Axis Fractures

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BACKGROUND: Traumatic fractures of the second cervical vertebra are common, representing nearly 20% of all acute cervical spinal fracture-dislocation injuries. They are divided into 3 distinct injury patterns: odontoid fractures, hangman's fracture injuries, and fractures of the axis body, involving all other fracture injuries to the C2 vertebra.

OBJECTIVE: An evidence-based overview of the medical and surgical treatment strategies for each axis fracture injury sub-type.

RESULTS: Current medical and surgical management of traumatic fractures of the axis.

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Fractures of the axis are common traumatic injuries of the upper cervical spine that present management challenges to the practicing spinal surgeon. Axis fractures account for almost 20% of all acute cervical spinal fractures. The rates of neurological deficit and acute mortality associated with axis fractures from the largest institutional series of axis fractures were 8.5% and 2.4%, respectively.[1] Autopsy studies have revealed that a significant proportion of deaths at the scene of traffic accidents are associated with fractures of the upper cervical spine; of these, axis fractures are estimated to range from 25% to 71%.[2-5] The unique anatomy and biomechanics of the C2 vertebra and its ligamentous attachments with the atlas necessitate full evaluation of the C1 and C2 vertebral complex before a management decision is rendered.

Since our original series more than 20 years ago,[6] much has evolved in the evaluation and management of axis fractures. Fine-cut computed tomography scans with multiplanar reconstructions provide a more detailed evaluation of the fracture characteristics than previously possible. Magnetic resonance imaging allows direct assessment of the ligamentous structures and of the underlying spinal cord. External orthosis or cable internal fixation constructs were originally the mainstays of treatment. Currently, dens screws, transarticular screws, and screw-rod systems are being used with increasing frequency to augment arthrodesis, often without orthoses. This review serves to document the different fracture types and ligamentous injuries of the axis as well as provide a medical evidence–based discussion of their treatment.

ODONTOID FRACTURES

Historical Overview

The first description of the surgical management of an odontoid fracture occurred in 1910 and is credited to Mixter and Osgood.[7] In 1928, Osgood and Lund[8] were among the first to bring a series of fractures of the odontoid process to the attention of the medical field. Their review included 55 cases reported to date in the medical literature. In contrast to what we now know, they found a high incidence of death and neurological injury in patients with these fractures. Ten patients whom they reported were not paralyzed by their initial C2 fracture injury, but then died after a second trivial traumatic event caused paralysis. Based on their review, Osgood and Lund opined that union after an acute C2 dens fracture was rare.

Classification

The classification of odontoid fractures was first developed by Anderson and D'Alonzo[9] in 1974. The authors based their study on 60 patients with acute fractures of the dens. Their classification scheme is used today with little modification. This historic article identified 3 types of fractures based on the anatomic location of the fracture line and is described here in the authors' original language: "Type I is an oblique fracture through the upper part of the odontoid process itself and probably represents an avulsion fracture where the alar ligament attaches to the tip of the odontoid process. Type II is a fracture occurring at the junction of the odontoid process with the body of the second cervical vertebra). Type III is a fracture line that extends downward into the cancellous portion of the body and is really a fracture through the body of the axis." They further classified each of these types as displaced or nondisplaced (Figures 1-4).

Hadley et al[10] provided the only accepted modification to the Anderson and D'Alonzo classification of odontoid fractures. In 1988, Hadley et al[10] described the type IIA odontoid fracture. This subclass of odontoid type II fracture has additional chip fracture fragments at the anterior or posterior aspect of the base of the dens. This classification modification is significant because this fracture subtype is markedly unstable and uniformly leads to nonunion irrespective of the direction or degree of initial dens placement. Most clinicians argue that odontoid type IIA fractures should therefore be considered for early surgical stabilization and fusion. This subclass of fracture accounts for 5% of type II fractures.

