 = Inferior anterior horizontal artery *4 = Posterior horizontal artery*
5 = Apical arcade

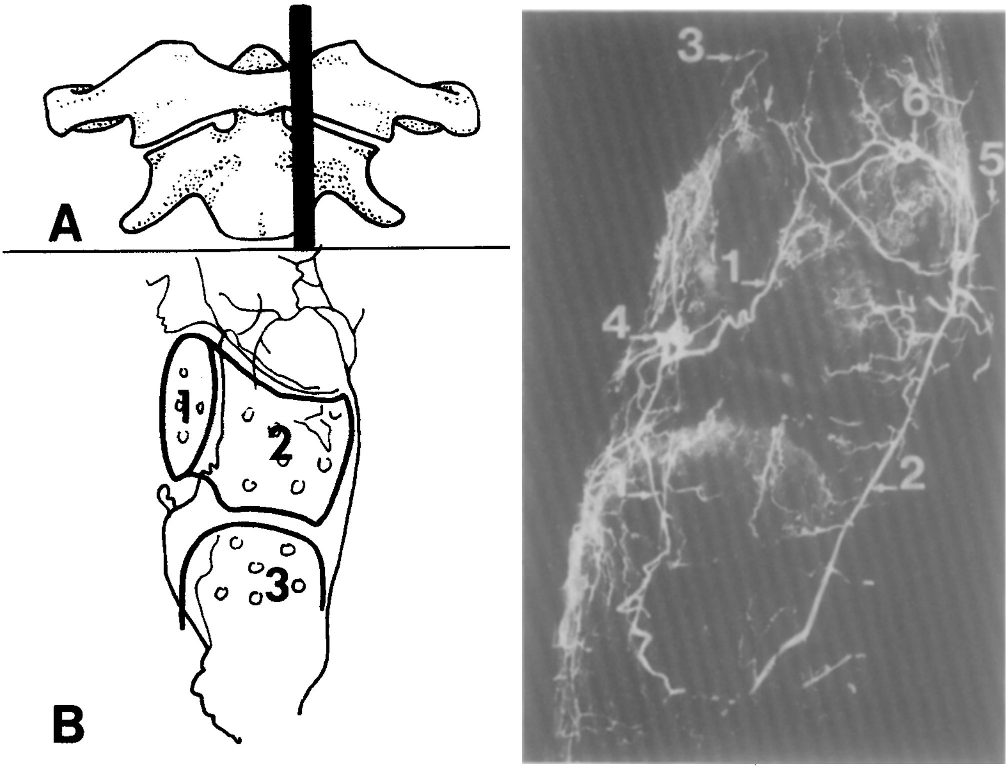

Figure 44. A: Location of the sagittal slice of the upper cervical spine in Figure 44 C.
B: Schematic drawing of Figure 44 C.
1 = Anterior arch of the atlas 2 = Part of the massa lateralis of the atlas 3 = Axis
C: Sagittal slice through the upper cervical spine (slice thickness 5 mm). Radiograph of Spalteholtz preparation.
1 = Anterior ascending artery *2 = Posterior ascending artery*
3 = Superior anterior horizontal artery *4 = Inferior anterior horizontal artery*
5 = Posterior horizontal artery *6 = Part of the apical arcade*
7 = Anastomosing artery between the superior anterior horizontal artery and the apical arcade

As the intrinsic arterial supply of the odontoid process did not appear to have been satisfactorily investigated in previous studies and we wanted to correlate it, as well as the extrinsic supply, with experimentally produced odontoid fractures, we found it necessary further to study the arterial supply of the odontoid process (Althoff and Goldie 1977). It was confirmed that this bone is supplied from the vertebral arteries via paired anterior and posterior ascending arteries (Figures 43 and 44) and from the internal carotid arteries via anterior horizontal arteries, which anastomose with the anterior ascending arteries at the base of the odontoid process. We also found anterior horizontal arteries higher up ("superior") forming anastomoses with the apical arcade; like the previously described anterior horizontal arteries ("inferior"), they arose from the internal carotid arteries. Furthermore, we found posterior horizontal arteries forming anastomoses with the apical arcade; they arose from the ascending pharyngeal arteries.

The apex of the odontoid process was penetrated by arteries running along the alar and apical ligaments and the base by arteries running along the accessory ligaments; the base was also penetrated by arteries anteriorly and posteriorly. The arteries entering the apex anastomosed inside the odontoid with those entering the base.

It was concluded that the odontoid process is located in the centre of a rich arterial network. The apical arcade forms anastomoses not only with the ascending arteries from the vertebral arteries but also with the superior anterior horizontal arteries (from the internal carotid arteries) and the posterior horizontal arteries (from the ascending pharyngeal arteries). The superior anterior horizontal arteries and posterior horizontal arteries do not pass the region where a fracture of the odontoid process is situated.

The purpose of the present investigation has been to study the influence experimentally produced fractures have on the arterial supply to the odontoid process.

OWN INVESTIGATION

Material and methods

The material consisted of 15 human cervical columns attached to the occiput. Clinically there was evidence of vascular disease in 7 cases but as later became obvious this did not influence the degree of arterial filling nor the pattern of arterial supply to the odontoid process (Table 8). The ages of the individuals from whom the specimens were taken varied from 33 to 78 years.

In six excised neck specimens the arteries were filled through catheters in the vertebral and common carotid arteries with one part micropaque mixed with two parts 10 per cent formaldehyde solution. The specimens were then fractured after 1/2 an hour. The experimental fractures were produced by a pendulum hitting the anterior, posterior, anterolateral or lateral aspects of the skull under given conditions (page 38).

The specimens were radiographed after the production of the fracture. Following this the Spalteholtz clearing procedure (Spalteholtz 1914) was used to clear the specimen and thus to obtain a three-dimensional demonstration of the arteries in order to achieve a better analysis of their relationship to the fracture.

In nine specimens experimental fractures were produced before filling the arteries with the micropaque solution. Radiography was carried out and preparation according to the Spalteholtz method was done. For further details of the injection procedure see Althoff and Goldie (1977).

Table 8. Cause of death.

Experiment	Type of fracture	Age/years	Sex	Diagnosis
1	D	53	M	Myocardial infarction
2	A	67	M	Cerebral hemorrhage
3	D	49	M	Circulatory insufficiency
4	B	78	F	Pneumonia
5	D	50	M	Myocardial infarction
6	B	59	F	Cancer of the liver
7	A	61	M	Cancer of the oesophagus
8	D	76	M	Cancer of the colon
9	A	71	M	Myocardial infarction
10	B	77	F	Pulmonary embolus
11	A	33	F	Cancer of the breast
12	A	72	M	Cancer of the kidney
13	B	73	M	Myocardial infarction
14	B	67	M	Myocardial infarction
15	D	56	F	Liver insufficiency

Results

Irrespective of filling the arteries with contrast medium before or after the production of an odontoid fracture the difference in the vascular architecture was virtually the same.

Leakage of the contrast medium occurred from the vessels on the surface of the specimens, from the vessels around the spinal cord and finally from those arteries which had become ruptured in the fracture zone on producing the fracture. Some difficulties therefore arose in the analysis of the arterial distribution within the individual specimen. This applied to both the radiographic and Spalteholtz examinations. In the following description these complications have been expressed as technical failure.

The following observations could be made and are presented in Table 9.

Table 9. The integrity of the arteries to the odontoid process after experimental odontoid fractures

		Ascending arteries				Horizontal arteries					
		Anterior		Posterior		Inferior Anterior		Superior Anterior		Posterior	
Specimens filled before fracture	Type of fracture	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left
1	D	–	–	+	+	?	?	?	+	+	+
2	A	?	?	+	+	+	+	+	+	+	+
3	D	?	?	?	–	?	?	?	?	?	?
4	B	?	?	–	+	?	?	?	?	+	?
5	D	?	?	–	+	?	?	?	?	+	+
6	B	+	+	–	+	+	+	+	+	?	+
Specimens filled after fracture											
7	A	+	+	+	+	?	+	?	+	+	+
8	D	–	–	+	+	–	–	?	+	+	+
9	A	?	?	+	+	?	?	?	?	+	+
10	B	?	?	+	?	?	?	?	?	+	+
11	A	?	?	+	+	?	?	?	?	+	+
12	A	?	?	+	+	?	?	+	+	+	+
13	B	?	?	+	?	?	?	+	?	+	+
14	B	?	?	+	?	?	?	+	+	+	+
15	D	?	?	+	+	?	?	?	?	+	+
Intact (+)		2+	2+	11+	11+	2+	3+	5+	7+	13+	13+
Loss of continuity (–)		2–	2–	3–	1–	1–	1–	0–	0–	0–	0–
Technical failure (?)		11?	11?	1?	3?	12?	11?	10?	8?	2?	2?

Anterior ascending arteries

In 2 specimens the anterior ascending arteries were intact on both the right and left sides.

In 2 specimens the anterior ascending arteries lost their continuity at the site of the fracture on both the right and left side.

In 11 specimens it was impossible due to technical failure to make any satisfactory analysis.