FIGURE 1. *Lateral view of a type II odontoid fracture with greater than 5 mm posterior displacement.*

FIGURE 2. *Coronal computed tomography of a type II odontoid fracture.*

In 2005, Grauer et al[11] proposed a modified classification system of odontoid fractures to help aid in fracture management. The system modified and redefined the Anderson and D'Alonzo type II and III odontoid fracture subtypes. Type II fractures in their scheme could have a fracture line that went into the C2 body, as long as it did not involve the superior articular facets. A type III odontoid fracture included those with a fracture line that involved the superior articular facet. Type II fractures were divided into 3 subtypes. A type II subtype A dens fracture is a transverse fracture without comminution and less than 1.0 mm of displacement. The authors believe that this subtype is best treated with external immobilization. A type II subtype B dens fracture is a fracture that passes from anterosuperior to posteroinferior or a transverse fracture with displacement greater that 1.0 mm. This subtype is thought to be ideal for anterior screw fixation. A type II subtype C dens fracture is defined as a fracture that passes from anteroinferior to posterosuperior or a fracture with significant comminution of the dens. According to the authors, this subtype is best treated with posterior atlantoaxial fixation. Their analysis did not assess their classification scheme with respect to treatment. They attempted to discern whether their classification subtypes could be consistently and reliably reproduced by different evaluators. The utility of their scheme with respect to outcome is now under investigation.

FIGURE 3. *Sagittal computed tomography of a type II odontoid fracture with 2 mm of posterior displacement.*

FIGURE 4. *Coronal view on computed tomography of a complex type III odontoid fracture.*

Incidence

Odontoid fractures represent the most common fractures of the axis. In the Greene et al[1] series of 340 axis fractures, odontoid fractures accounted for 199 of the axis fractures (59%) that they encountered. The type I odontoid fracture is by far the least prevalent. In the Greene et al[1] series, it accounted for only 2 of all odontoid fractures (1%). Anderson and D'Alonzo reported only 2 type I dens fractures (3%) in their series of 60 dens fractures. The type II odontoid fracture is the most common dens fracture. Greene et al reported 120 (60%) in their series and Anderson and D'Alonzo had 32 (54%). The type III odontoid fracture was the second most common in both the Greene et al and Anderson and D'Alonzo reviews with 39% (77 of 199 fractures) and 42% (25 of 60 fractures), respectively.

Management

In 1985, the Cervical Spine Research Society[12] published a multicenter review addressing the management of odontoid fractures. This report included 18 patients with type II odontoid fractures and 3 patients with type III odontoid fractures who received no treatment. None of these patients achieved bony fusion. The authors of this review concluded that no treatment of odontoid fractures is an unacceptable management option.

There have been many treatment strategies proposed for odontoid fractures. These strategies are based on fracture type, the degree of initial dens displacement, the angle of the fracture line with respect to the body of the axis, the integrity of the transverse ligament, and the age of the patient. Treatment options include both nonoperative and surgical strategies. There are several external immobilization orthoses available for nonoperative management of odontoid fractures, each with variable results. Surgical options include both anterior and posterior approaches. Anterior approaches include odontoid screw fixation and a rarely used salvage technique of anterior transarticular screw fixation. Posterior arthrodesis approaches include the use of wiring techniques, Halifax clamps, screw and rod constructs, and posterior transarticular screw fixation.

Traction/Cervical Collar

Traynelis[13] and Julien et al[14] performed reviews of the literature on odontoid fractures treated with traction for 4 to 6 weeks followed by cervical collar immobilization for varying periods of time. Julien et al cited 7 articles containing class III medical evidence regarding the use of traction.[9,13,15-19] Type I odontoid fractures demonstrated a 100% fusion rate in 3 cases. Type II odontoid fractures were found to have a 57% fusion rate (55 of 97 fractures) when managed this way. In patients with type III fractures, bony fusion was obtained at a rate of 88% (57 of 65 fractures). For type I and III fractures, the rates of fusion for this treatment strategy are considered acceptable. However, type II fracture healing outcomes with the use of traction followed by collar immobilization are less than attractive and suggest that this treatment strategy is not ideal for most type II fracture injuries. Most clinicians argue that it is intuitively obvious that extended periods of traction followed by cervical collar immobilization is not an acceptable treatment for any odontoid fracture. This method of treatment should only be applied to extremely unstable, critical care patients who are unable to undergo any other type of treatment for their C2 injury.

Cervical collar immobilization alone has also been used in the management of acute dens fractures. For type I fractures, this treatment alone seems sufficient.[9,13,15] Even though accepted as the mainstay of treatment for type III odontoid fractures, use of a cervical collar had an associated 10% incidence of nonunion and a 40% incidence of malunion in a series by Clark and White.[12] Conversely, Polin et al[19] demonstrated 100% fracture healing and stability on postimmobilization flexion and extension radiographs in 18 patients with type III fractures whom they managed with collar immobilization. These 2 studies are retrospective and are limited in power by small numbers. For type II odontoid fractures, Polin et al[19] demonstrated a fusion rate of only 53% in patients managed with a cervical collar. In an earlier study, Wang et al[20] described similar results with type II fractures treated with cervical collar immobilization. They cited a bony fusion rate of only 57% after treatment.

Halo-Device Immobilization

Greene et al[1] treated 2 patients with type I fractures with halo-vest immobilization; bony fusion was obtained in both at 12 weeks. This result is similar to that found by the Julien et al[14] analysis, which reviewed 9 case series.[12,15,18,21-26] Among the 9 series that they summarized, 3 type I fractures were identified and all (100%) experienced successful union after immobilization in a halo device.

In the Greene et al[1] series of 340 axis fractures, 69 patients with type III odontoid fractures were treated with halo-vest immobilization, and bony fusion was obtained in all but 1 patient. This translates into a 1.4% nonunion rate for type III fractures treated with halo-vest immobilization. Treatment duration ranged from 10 to 20 weeks, with a median treatment time of 12 weeks. Polin et al[19] reported similar results with type III fractures, noting that bony union was obtained in 100% (13 of 13). These 2 studies had slightly better results than those in the 67 of 80 patients (84%) with type III fractures in whom bony union was obtained after treatment with a halo vest or Minerva jacket in the Julien et al[14] analysis. Of the 13 failures in their report, 7 cases were described as malunion (bony healing in a nonanatomic/malaligned position). Six cases in their series met criteria for nonunion (7.5%). This collective class III experience suggests that rigid immobilization is an effective management strategy for patients with either type I or III odontoid fracture injuries.

The management of acute type II odontoid fractures with a halo-vest device reveals fairly consistent results in the literature, but there are subgroups of patients who fare better than others. There were 120 patients with a type II odontoid fracture in the Greene et al[1] series of 340 axis fractures. Of these, 88 patients with type II dens fractures initially managed nonoperatively were available for long-term follow-up. Bony fusion failed to be achieved in 25 patients (28.4%) with type II fractures managed with a halo-immobilization device. Of the 25 patients with nonunion, 7 were treated for extended durations in the halo-vest device and bony fusion was eventually obtained. The Julien et al[14] analysis included 168 patients with type II odontoid fractures treated with a halo-vest orthosis. Union was not obtained in 50 patients (29.7%). An additional 8 patients with type II fractures were classified as having malunions. The Polin et al[19] review described different measures of success of treatment. Ultimately, when bony fusion of the type II dens fracture was the endpoint, halo-vest immobilization failed to accomplish fusion in 5 of 19 patients (26.3%) managed this way.

Prognostic Factors for Type II Odontoid Fractures Treated With Halo-Device Immobilization

There are many theories to explain why type II odontoid fractures are more susceptible to nonunion compared with type I and III dens fractures. As summarized by Maiman and Larson,[27] there are 2 vascular arcades that provide blood supply to the axis (originally described by Schiff and Park[28] in 1973). One arcade supplies the body of the axis and the other arcade supplies the tip of the odontoid process. In between the 2 arcades, there is an area of relatively poor blood supply at the base of the dens. This zone may become avascular after fracture, particularly with displacement or instability. In addition, the odontoid process is enveloped in a synovium and lacks a periosteal blood supply. This too likely plays a role in the relative ischemia of the base of the dens after acute fracture. Another factor that may contribute to failure of fusion of a type II fracture is the orientation of the apical ligaments. After fracture, the apical ligaments create a distraction effect pulling the fracture plane apart, creating a gap that obviates endosteal healing of the odontoid break.