Posterior ascending arteries

The posterior ascending arteries were intact on both sides in 8 specimens.

There was a loss of arterial continuity on the right side in 3 specimens but the left was intact. In 1 specimen the continuity was lost on the left side. The right artery could not be followed.

Due to technical failure in 3 more specimens the left artery could not be followed. The right artery was intact.

Inferior anterior horizontal arteries

These were intact in 2 specimens on both sides. In 1 additional specimen the left was intact. In this specimen the right could not be followed.

There was a loss of arterial continuity on both sides in 1 specimen.

Due to technical failure further analysis was impossible in 11 specimens on both the right and left sides.

Superior anterior horizontal arteries

Intact arteries were observed in 4 specimens on both sides. In 4 additional specimens one of the arteries was intact (one on the right and three on the left side). In these specimens the contralateral artery could not be followed.

Loss of arterial continuity was not observed in any specimen.

Due to technical failure further analysis was impossible in 7 specimens on both sides.

Posterior horizontal arteries

These were intact in 12 specimens on both sides. In 2 additional specimens one artery was intact (one on the right side and one on the left). In these specimens the contralateral artery was impossible to follow.

Loss of arterial continuity was not observed in any specimen.

Due to technical failure further analysis was impossible in 1 specimen on both sides.

Intraosseous arteries

In those specimens in which fractures were produced *before* the injection of the contrast medium, the arteries within the odontoid fragment were filled. This arterial filling occurred irrespective of the level where the fracture had been produced. A type D fracture (page 9) is demonstrated in Figure 45, a type B (page 8) in Figure 46, and a type A (page 8) in Figure 47.

Figure 45. Sagittal slice (thickness 5 mm) through the odontoid process. Radiograph of Spalteholtz preparation. A type D odontoid fracture was produced b e f o r e the injection of contrast medium. The fracture is marked by a large arrow. The small arrows outline the odontoid process. a = anterior arch of atlas. d = disc between axis and C III.

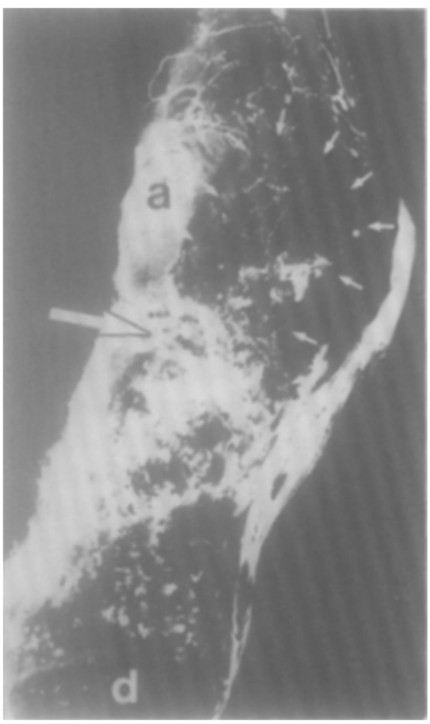

Figure 46. Sagittal slice (thickness 5 mm) through the odontoid process. Radiograph of Spalteholtz preparation. A type B odontoid fracture was produced b e f o r e the injection of contrast medium. The fracture is marked by a large arrow. The small arrows outline the odontoid process. a = anterior arch of atlas. d = disc between axis and C III.

Figure 47. Sagittal slice (thickness 5 mm) through the odontoid process. Radiograph of Spalteholtz preparation. A type A odontoid fracture was produced b e f o r e the injection of contrast medium. The fracture is marked by a large arrow. The small arrows outline the odontoid process. a = anterior arch of atlas. d = disc between axis and C III.

DISCUSSION

In this investigation both the extra and intraosseous arteries of the odontoid process have been filled with contrast medium. Our interest has been focussed to the influence of an experimental fracture on the intraosseous arteries when, after the production of the fracture, an injection had been made of contrast medium into the carotid and/or the vertebral arteries. It was found that despite the injury caused by the fracture to extraosseous arteries supplying the odontoid process there are remaining arterial sources which can supply the intraosseous arterial network. Irrespective of level of experimentally produced fracture the interior arterial network was filled with contrast medium.

The observations in this investigation cannot be transferred to live conditions. It may, nevertheless, be permitted to speculate that, despite the pathophysiologic events in trauma, the arterial supply need not necessarily be injured to such an extent that the odontoid process in cases of fracture is rendered ischemic so that union of a fracture either becomes delayed or fails completely. The development of pseudarthrosis in fractures of the odontoid process need not necessarily be caused by a disturbance in the arterial supply to the odontoid (Schatzker et al. 1971), but rather by a lack of stabilization, a well known and accepted reason for delayed union in fracture surgery.

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FRACTURE OF THE ODONTOID PROCESS

A clinical and radiographic study

by

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INTRODUCTION

The rate of non-union in conservatively treated patients with odontoid fractures varies between 0 – 80 % (Table 10). This may depend on variations in the treatment, and on differences in the follow-up of the patients.

Some authors (Blockey and Purser 1956, Solovay 1960, Kattan 1975) consider that in some instances of non-union there is firm fibrous union which may be nearly as strong as bone union. This conclusion was made after a study of radiographs in lateral projection of the odontoid process in flexion and extension, when no mobility was observed.

The frequency of bone union is higher in fractures involving part of the body of the axis as compared to those involving the isthmus (Bailey 1973, Anderson and D'Alonzo 1974). Other factors have also been considered to influence the union as age, and the direction and degree of displacement.

In this presentation we intend to describe the clinical course and radiographic features of fractures of the odontoid process in 78 patients, treated in Western Sweden between 1965 and 1974. In 1978, a clinical and radiographic examination was carried out in 48 patients.

BASIC MATERIAL

In order to obtain a representative material this was collected from seven hospitals in Western Sweden (The Sahlgren Hospital in Göteborg, the Hospitals in Alingsås, Borås, Mölndal, Trollhättan, Uddevalla and Vänersborg). Seventy-eight patients had sustained an fracture of the odontoid process between 1965 and 1974. No children were included in this investigation.

Table 10. Reported results of conservatively treated odontoid fractures.

	Number of patients	Number of non-union	Per cent non-union
Amyes and Anderson (1956)	63	3	5
Blockey and Purser (1956)	35	22	63
Rogers (1957)	9	4	44
Nachemson (1960)	18	8	44
Solovay and Brice (1960)	9	5	56
Böhler (1965)	36	2	6
Baker et al. (1966)	35	22	63
Hentzer and Schalimtzek (1971)	7	4	57
Schatzker et al. (1971)	37	23	62
Mourgues et al. (1972)	52	12	23
Roberts and Wikstrom (1973)	40	8	20
Paradis and Janes (1973)	13	2	15
Husby and Sörensen (1974)	21	3	14
Hörlyck and Rahbek (1974)	11	2	18
Anderson and D'Alonzo (1974)	35	9	26
Stöwsand et al. (1974)	11	9	82
Symeonidis et al. (1976)	15	3	20
Ramadier et al. (1977)	26	12	46
Schweigel (1977)	14	0	0
Seljeskog (1978)	27	2	7
Apuzzo et al. (1978)	45	13	29
	535	168	31 %

Method

The medical record in each case was studied and an analysis was made of the cause of the injury, associated injuries and clinical features at the time of the injury and thereafter.

All earlier radiographs of the patients including tomographs were reviewed.

Age and sex

Age and sex of the 78 patients are presented in Figure 48. The men represented 70 % (55 patients) and the women 30 % (23 patients). The youngest patient was a 16-year-old girl and the oldest an 88-year-old lady. The mean age for men was 48 years and for women 65. The mean age for the total material was 54 years.

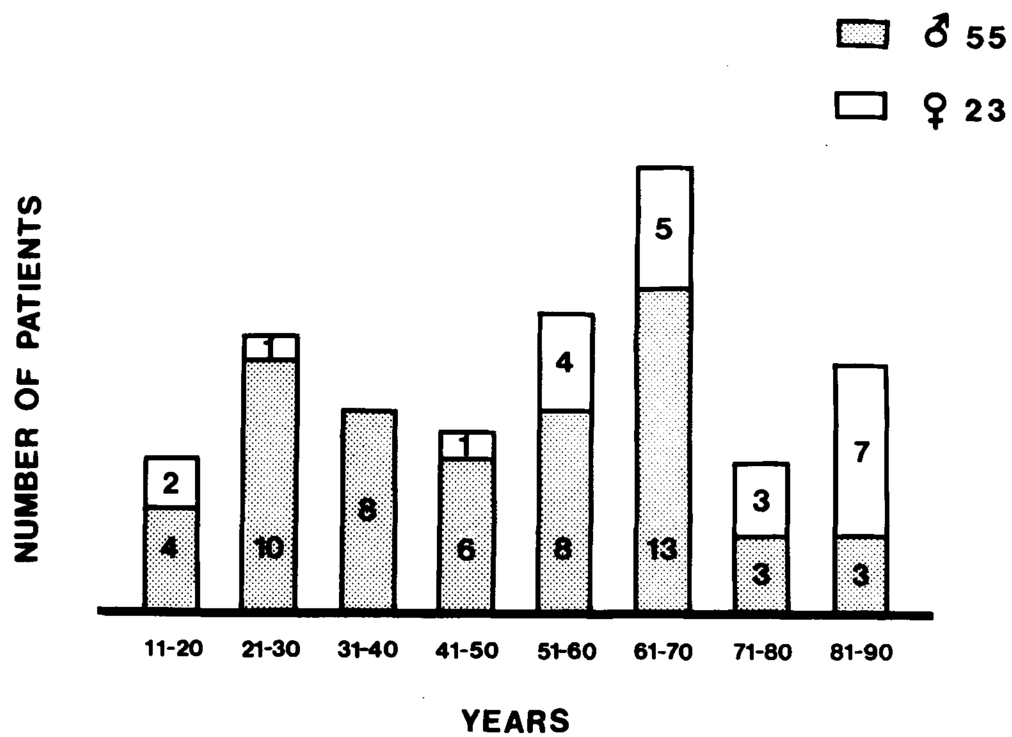

Figure 48. Age and sex distribution in 78 patients with odontoid fracture.