Several studies have attempted to evaluate halo-vest treatment of type II fractures to determine which fracture types might be best treated with the halo vest and conversely which should be managed with surgical internal fixation and fusion. One such injury is the type IIA odontoid fracture.[1,10] This fracture uniformly leads to nonunion with halo-vest immobilization irrespective of the direction or amount of initial dens displacement and therefore should be considered for early surgical stabilization and fusion. Hadley et al[6] in 1985 reported that type II odontoid fractures with a dens displacement of 6 mm or greater had a nonunion rate of 67% after halo-device immobilization. Patients with less than 6 mm of dens displacement had a nonunion rate of only 26%. This was statistically significant regardless of patient age, direction of dens displacement, or neurological deficit. This relationship was later confirmed by Greene et al[1] in a larger series in published 1997. A correlation between dens displacement and healing was found by other investigators as well. Apuzzo et al,[29] Clark et al,[12] Dunn and Seljeskog,[24] Ekong et al,[25] and Lind et al[26] all reported that the degree of initial dens displacement after fracture injury has a negative correlation with healing when managed with external orthosis.

Patient age has also been cited as important with respect to fusion failure or success after type II dens fracture. In a case-controlled class II medical evidence study, Lennarson et al[30] evaluated 33 patients with isolated type II odontoid fractures treated with halo-vest immobilization. The authors found that age older than 50 years was a significant factor for failure of fusion in a halo immobilization device. Patients 50 years of age and older had a risk of nonunion 21 times higher than that found for patients younger than 50 years of age. No significant effect on outcome could be attributed to other medical conditions, the sex of the patient, degree of fracture displacement, direction of fracture displacement, length of hospital stay, or length of follow-up in their comparative review.

Operative Treatment of Odontoid Fractures

Evolution of Operative Treatment

Posterior cervical internal fixation and fusion were the mainstay of operative treatment for unstable odontoid fractures for decades. The earliest literature on operative treatment of odontoid fractures dates back to the early 1900s. In 1910, Mixter and Osgood[7] reported the first surgically treated cases. Originally, the constructs involved bone-wire techniques. In 1939, Gallie[31] was the first to describe such a technique. Since that early report, there have been several bone-wire/cable and bone-wire/cable-bar constructs that have been described, each with respective advantages and disadvantages. Although these techniques have largely given way to newer internal fixation methods, they still are good constructs for rescue and supplementation.

In 1975, Tucker[32] described the use of interlaminar clamps. This method enjoyed a brief period of being in vogue among surgeons, but was never widely accepted. In 1979, Magerl[33] developed a technique of atlantoaxial screw fixation via a dorsal transarticular approach. In 1981, Böhler[34] described a unique method of treatment for odontoid fractures. Böhler's screw osteosynthesis technique was novel in that it was an anterior approach and provided immediate internal fixation and stabilization of the actual odontoid fracture. In 1994 and later in 2001, Goel et al[35] and Harms and Melcher,[36] respectively, described the use of a C1 lateral mass and C2 pedicle screw and rod technique of atlantoaxial stabilization. Most recently, in 2004, Wright[37] described a polyaxial screw and rod technique using bilateral crossing C2 laminar screws instead of pedicle screws to fixate C1 to C2.

Posterior Cervical Fixation

Wire/Cable-Bone Techniques

Wire Versus Cable. Different metals have different stiffness, flexibility, fatigue susceptibility, strength, and elasticity.[38] Stainless steel was long the alloy of choice in spinal instrumentation because it is strong and not excessively stiff. Although titanium produces less artifact than steel, it has the disadvantage of being stiff and difficult to contour. Titanium wires are notch sensitive. They are susceptible to fatigue and break more easily than steel. Traditionally, monofilament stainless steel was used in spinal instrumentation. Stainless steel wire is usually available in 20 and 18 gauges. The 18-gauge wire is stronger, but one must sacrifice workability for its increased strength. Acute bends, kinks, notches, and excessive twisting all can play a role in wire fatigue and breakage.