Cause of injury (Table 11)

An analysis of the cause of the injury suggested that most fractures were a result of a high velocity force. Twenty-six of the patients had fallen downstairs or from ladders, 25 were drivers or passengers in a car accident and 14 had fallen on the floor or on the ground. Nine were unprotected traffic victims. One patient with rheumatoid arthritis sustained a fracture during physiotherapy. One patient had a spontaneous fracture caused by a metastatic mammary carcinoma. In 2 patients the cause of the injury could not be determined. They had been too intoxicated to remember what had happened.

Table 11. Cause of injury in 78 patients with odontoid fracture

Cause	Number of patients
Fall downstairs/from ladders	26
Drivers/passengers in car accidents	25
Fall on the floor/ground	14
Unprotected traffic victims	9
Physiotherapy	1
Spontaneous	1
Undetermined	2

Relation of cause of injury to age

The type of accident was related to the ages of the patients. The patients who had fallen downstairs (mean age 60) and especially those who had fallen on the ground or on the floor (mean age 73) were older than those with fractures in car accidents (mean age 39). The ages of the unprotected traffic victims were evenly distributed in the material (mean age 50).

Symptoms

Fractures of the odontoid process may be difficult to diagnose. The most common symptoms in this material were pain and stiffness in the neck. Two patients complained of a feeling of instability in the neck and were unable to keep their head upright.

Early neurologic symptoms

Eighteen patients had neurological symptoms on arrival at the hospital. Eight had only a feeling of numbness or paresthesiae, which were located in the upper extremities in 6 patients and in both the upper and lower extremities in 2. Motor disturbances in the upper extremities were found in 8 patients. One patient had generally exaggerated tendon reflexes and a disturbed bladder function. One patient was tetraplegic.

One patient without neurologic symptoms on admission to the hospital suddenly died two days later because of respiratory insufficiency; the spinal cord had been compressed by the fractured odontoid process as diagnosed at radiography and autopsy.

Outcome of the early neurological symptoms: Of the 18 patients, 13 recovered completely and 2 incompletely. Of the remaining 3, 2 died within a month in hospital because of respiratory insufficiency; in 1 of them the reason was compression of the spinal cord because of dislocation of the odontoid fragment. After an initial improvement, the third patient died eight months after the accident because of compression of the spinal cord as a result of redislocation of the odontoid fragment.

Type of injury

Level of the fracture (Table 12)

Thirteen fractures belonged to type A, 40 to type B, 10 to type C and 15 to type D (page 8).

Table 12. Classification of odontoid fractures in 78 patients.

Level of fracture	Number of patients
Type A	13
Type B	40
Type C	10
Type D	15

Table 13. Displacement and angulation of the fractured odontoid process in 78 patients.

Direction of displacement and angulation	Number of patients
Anterior	23
Anterior with lateral angulation	5
Anterolateral	5
Posterior	19
Posterior with lateral angulation	5
Posterolateral	8
Lateral	3
Undisplaced	6
Undisplaced with lateral angulation	4

Displacement and angulation of the fractured odontoid process (Table 13)

In 23 patients the fractured odontoid process was displaced anteriorly, in 5 anteriorly with lateral angulation, in 5 anterolaterally, in 19 posteriorly, in 5 posteriorly with lateral angulation, in 8 posterolaterally, and in 3 laterally. The fractured odontoid process was undisplaced in 10 patients, but in 4 of these, there was lateral angulation.

Associated injuries (Table 14)

Facial and/or skull wounds were seen in 27 patients. Ten patients had been unconscious. Two had a fracture in the parietal bone. Fracture in the face was diagnosed in 3 patients, 1 in the maxilla and 2 in the mandibula.

Seven patients had atlas fractures, most of them in the posterior arch (5 patients). Fractures elsewhere in the spine were seen in 5 patients; 1 patient had an arch fracture of the axis and 4 a compression fracture of C III, C VII, Th VII or L I.

Eight patients had injured their thorax and/or abdomen. Most of them had rib fractures, some a concomitant hemothorax. Hematuria or liver or spleen rupture was also diagnosed in some patients in this group.

Nine patients had fractures of the arms and/or the legs. On admission to hospital it was recorded that 11 patients were intoxicated by alcohol.

Table 14. Associated injuries in 78 patients with odontoid fracture.

Type of injury	Number of patients
Facial and/or skull wounds	27
Unconsciousness	10
Skull fracture	2
Facial fracture	3
Vertebral fracture	12
Thorax and/or abdominal injury	8
Arm and/or leg fracture	9

Initial treatment

The initial treatment varied greatly, partly because the different orthopaedic surgeons tried to individualize the treatment, partly because some patients refused skull traction. Therefore, these latter patients received less stabilizing treatment.

Patients not surviving the first six weeks (Table 15)

Ten patients died in the hospital within the first six weeks (2 because of the fracture, 6 of cardiovascular complications, 1 of intoxication, 1 of malignancy). All were treated in bed; 4 in skull traction, 5 with sand bags or a collar, and 1 after operation with posterior fusion.

Table 15. Initial treatment of 10 patients with odontoid fracture surviving less than 6 weeks.

Type of treatment	Number of patients
Skull traction	4
Bedrest and sandbags or collar	5
Early posterior fusion	1

Patients surviving the first six weeks (Table 16)

Of the remaining 68 patients, 26 had skull traction for more than six weeks followed by mobilization in a collar; 9 had a short period of skull traction (less than six weeks) followed by mobilization in a collar, and 11 were treated in bed with sand bags, collar or a Glisson sling. Seventeen patients were mobilized soon after the fracture in a "four poster collar" and 3 in a Minerva jacket. One patient who made her consultation six weeks after the injury only got a soft collar. One patient was operated early (the 15th day) with posterior fusion.

Table 16. Initial treatment of 68 patients with odontoid fracture surviving the first 6 weeks.

Type of treatment	Number of patients
Skull traction (more than 6 weeks)	26
Skull traction (less than 6 weeks)	9
Bedrest and sandbags, collar or Glisson sling	11
"Four poster collar"	17
Minerva jacket	3
Soft collar	1
Early posterior fusion	1

Reduction of displaced fractures

It was impossible to analyse the reduction of the displaced fractures treated with skull traction as they were radiographed only in one projection (lateral).

The patients mobilized in collar or Minerva jacket had none or only minor displacement in their fracture. The displaced fractures in this group were not reduced.

Delay in treatment

Fifty-one of the 78 patients were treated without delay. Five came to the hospital on the day of the accident but only after several hours. In 18 patients the diagnosis was made between one day and one week after the accident. In 4, the diagnosis was made more than one week after the accident.

Cause of delay in treatment (Table 17)

Twelve patients who had minor symptoms sought medical advice only after some time. In 4 patients, the reason for delay was multiple injuries. In another 4, the diagnosis was missed primarily but it was made within a week. In 2 patients, who sought medical advice late, the diagnosis was established only after repeated consultation.

Table 17. Cause of delay in treatment in 22 patients with odontoid fracture

Cause of delay	Number of patients
Patient	12
Multiple injuries	4
Doctor	4
Patient and doctor	2

Late complications (after six weeks)

Neurologic symptoms

Two patients developed paresthesiae or motor disturbances five and six months after the fracture. These patients then had a non-union at radiography and were operated on with posterior fusion. After operation their neurologic symptoms disappeared.

With onset three years after the accident, 1 patient had cervical pain with radiation and diminished motor power in the left arm and leg. No radiography was performed at that time and the symptoms vanished. That patient died in myocardial infarction before he could be examined by us.

One patient had episodes of loss of motor power in his right arm and leg, occurring at irregular intervals and lasting each time for about one hour. These symptoms began three years after the fracture. Radiography has shown a mobile pseudarthrosis but the patient has not accepted an operation.

One old lady (83) with a non-union developed episodes of jerking in her right quadriceps.

As already mentioned, 1 patient with early neurological symptoms died eight months after the accident because of compression of the spinal cord as a result of redislocation of the odontoid process.