Over time, wiring techniques evolved to the use of braided cables instead of monofilament wire. Braided cables have the advantage of being flexible, strong, and resistant to distortion and fatigue. Braided cables also are not susceptible to overtwisting because a crimping mechanism is used to securely lock and fixate the construct. Braided cables, however, can cut through bone via a Gigli saw-type action. Therefore, it is recommended that crimping not exceed a torque of 8 to 12 in-lb of force for normal healthy lamina and 6 to 8 in-lb for osteoporotic bone.

Gallie Fusion. Gallie31 described his method of C1–C2 arthrodesis in 1939. He used a notched bone graft between the dorsal portion of the arch of C1 and the superior part of the spinous process and medial parts of the laminae of C2. He secured the graft with a sublaminar wire under C1 that he wrapped under the spinous process of C2. The drawback of his technique is that it is a solitary, midline fixation and fusion construct. This makes the Gallie C1–C2 fixation technique susceptible to rotational forces.

Brooks and Jenkins Fusion. Brooks and Jenkins[39] described their modification of C1–C2 arthrodesis in 1978 and designed it to overcome the rotational deficiencies of the Gallie method. They accomplished this by using bilateral interlaminar bone grafts. Bilateral sublaminar wires are passed under the lamina of C1 and the lamina of C2 to secure the individual wedge grafts that are placed between the C1 ring and the C2 lamina bilaterally. Brooks and Jenkins used a single wire on each side. Griswold et al[40] modified this technique by using 2 sublaminar wires on each side. The disadvantage of this technique is an increased risk of neurological injury with passing sublaminar wires under both C1 and C2.

Sonntag's Modified Gallie Fusion. Sonntag's interspinous method, as described by Dickman et al,[41] uses a bicortical bone graft that is wedged between the decorticated inferior edge of the C1 lamina and the decorticated superior edge of the C2 lamina and spinous process. Wires are passed under C1 only and then around the base of the C2 spinous process. This method has several advantages over the original Gallie technique. First, the vertically oriented bone graft acts as a strut and provides immediate segmental stability of the atlantoaxial complex upon successful wiring of the construct. Second, the prepared cancellous edges of the C1–C2 lamina are in direct contact with the cancellous edges of the bone graft, creating an excellent fusion surface. Last, the wire has 4 points of contact with the graft when it wedges the graft between C1 and C2. This stabilizes the construct in the anteroposterior, superoinferior, and rotational planes. The advantage of the Sonntag method over the Brooks and Jenkins fusion method is that it avoids passing wires under the lamina C2.

Effectiveness of Wire/Cable Fixation. Posterior cervical fixation and fusion has been successfully used in the treatment of acute odontoid fractures. Although no criteria defining the indications for surgical fixation have been established, a number of retrospective case series using bone-wire techniques suggest treatment options.[12,15,18,21,24,27,42,43] These articles describe a total of 147 patients who underwent posterior cervical fusion for type II odontoid fractures and 29 patients treated similarly for type III fractures. Also included is 1 patient with a type I odontoid fracture that was treated successfully with posterior cervical fusion. The overall fusion rates for type II and III fractures managed with surgical fixation and fusion were 87% and 100%, respectively. The Maiman and Larson[27] series documented a fusion rate of only 35% across the dens fracture line, but a dorsal fusion rate of 100%. Of note, all the bone-wire technique procedures described typically involved the use of a halo-vest immobilization device for a variable duration during the postoperative period.