Redislocation

Seven patients without neurological symptoms had mobility in a pseudarthrosis or redislocation of the odontoid process six weeks to four years after the injury. Three of these patients were operated on with posterior fusion.

Patients not available for follow-up examination

Four patients did not want to participate and 26 were dead. The cause of death and time of survival are presented in Table 18. On examining the radiographs of the dead patients, definite non-union was diagnosed in 5 of them six months to four years after the accident. The radiographs of 1 not participating patient showed no sign of healing four months after the accident.

Mortality

The integrity of the odontoid process is necessary to provide stability between the atlas and the axis. Three patients in this material died because of compression of the spinal cord as a result of the fracture.

Comment: This frequency (4 %) corresponds with that reported by Amyes and Anderson (1956), who found 2 dead of 63 patients. It must be pointed out that no patient succumbing immediately is included in the present material. To diagnose an immediate death caused by compression of the spinal cord may be extremely difficult as the microscopic alterations necessary for a correct diagnose demand some time of survival in order to occur (Sköld 1979, personal communication).

Table 18. Cause of death and time of survival in 26 patients with an odontoid fracture.

Age	Cause of death	Survival	Remarks
89	Circulatory insufficiency	2 days	
88	Circulatory insufficiency	7 days	
88	Pneumonia	5 years	
88	Spinal cord compression (odontoid fracture)	2 days	
87	Circulatory insufficiency	13 days	
87	Pneumonia	9 months	
84	Myocardial infarction Pneumonia	2 years	
81	Circulatory insufficiency Pneumonia	14 days	
80	Circulatory insufficiency Pneumonia	4 years	
71	Pulmonary embolus	23 days	
67	Spinal cord compression (odontoid fracture) Rheumatoid arthritis	8 months	
67	Circulatory insufficiency	50 days	The fracture was mobile at the last radiographic examination one month after the injury. The patient refused treatment.
66	Cancer of the breast	24 days	
64	Cancer of the larynx	4 years	
65	Spinal cord compression (odontoid fracture) Pneumonia	25 days	
64	Circulatory insufficiency	6 years	Mobile pseudarthrosis at the last radiographic examination six months after the injury.
62	Pulmonary embolus	30 days	Fusion had been performed.
62	Cancer of the kidney	5 years	Fusion had been performed because of pseudarthrosis.
60	Renal insufficiency	11 years	
58	Lymphosarcoma	7 years	
58	Brain tumor. Pneumonia	10 years	
57	Delirium tremens. Intoxication	5 days	
55	Epilepsy	3 years	
49	Myocardial infarction	9 years	
28	Myocardial infarction. Liver insufficiency	9 years	Mobile pseudarthrosis at the last radiographic examination six months after the injury.
18	Drowning	7 years	Pseudarthrosis at the last radiographic examination two years after the injury.

Table 19. Relation between early mortality (within six weeks) and treatment – bed rest versus early mobilization – in 78 patients with odontoid fracture.

		Patients treated in bed			Patients early mobilized		
Age	Total number of patients	Number of survivals	Number of patients dead in hospital	Number of patients dead after leaving hospital	Number of survivals	Number of patients dead in hospital	Number of patients dead after leaving hospital
11 – 20	6	5		1			
21 – 30	11	6		1	4		
31 – 40	8	7			1		
41 – 50	7	5			2		
51 – 60	12	4	1	4	2		1
61 – 70	18	6	3	3	4		2
71 – 80	6	2	1	1	2		
81 – 90	10		5	2	2		1

Mortality in relation to bed rest and early mobilization (Table 19)

The evaluation of the treatment has not only to be made in relation to the rate of union of the fracture but also to the complications, which may arise during the treatment. In the basic material, 57 patients were treated in bed whereas 21 were mobilized early. Ten died in hospital during the first six weeks. All had been treated in bed.

Comment: The older people seemed especially vulnerable to bed rest. Of 16 patients over 70 years of age 6 died and 5 survived bed rest, whereas all 5, who were mobilized early, could leave the hospital.

FOLLOW-UP EXAMINATION

Material

Fourty-eight patients were follow-up examined in 1978, 3.5 to 13 years after the accident (Figure 49); their age and sex at the time of injury are presented in Figure 50. The men represented 73 % (35 patients) and the women 27 % (13 patients). The mean age at fracture time for men was 41 years and for women 54 years. The mean age for the total material was 44 years.

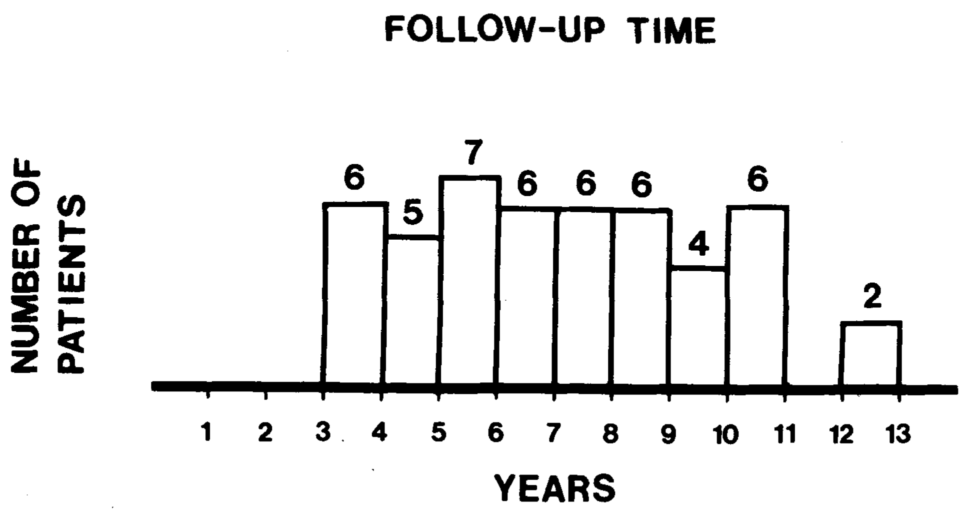

Figure 49. Follow-up time in 48 patients with odontoid fracture.

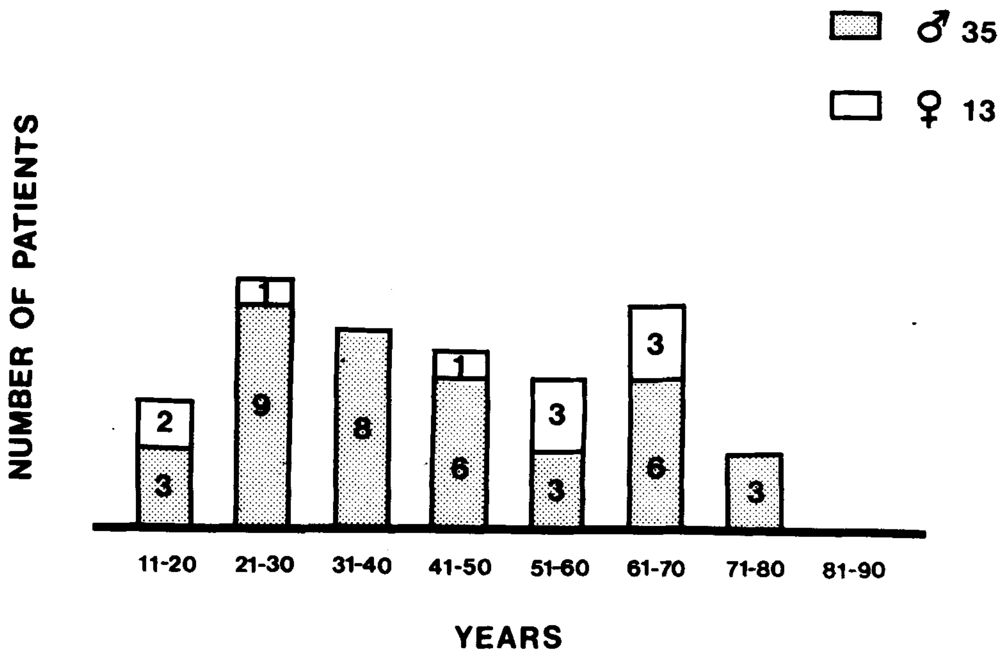

Figure 50. Age and sex distribution at time of fracture in 48 patients with odontoid fracture.

Method

1. A clinical examination was carried out. Special attention was paid to neurological symptoms and signs.
2. Routine radiography was performed. Additional films were taken with the head in maximal flexion, extension and lateral bending to both sides for testing the stability in the sagittal and coronal plane. Tomography was performed in 3 patients. Computer tomography was done in 8 patients; by this method the density of the tissue in the fracture area could be evaluated in order to get additional information regarding the healing.

   In cases of non-union, mobility was defined as an alteration of the location of the odontoid process exceeding 1 mm or an alteration of alignment exceeding 4°.

Results

Clinical examination (Table 20)

Of the 48 patients none had continuous pain or discomfort in the neck. Twenty patients had episodes of pain in the neck. This discomfort was minor in all of them and none had consulted a doctor because of these symptoms.

Twenty-eight patients were free from discomfort. In the period after the fracture and/or the fusion they had recognized a stiffness in the neck but this did not bother them at the present time.

Neurologic symptoms: Four of the patients suffering from episodes of pain in the neck had neurologic signs. This was already known from the medical records. These patients have been described under the heading "neurologic symptoms and late complications".

Table 20. Symptoms at follow-up of 48 patients with odontoid fracture.

Symptoms	Number of patients
Continuous pain or discomfort	0
Episodes of pain	20
No symptoms	28

Radiographic examination (Table 21)

Bone union was present in 24 patients who had been treated conservatively. One patient had been operated on earlier with posterior fusion (Figure 51) and 4 had undergone such an operation late, after conservative treatment which had resulted in non-union. All fusions had healed, but the state of the fracture could not be determined on the radiographs (tomography was not performed). Nineteen patients, all treated conservatively, had non-union; 1 of them had spontaneously developed a fusion between the anterior arch of the atlas and the body of the axis with bone formation in the region of the anterior longitudinal ligament (Figure 52). This patient had a 10 mm posterior dislocation of the occiput on the atlas when the skull was extended, but he was stable at the fracture site. Two other patients with non-union were also stable. Of the remaining 16 patients with non-union, 3 showed mobility in flexion-extension, 9 in lateral bending (Figure 53) and 4 in flexion-extension and lateral bending (Figure 54).

Thus, out of 47 conservatively treated patients with odontoid fracture 24 (51 %) had bone union and 23 (49 %) had developed non-union. Excluding patients with fusion, mobility at the fracture site was seen in all but 2 patients with non-union.

Table 21. Radiographic examination at follow-up of 48 patients with odontoid fracture

	Number of patients
Bone union	24
Healed early posterior fusion	1[1]
Healed late posterior fusion (performed because of non-union)	4[1]
Non-union	
with spontaneous anterior fusion	1
without mobility	2
with mobility in flexion-extension	3
with mobility in lateral bending	9
with mobility in flexion-extension and lateral bending	4

[1]) The state of the fracture could not be determined on the radiographs.(Tomography not performed.)

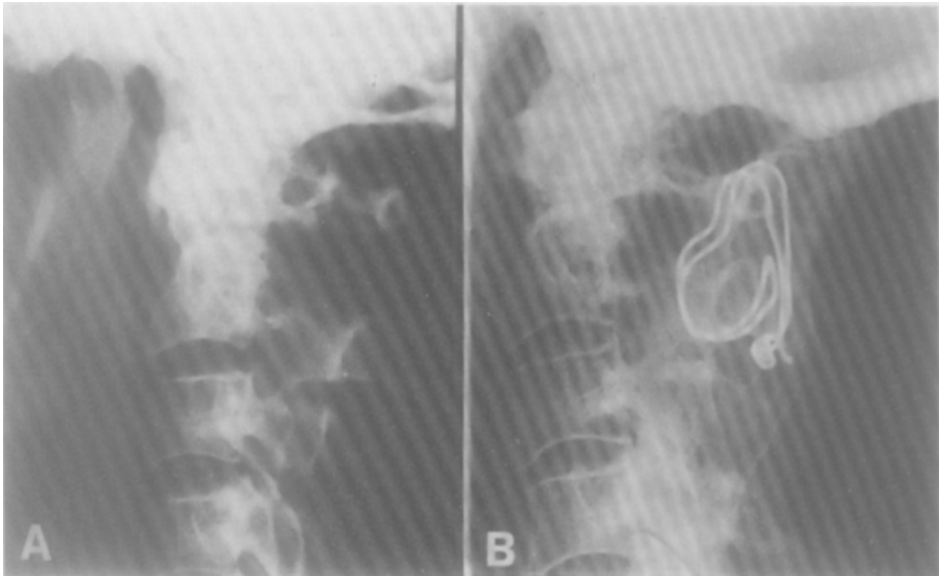

Figure 51. Radiography from a 54-year-old man who 8 years earlier sustained an odontoid fracture. A: Lateral view showing the reduced fracture. B: Lateral view showing a healed posterior fusion.

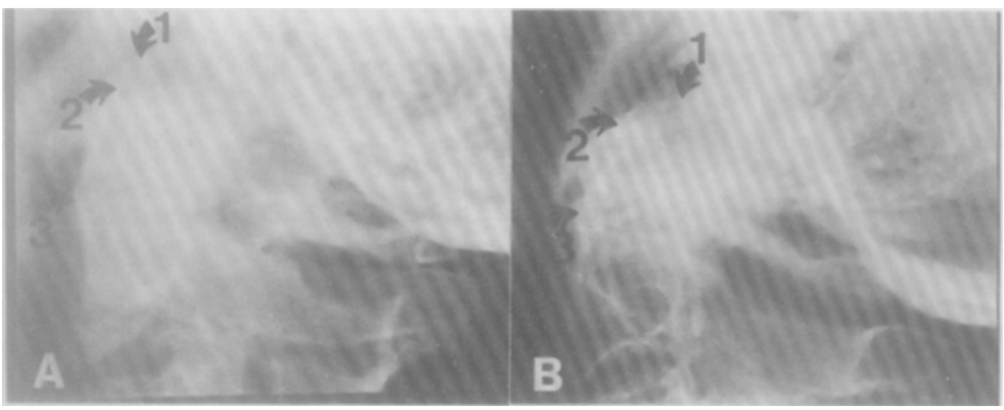

Figure 52. Radiographs from a 34-year-old man who 13 years earlier sustained an odontoid fracture. 1 = anterior border of the occipital condyles. 2 = anterior arch of the atlas. 3 = calcification in the region of the anterior longitudinal ligament between the anterior arch of the atlas and the body of the axis. A: Neutral position. B: Extension. The occipital condyle has moved backwards in extension.

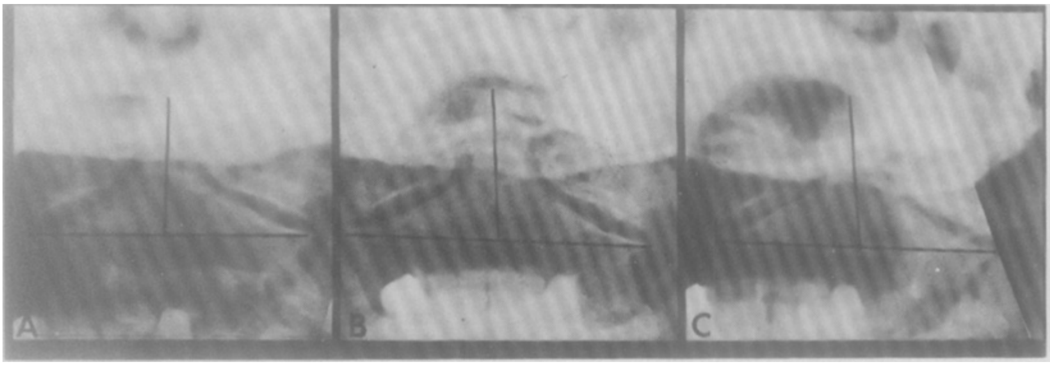

Figure 53. Radiographs from a 61-year-old man who 5 years earlier sustained an odontoid fracture. A: Bending to the right. B: Neutral position. C: Bending to the left. Lines illustrate the angulation of the odontoid process in relation to the body of the axis. Lateral bending demonstrates instability at the fracture site.

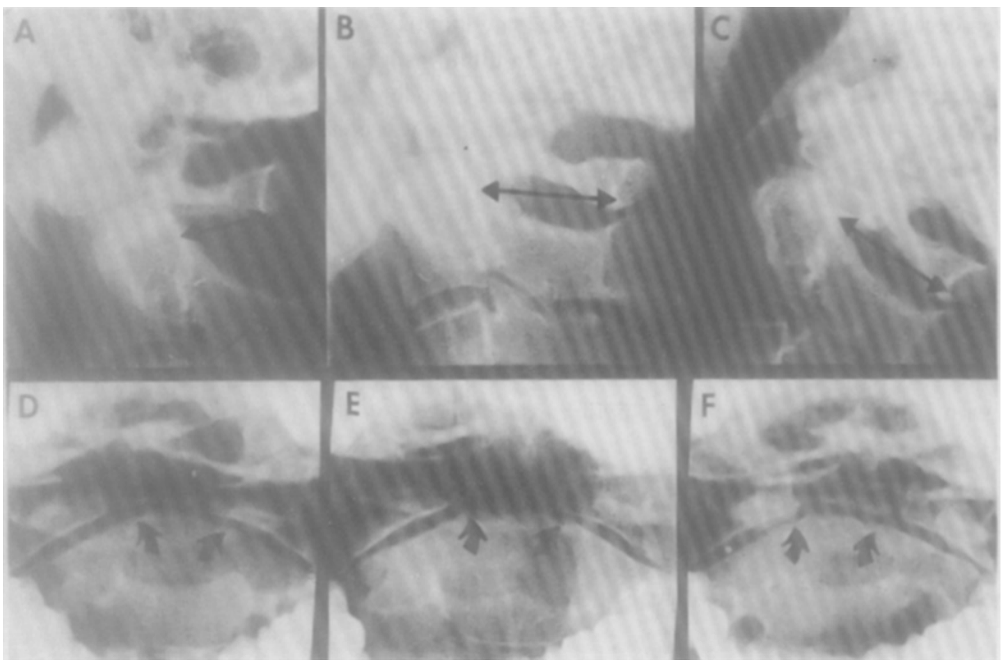

Figure 54. Radiographs from a 38-year-old man who 6 years earlier sustained an odontoid fracture. A: Flexion. B: Neutral position. C: Extension. The odontoid process is mobile forwards. The arrows indicate the distance between the posterior arch of the atlas and the body of the axis (the sagittal space for the medulla). D: Lateral bending to the right. E: Neutral position. F: Lateral bending to the left. The odontoid process is mobile to the left. The arrows indicate the medial borders of the superior articular facets of the axis.