Interlaminar Clamps

Halifax clamps were initially described by Tucker[32] in 1975. The use of these clamps avoids passing sublaminar wires under C1 and C2 and allowed compression of the interlaminar graft to provide immediate stabilization. Several problems were observed with these clamps, and they ultimately fell out of favor. One problem was that in tightening the clamps, the odontoid could be angulated dorsally, causing ventral encroachment upon the spinal cord. There were several other issues reported. The superior clamp sometimes did not mate well with the C1 lamina. The screws and therefore clamps became loose with time. A large C2 spinous process makes vertical alignment of the clamps difficult, causing suboptimal interface of the clamp with the C1 lamina. Any one of these problems could cause the clamps to disengage. Statham et al[44] reported complications in 14 of 45 patients in whom they used the device. Ten patients had screw loosening and 4 had clamp disengagement. Nine (20%) required reoperation. In contrast, Huang and Chen[45] reported a series of 32 patients with C2 fractures managed with Halifax clamps; successful fusion was obtained in patients. They treated these patients with halo-vest immobilization for 3 months after clamp arthrodesis.

FIGURE 5. *Lateral plain radiograph demonstrating a chronic type II dens fracture in a 56-year-old patient with myelopathy and a history of a neck injury 5 years before presentation. This fracture could not be reduced with craniocervical traction.*

FIGURE 6. *Lateral plain radiograph after Harms and Melcher internal fixation and fusion after C1 laminectomy. Note ankylosis anteriorly preventing late closed reduction of chronic C1–C2 subluxation. The Harms-Melcher fixation is ideal for fractures with C1–C2 subluxation that cannot be reduced.*

Transarticular Screw Fixation

Transarticular screw fixation of C1 and C2 was first described by Magerl.[33] This method provides immediate stabilization of C1 and C2 and does not require a competent C1 arch. In most cases, when both the C1 and C2 dorsal arches are competent, a Sonntag-modified Gallie arthrodesis is also performed (Figures 5 and 6). Before transarticular screws are placed, fine-cut computed tomography must be performed to assess that screw passage will not injure the vertebral arteries (Figure 7). As many as 20% of patients have a vertebral artery anomaly, such as a medial passage at C1 or C2, that precludes placement of bilateral transarticular screws.[46] The occiput–C3 is exposed in the typical subperiosteal fashion. The placement of a transarticular screws often requires separate stab incisions below the dissection to accommodate the extremely steep angle required to cannulate the C1 lateral mass. Fluoroscopy should be used to aid the trajectory. The entry point on C2 is 2 mm lateral from the medial edge of the facet and 3 mm superior to the caudal edge. The trajectory is straight up across the C1 and C2 articular surfaces and into the lateral mass of C1. The surgeon can use a probe to palpate the medial surface of the C2 pedicle to assist with trajectory. The drill must be aimed with the goal of exiting the posterior third of superior C2 facet surface. The trajectory is usually

FIGURE 7. *Sagittal computed tomography imaging of the same patient as in Figure 5 reveals spinal canal/cord compromise by the dorsal cervical arch of the atlas.*

FIGURE 8. *Postoperative lateral view of C1–C2 transarticular internal fixation with Sonntag arthrodesis augmentation.*

ideal when the drill is aimed at the superior portion of the C1 anterior arch. This must be performed with a Kirschner wire first, then followed by a drill. A preferred method of some surgeons is to use 2 drills. The initial drill can be left in place to stabilize the C1–C2 relationship while the opposite side is drilled. If vertebral artery bleeding is encountered, then the attempt at transarticular screw on the opposite side should be abandoned. Screw length (typically 40 mm) is determined by the Kirschner wire depth. A lag screw can be used to reduce a distracted joint.

The success rate of bony fusion with the Magerl technique is approximately 90%, with a reported range of success rates of 78% to 99%.[47-53] The rate of vertebral artery injury with the Magerl technique has been reported to be between 3.7% and 8.2%.[47,48,51-54]