Analysis of results of follow-up examination

Symptoms in relation to healing (Table 22)

Twenty-eight patients had no subjective symptoms. Of these, 14 had bone union and 9 non-union. Four had been operated on with posterior fusion; 1 operated early (15th day) and 3 because of non-union. One patient with non-union had a spontaneous fusion of the atlas to the axis with atlanto-occipital instability.

Twenty patients had minor symptoms from the neck. Of these, 10 had bone union and 9 non-union. One patient had been operated on with posterior fusion because of non-union.

Neurologic symptoms were found in 4 patients; all had non-union.

Comment: There seems to be no relation between symptoms and non-union. This observation corresponds with the findings by Nachemson (1960).

Two of the patients with neurologic symptoms had got these symptoms when fracturing the odontoid process. In these 2 patients it is impossible to estimate whether the symptoms at the present time are caused by the initial injury or the non-union.

In cases of non-union some authors have described a delayed cord lesion starting several years or even decades after the original injury (Osgood and Lund 1928, Blockey and Purser 1956, Amyes and Anderson 1956, Nachemson 1960). In this investigation one patient died eight months after the accident because of redislocation of the odontoid fracture.

The subjective symptoms did not indicate whether there was bone union or not. This could only be determined by radiography.

Table 22. Symptoms in relation to healing at follow-up of 48 patients with odontoid fracture.

	Number of patients	Bone union	Non-union	Posterior fusion	Spontaneous fusion
No symptoms	28	14	9	4[1]	1
Symptoms	20	10	9	1	

[1] One operated on the 15th day. Three operated because of non-union

Treatment in relation to healing (Table 23)

In the 47 conservatively treated patients, skull traction during at least six weeks gave the best result. There were 21 patients in this group; 14 had bone union and 7 non-union. If the fracture was mobile when taking away the traction after two months, it seemed to be of no use to continue the traction. In 3 patients being unstable after two months' skull traction an additional month of this treatment did not result in healing.

Five patients had had skull traction for less than six weeks followed by mobilization in a collar. Two had bone union and 3 had non-union.

Seven had been treated in bed with sand bags, collars or a Glisson sling. Of these, 4 had bone union and 3 non-union.

Of the 14 patients who had had a collar or a Minerva jacket two to four months, 4 had bone union and 10 non-union.

Comment: The best results were obtained in the group treated with skull traction more than six weeks. When comparing this group with those treated with a collar or a Minerva jacket the result was significantly better ($p < 0.05$).

Table 23. Treatment in relation to healing at follow-up of 47 conservatively treated patients with odontoid fracture.

Treatment	Number of patients	Bone union	Non-union
Skull traction > six weeks	21	14	7
Skull traction < six weeks	5	2	3
Bed rest and sandbags, collar, or Glisson sling	7	4	3
Collar or Minerva jacket	14	4	10

Delay in treatment in relation to healing (Table 24)

Treatment between one and seven days: There were 13 patients in this group; 7 had bone union and 6 non-union.

Treatment after seven days: There were 3 patients in this group; 2 had bone union and 1 non-union.

Comment: In this material a delay in treatment did not cause a higher incidence of non-union. On the other hand it should be pointed out that in most patients the delay was only a few days.

Table 24. Delay in treatment in relation to healing at follow-up of 47 conservatively treated patients with odontoid fracture.

Delay in treatment	Number of patients	Bone union	Non-union
1 – 7 days	13	7	6
More than 1 week	3	2	1

Age in relation to healing (Table 25)

Eleven (50 %) of 22 patients 40 years of age or less and 13 (52 %) of 25 patients over 40 years of age healed with bone union.

Comment: Age has also been regarded as a factor that might influence the healing rate. Arteriosclerosis develops with increasing age. It has been postulated that arteriosclerosis may cause a decrease in the arterial blood supply to the odontoid process (Apuzzo et al. 1978). Non-union may develop as a result of insufficient arterial blood supply. The figures in this investigation do not give any support to such an assumption.

Table 25. Age in relation to healing at follow-up of 47 conservatively treated patients with odontoid fracture.

Age	Number of patients	Bone union	Non-union
11 – 20 years	5	5	0
21 – 30 years	10	2	8
31 – 40 years	7	4	3
41 – 50 years	7	5	2
51 – 60 years	6	3	3
61 – 70 years	9	5	4
71 – 80 years	3	0	3

Level of fracture in relation to healing (Table 26)

Of 11 patients with a type A fracture, 4 (36 %) had bone union and 7 (64 %) non-union. All patients with non-union showed mobility at the fracture site during provocation roentgen examination, 2 both in flexion-extension and lateral bending, 5 only in lateral bending.

Of 22 patients with a type B fracture, 10 (45 %) had bone union and 12 (55 %) non-union. Nine of the patients with non-union showed mobility, 2 both in flexion-extension and lateral bending, 3 only in flexion-extension, and 4 only in lateral bending. In 2 of the 3 remaining patients with non-union, a posterior fusion had been performed and in 1 an anterior fusion had developed spontaneously.

Of 6 patients with a type C fracture, 3 (50 %) had bone union and 3 (50 %) non-union. None of the patients with non-union showed mobility; in 1 of them a posterior fusion had been performed.

Of 8 patients with a type D fracture, 7 (87 %) had bone union and 1 (13 %) non-union. The patient with non-union, in whom a posterior fusion had been performed, showed no mobility.

Comment: These figures indicate that when comparing the different fracture types, the rate of bone union was significantly ($p < 0.05$) increased the more of the body of the axis the fracture involved.

It has been postulated that in some instances of non-union there is a firm fibrous union which might be almost as stable as a bone union (Blockey and Purser 1956, Solovay 1960, Kattan 1975). In this investigation only 2 of 18 patients with non-union (fusions excluded), were stable roentgenologically in all directions. Nine were stable in flexion-extension but mobile in lateral bending (5 type A and 4 type B fractures); 3 were stable in lateral bending but mobile in flexion-extension (type B fractures); 4 were mobile in both flexion-extension and lateral bending (2 type A and 2 type B fractures). The reason for this difference in mobility might be the ligament arrangement in the surroundings of the fracture, the shape of the fracture and the ligamentous injuries caused by the fracture. Both anteriorly and posteriorly the odontoid fracture is supported by the longitudinal ligaments. Laterally, ligamentous support is missing. In cases of lateral mobility but flexion-extension stability, the stability mainly may be determined by the longitudinal ligaments.

Table 26. Level of the fracture in relation to healing at follow-up of 47 conservatively treated patients with odontoid fracture.

Level of fracture	Number of patients	Bone union	Non-union
Type A	11	4	7
Type B	22	10	12
Type C	6	3	3
Type D	8	7	1
	47	24	23

Displacement of fracture in relation to healing (Tables 27 and 28)

Degree of displacement (Table 27): Sixteen patients had fractures displaced more than 4 mm; 8 had bone union and 8 non-union. Twenty-three patients had fractures displaced 4 mm or less; 11 had bone union and 12 non-union. Eight patients had no displacement; 5 had bone union and 3 non-union.

Comment: The degree of displacement has been discussed as a factor influencing the healing rate (Schatzker 1971, Roberts and Wikstrom 1973, Apuzzo 1978).

The figures in this investigation do not give support to this assumption. When comparing fractures displaced more than 4 mm with fractures displaced 4 mm or less no difference could be found between the groups.

Table 27. Degree of displacement at fracture site in relation to healing at follow-up of 47 conservatively treated patients with odontoid fracture.

Degree of displacement	Number of patients	Bone union	Non-union
More than 4 mm	16	8	8
4 mm or less	23	11	12
Undisplaced	8	5	3

Table 28. Direction of displacement at the fracture site in relation to healing at follow-up of 47 conservatively treated patients with odontoid fracture.

Displacement	Number of patients	Bone union	Non-union
Anterior	19	14	5
Anterolateral	2	1	1
Posterior	12	3	9
Posterolateral	4	0	4
Lateral	2	1	1
No displacement	8	5	3

Direction of displacement (Table 28): Of 19 patients with anterior displacement, 14 had bone union and 5 non-union. Of 2 patients with anterolateral displacement, 1 had bone union and 1 non-union. Of 12 patients with posterior displacement, 3 had bone union and 9 non-union. All 4 patients with posterolateral displacement had non-union. Of 2 patients with lateral displacement, 1 had bone union and 1 non-union. Of 8 patients with undisplaced fracture, 5 had bone union and 3 non-union.

Comment: Direction of displacement has also been discussed as a factor influencing the healing rate (Schatzker 1971, Roberts and Wikstrom 1973, Apuzzo 1978).

In this investigation anterior displacement was found to give a higher incidence of bone union (74 %), than a posterior displacement (25 %). These figures are significant ($p < 0.05$). When adding the obliquely displaced fractures the difference in bone union between anterior and posterior displacement was further increased ($p < 0.01$).

GENERAL DISCUSSION

After reviewing the literature and studying the results of this investigation there are problems which still remain unsolved. On the other hand, there are some problems which have been better understood.

Experimental study of the fracture mechanism

In all, 26 experimental odontoid fractures have been found in the literature (Orfila 1848, Selecki et al. 1970, Voigt et al. 1978, Mouradian et al. 1978). In each of the three first cited investigations, 1 odontoid fracture occurred when the authors were studying the influence of different types of forces on the cervical spine. Mouradian et al., however, tried to produce odontoid fractures and they succeeded in 23 experiments. In their investigation the axis was fixed and the force was applied to the odontoid process, the atlas or the skull base.

In the experimental part of this investigation, 30 odontoid fractures were produced. C III was fixed but the axis and the atlas were free. A wooden block was fixed to the skull base. The impact was directed to this block, which simulated the skull. The junctions occiput-atlas, atlas-axis and axis-C III were mobile in all experiments.

Theories on hyperflexion, hyperextension and horizontal shear as the cause of odontoid fractures (Jefferson 1920, Wüsthoff 1923, Osgood and Lund 1928, Plaut 1938, Amyes and Anderson 1956, Blockey and Purser 1956, Howorth and Petrie 1964, J. Böhler 1965, Kattan 1975, Mouradian et al. 1978, Sköld 1978) could not be verified in this investigation. These types of impact caused injuries below the axis. A new hypothesis was formed, and when performing experiments according to this, using an impact that combined horizontal shear and vertical compression, fractures of the odontoid process could be produced. Moreover, by changing the direction of the impact in relation to the sagittal plane through the axis, different types of odontoid fractures were produced.

The connection between the direction of the impact in relation to the sagittal plane and the fracture types has not earlier been described in the literature. With an impact straight in the sagittal plane (anterior or posterior), type D fractures were produced. With an impact 45° to the sagittal plane (anterolateral), type B fractures were produced. With an impact 90° to the sagittal plane (lateral), type A fractures were produced.

After reviewing the literature, Schatzker et al. (1971) suggested that the component of horizontal shear in a blow on the head was responsible for the displacement of the odontoid fracture. In the present investigation, it was found that all the different fracture types could be displaced or angulated in the direction of the component of horizontal shear in the impact, and more so anteriorly or posteriorly than laterally. The same amount of energy that caused a total separation of the specimen when producing a type D fracture (impact in the sagittal plane) caused only a slight lateral angulation of the odontoid process when producing a type A fracture (lateral impact). It was further observed that the type B fracture (anterolateral impact 45° to the sagittal plane) was displaced more posteriorly than laterally.

Excluding 2 experiments (total separation of the specimen), the type D fractures (anterior or posterior impact) were accompanied by elongation or rupture of the longitudinal ligament on the impact side, whereas the opposite longitudinal ligament was intact in length but torn from the body of the axis. Similar ligament injuries were seen in type B fractures. In type A fractures, no injury to the longitudinal ligament could be observed.

It may be speculated that the atlanto-axial joints owing to their shape protect the odontoid process and the longitudinal ligaments better against a lateral impact than against one acting in the sagittal plane. If this is true, the odontoid fracture ought to be more displaced anteriorly or posteriorly than laterally. Accordingly, in clinical materials, several authors report more anterior or posterior displacement than lateral (Nachemson 1960, Schatzker et al. 1971, Husby and Sörensen 1974).

In the present investigation, odontoid fractures were produced only when the forces were directed so that no or only minimal flexion, extension and lateral bending occurred in the atlanto-occipital joints and upper cervical spine. This contradicts the opinion that odontoid fractures are produced by hyperflexion or hyperextension (Jefferson 1920, Wüsthoff 1923, Osgood and Lund 1928, Amyes and Anderson 1956, Blockey and Purser 1956, J. Böhler 1965, Kattan 1975, Sköld 1978, Mouradian et al. 1978). Indirectly, support to the observations in the present investigation is obtained from Mouradian et al. (1978) when they say about their extension experiments: "The major difficulty was inability to obtain suitable fixation of the anterior surface of the axis in the epoxy preparation". This statement supports the basic idea in the present investigation that an extension will create a distraction force of the anterior aspect of the specimen and cause injury below the axis.

Comparison between experimental and clinical odontoid fractures

It was difficult to find out from the medical records where the impact causing the fracture had struck the patient. At follow-up, many patients had forgotten the details of any hematoma or swelling in the face or the skull they might have had after the accident. In the experimental study, the level of the fracture, direction of the displacement, and the pattern of concomitant ligament injuries were decided by the direction of the impact in relation to the sagittal plane. Therefore, if one knows, after an accident, the direction of the impact that has caused an odontoid fracture, one should be able to calculate in which position the fracture is most stable and in which direction there is a risk for increased displacement.

The degree of displacement of an odontoid fracture may reflect the degree of the concomitant ligament injuries: with increasing displacement, the ligaments may give less support to the fracture. Schatzker et al. (1971) and Apuzzo et al. (1978) found that the rate of non-union increased with increasing displacement. In this investigation such a correlation between non-union and increasing displacement could not be seen. This could be explained by the difference in treatment. The majority of patients treated in a collar or Minerva jacket had no or only minor displacement; an insufficient immobilization in these patients probably has increased the rate of non-union.

Radiography in maximal flexion, extension and lateral bending

Radiographic examination with the head in maximal flexion and extension is almost a routine for diagnosing instability of the cervical spine. Since all the experimental fractures were mobile also in lateral bending (type A only in this direction), it was interesting to test the stability of the non-united odontoid fractures also in lateral bending. Of the follow-up examined patients, 19 had non-union. One of them had spontaneously developed an anterior fusion. This patient and 2 others with non-union showed stability at the fracture site when they were radiographically examined in maximal flexion, extension and lateral bending. The remaining 16 patients showed mobility, 3 in flexion-extension, 9 in lateral bending, and 4 both in flexion-extension and lateral bending. The large number of patients with mobility, 16 of 18 if the patient with anterior fusion is excluded, might indicate that the fibrous tissue in the gap of the fracture in patients with non-union is not as firm as has been supposed earlier (Blockey and Purser 1956, Solovay et al. 1960, Kattan 1975).

Treatment

Conservative treatment: The treatment in this investigation had varied partly because the different orthopaedic surgeons had tried to individualize it and partly because some patients had refused skull traction. Twenty-four of 47 conservatively treated patients had developed bone union and 23 non-union. This result is similar to those reported earlier.

There was a statistically significant higher rate of bone union in the patients treated more than six weeks in skull traction than in those treated with a collar or Minerva jacket ($p < 0.05$). The importance of the stability of the fixation has been pointed out by Schatzker et al. (1975). They found in experimental work on dogs that bone union occurred after osteotomy of the odontoid process in all instances in which the odontoid process was adequately fixed. They concluded that mobility of the odontoid process might be an important factor in the development of non-union.

Conservative treatment has been advocated by many authors, e.g. Blockey and Purser (1956), Nachemson (1960), and J. Böhler (1965); the treatment consists in bed rest and skull traction followed by a period of immobilization in a collar. According to Nachemson (1960) this conservative treatment always results in stable healing, providing it is instituted without delay.

Stable external fixation permitting early mobilization: The Halo apparatus offers such a possibility, and may prove superior to other conservative methods in the treatment of odontoid fractures. The Halo, fixed to the skull, is connected to a vest of proper size by adjustable bars. The position of the head and the cervical spine can be controlled by adjustment of the Halo in relation to the bars. Thus, it is possible to reduce an odontoid fracture and to keep it in reduced position by moving the head in a direction opposite to that of the impact that has caused the fracture. In this way, it may be possible to give adequately directed tension to uninjured ligaments which can restrict the mobility of the fractured odontoid process. Recently, three series of Halo-vest treatment of odontoid fractures have been reported. Schweigel (1977) treated 14 patients, 5 with posterior and 9 with anterior displacement; all fractures healed. Seljeskog (1978) treated 15 patients in a Halo-vest for eight weeks and 12 in skull traction for six weeks; 2 fractures failed to unit, but it was not stated which group they belonged to, nor was any difference made between fibrous union and bone union. Apuzzo et al. (1978) treated 5 patients; the result was non-union in 3. Nothing was said in these three reports about the position in which the fracture was fixed in the Halo apparatus.

Early surgical fusion: The aim of an early posterior fusion has been to avoid late complications (Gallie 1939, Rogers 1942, Alexander et al. 1958). In this investigation, 1 patient had died eight months after the accident because of redislocation; early surgical fusion might have prevented this complication. One patient had been operated on early with posterior fusion, which had healed.

Late surgical fusion: A primarily conservative treatment followed by surgical fusion in cases of redislocation or when the fracture shows no tendency to heal has been suggested by some authors, e.g. Grogono (1954) and Braakman and Penning (1971). In this investigation, 5 patients had been operated on late because of non-union. The fusion had healed in all of them.

Treatment in respect of fracture level: Several authors maintain that there is a high risk for non-union when the fracture passes through the odontoid process without involving any part of the body of the axis, and that bone union is increasingly likely to occur the more the fracture involves of the body of the axis (Roberts and Wikstrom 1973, Bailey 1974, Husby and Sörensen 1974). The results of our investigation support this opinion. Roberts and Wikstrom (1973), and Husby and Sörensen (1974) have proposed early surgical fusion in fractures not involving any part of the body of the axis.

Treatment in respect of age: Braakman and Penning (1971) found that 5 of their elderly patients who were treated conservatively died during bed rest. They therefore proposed early reduction and ambulation in a collar as soon as possible in older patients. Such treatment seems advisable also in respect of observations made in the present investigation. Of 16 patients over 70 years of age 6 died, and 5 survived treatment in bed, whereas all 5, who were mobilized early, could leave the hospital.

Arterial supply of the odontoid process in relation to fracture level

Schatzker et al. (1975) studied the arterial supply of the odontoid process in dogs. They made osteotomies through the odontoid process at the isthmus and at the base. They found that the contrast medium filled the arteries within the odontoid process independent of the level of the osteotomy. They concluded that a disturbance in the arterial supply to the odontoid process would not have any great influence on the development of non-union.

When, in the present investigation, experimental odontoid fractures were produced it was found that more injuries to the soft tissues surrounding the fracture occurred the deeper the fracture passed into the body of the axis. Most injuries to the longitudinal ligaments were found in type D fractures despite that such fractures were produced using the smallest amount of energy; in type A fractures (the highest type), no injuries to the longitudinal ligaments were observed. The ascending arteries (paired anterior and posterior) run in close relation to the anterior and posterior longitudinal ligaments. From the study of the fracture mechanism of odontoid fractures it may be speculated that the ascending arteries would sustain more injuries the lower the fracture is situated. It was difficult to detect injuries to the ascending arteries because of leakage of contrast medium around the fracture. However, in those experiments in which injuries to the ascending arteries were found, type D or type B fractures had occurred.

In type A fractures, the odontoid process looses its supply from the arteries entering at its base. In spite of this, arteries within the odontoid process became filled when contrast medium was injected after the production of type A fractures. This filling must have been mediated by arteries entering at the apex of the odontoid process.

CONCLUSIONS

The following conclusions can be made:

1. It was possible to produce fractures of the odontoid process by an impact to the skull.
2. Fractures of the odontoid process could be produced by a combination of a horizontal shearing force and a vertical compression force.
3. The level of the odontoid fracture was determined by the direction of the impact in relation to the sagittal plane through the axis.
4. The sloping of the fracture and the associated ligament injuries allowed the odontoid process to be displaced in the direction of the impact and stabilized in the opposite direction.
5. After an experimental odontoid fracture there was arterial supply to the odontoid process independent of the level of the fracture.
6. The rate of bone union was significantly ($p < 0.05$) higher the more the fracture involved the body of the axis, when comparing the fracture types.
7. The rate of bone union was significantly ($p < 0.05$) higher in fractures displaced anteriorly compared to those displaced posteriorly.
8. The rate of bone union was significantly ($p < 0.05$) higher after skull traction > 6 weeks compared to treatment in a collar or Minerva jacket.

SUMMARY

The object of this investigation has been:

to carry out an experimental study on the fracture mechanism in odontoid fractures,

to study whether the extrinsic and intrinsic arterial supply to the odontoid process suffers any damage by the production of experimental fractures,

to study a clinical material of odontoid fractures including a follow-up examination.

Experimental fractures of the odontoid process

Forty-one experiments were carried out to analyse the fracture mechanism in odontoid fractures. Cervical spine specimens from cadavers were fixed in a metal box leaving the axis and atlas free. A wooden block was attached to the skull base. This block, simulating the skull, was subjected to an anterior, posterior, anterolateral, posterolateral, or lateral impact by a pendulum. Earlier theories on hyperflexion, hyperextension, and horizontal shear (anterior or posterior) as the cause of odontoid fractures were tested. However, no odontoid fracture could be produced; the injuries were below the axis. Vertical compression also failed to produce odontoid fractures; it resulted in fractures of the atlas.

Since previously advanced theories could not be verified by these experiments, the question was raised: Could a fracture of the odontoid process be produced by a combination of horizontal shear and vertical compression?

Using such a combined type of impact it became possible to produce fractures of the odontoid process, and by changing the direction of the impact in relation to the sagittal plane through the axis, it also became possible to decide the level at which the fracture occurred.

It was found practical to use a new classification:

type A: fracture through the isthmus of the odontoid process,

type B: fracture passing down into the most superior part of the body, but not involving the superior articular facets of the axis,

type C: fractures through the superior part of the body and the medial part of one of the superior articular facets of the axis (clinical only),

type D: fracture through the superior part of the body and the medial part of both the superior articular facets of the axis.

When the impact was a combination of horizontal shear and vertical compression in the sagittal plane (anterior or posterior impact), 8 type D fractures were produced.

When the same combined type of impact was directed 45° to the sagittal plane (anterolateral impact), 3 type B odontoid fractures were produced.

When the same combined type of impact was directed 90° to the sagittal plane (lateral impact), 4 type A odontoid fractures were produced.

No type C fracture was produced.

A prerequisite for the production of odontoid fractures was that the combined forces, horizontal shear and vertical compression, were arranged in such a way that no or only minor movement occurred in the atlanto-occipital joints and upper cervical spine.

All the odontoid fractures sloped downwards in the direction of the impact.

Excluding 2 fractures in which there was a total separation of the specimen, the fractures could be displaced in the direction of the impact and stabilized in the opposite direction.

The energy used for producing fractures at different levels of the odontoid process differed. Type D fractures were produced using approximately 1/2 and type B fractures approximately 3/4 of the energy required for the production of type A fractures.

Fifteen additional odontoid fractures were produced when studying the effect of odontoid fractures on the arterial supply of the odontoid process.

Arterial supply of the odontoid process

The normal arterial supply of the odontoid process has been studied in a previous investigation. It was found that this bone is located in the centre of an arterial network, and that arteries entering at the apex of the odontoid process form intra-osseous anastomoses with arteries entering at the base. The damage to this network, and to intra-osseous arteries, sustained by fracturing the odontoid process was studied experimentally. Fifteen odontoid fractures were produced (5 type D, 5 type B, and 5 type A): they were similar to those occurring in patients.

The arteries of the cervical spine from 6 human cadavers were filled with Micropaque® solution *prior* to the experimental fracture. Nine specimens were filled *after* the fracture had been produced. The experimentally produced fractures, irrespective of type, did not prevent the arteries in the odontoid process on either side of the fracture to be filled with contrast medium.

Clinical and radiographic follow-up study

In odontoid fractures, a rate of non-union between 0 and 80 % has been reported. The purpose of this investigation was to describe the clinical course and radiographic features in patients with odontoid fractures.

The medical records and radiographs from 78 patients were collected from different hospitals in western Sweden. A follow-up study including a clinical and radiographic examination was performed in 48 patients during 1978 with a follow-up time ranging between 3.5 and 13 years. Most fracture were caused by a high velocity force. Eighteen patients had neurological symptoms on arrival at hospital, mostly slight symptoms, but 1 patient had tetraplegia.

Thirteen fractures belonged to type A, 40 to type B, 10 to type C, and 15 to type D. In 30 patients not available for follow-up examination, earlier radiographs had shown non-union in 5 patients. Three patients had died because of the odontoid fracture (after two days, three weeks, and eight months).

At the follow-up examination, 20 patients had slight discomfort and 28 no symptoms.

Twenty-four patients had bone union. One had been operated on early with posterior fusion, and 4 had undergone such an operation late (because of non-union). All fusions had healed, but the state of the fracture could not be determined on the radiographs (tomography was not performed). Nineteen patients had non-union, 1 of them with spontaneous anterior fusion between the axis and the atlas. This patient and 2 others with non-union were stable; of the remaining 16 patients with non-union, 3 showed mobility in flexion-extension, 9 in lateral bending, and 4 in flexion-extension and lateral bending.

Of 57 patients treated in bed, 10 died within the first six weeks after the fracture. None of 21 patients, who were mobilized early, died within six weeks. Especially the older patients seemed to be vulnerable to bed rest.

When comparing bone union in patients treated in skull traction more than six weeks with patients treated in a collar or Minerva jacket, the result was significantly better after skull traction ($p < 0.05$).

Anterior displacement gave a significantly higher incidence of bone union than posterior displacement ($p < 0.05$).

The level of the fracture also influenced the outcome. When comparing the different fracture types, the rate of bone union was significantly ($p < 0.05$) increased the more of the body of the axis the fracture involved.

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