Goel and Laheri/Harms and Melcher Fixation

The use of lateral mass screws in C1 and pedicle screws in C2 with plate fixation was first described by Goel and Laheri[55] in 1994 and later with polyaxial screws and rods in 2001 by Harms and Melcher.[36] A point of difference between the 2 methods is that Goel and Laheri described distraction of the C1–C2 joint space with spacers. Resnick and Benzel[56] described a C1–C2 fixation method similar to the Harms and Melcher method using C1 and C2 pedicle screws. This method of atlantoaxial fixation is the procedure of choice for patients with C1–C2 fixed (unreducible) subluxation or an aberrant vertebral artery that may make transarticular screws difficult and/or dangerous (Figures 8-10). In both C1 and C2, 3.5-mm polyaxial screws are placed by fluoroscopic guidance. The C1 screw is placed under the C1 lamina where it joins the C1 lateral mass. The C2 nerve root can be mobilized or even sacrificed if necessary. Of note, sacrificing the nerve is often well tolerated (numbness) by patients, but can result in severe paresthesias, and rarely, terrible persistent occipital neuralgia. Care must also be taken to avoid injury to the vertebral artery that courses superior to the C1 lamina, cephalad to the insertion site of the C1 lateral mass screw. A drill is used to place a pilot hole in the lateral mass of C1 using a slightly superior and medial (10 degrees) trajectory. A Penfield no. 4 can be used to delineate the medial border of the C1 lateral mass. C1 lateral mass screw length is typically between 26 and 34 mm.[53] The C2 pars screw pilot hole is drilled in the inferior part of the C2 lateral mass at the midpoint of the C2–C3 facet joint. A 10- to 15-degree medial trajectory with slight superior angulation in the sagittal plane is achieved under fluoroscopic guidance. The length of the C2 pars screw is typically 12 to 14 mm.

FIGURE 9. *Anteroposterior/submental view of C1–C2 transarticular internal fixation and Sonntag cable/allograft augmentation.*

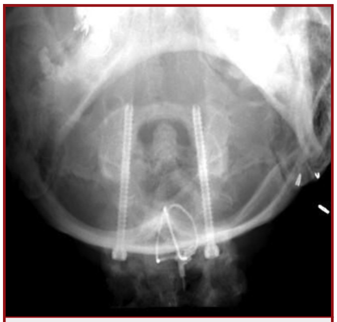

FIGURE 10. *Parasagittal computed tomography demonstrating the anatomy traversed by the C1–C2 transarticular screw.*

In the Goel et al[35] series, 160 patients were operated on over a 14-year period. Their bony fusion rate was 100%. Harms and Melcher[36] also reported a fusion rate of 100% in their series of 37 patients. Neither of these series reported injuries to the vertebral artery or spinal cord. Aryan et al[57] treated 102 patients with C1–C2 instability from chronic type II odontoid fractures (48 patients), rheumatoid arthritis (21 patients), os odontoideum (12 patients), subacute trauma (7 patients), and other diseases (14 patients). All but 2 patients had radiographic evidence of fusion or lack of motion on flexion and extension radiographs. The authors modified the Harms and Melcher technique in 39 cases by distracting between the C1 and C2 screws to place an allograft spacer into the decorticated C1–C2 joint.

Crossed C2 Intralaminar Screws

In 2004, Wright[37] described the most recent technique for screw fixation involving the axis. This technique involves the use of polyaxial screws inserted into the lamina of C2 in a bilateral crossing fashion. These screws are secured to C1 lateral mass screws, similarly to the Goel et al/Harms and Melcher fixation methods.

This modification can be used as a primary means of fixation or can be used if the C2 pedicle is small or if there is an aberrant vertebral artery. C2 laminar screws do not jeopardize the vertebral artery and thus can be used as a rescue technique should the vertebral artery be compromised earlier in the procedure. Obviously, the posterior elements of C2 must be intact and adequate in size.

The laminar screws enter at the spinolaminar junction of the opposite lamina at which they will be placed. Thus, the screw intended for the right lamina enters and has its polyaxial head on the left lamina. One side should be inserted at the rostral end of the lamina and the opposite side, the caudal end of the lamina. A pilot hole should be drilled to a depth of 30 mm from its entry on 1 lamina into the opposite lamina following the angle of the contralateral lamina. In most instances, a 4.0 × 30-mm polyaxial screw is used.

Wright[37] and Menendez and Wright[58] separately reported 100% fusion rates and no complications with this technique. However, the authors warn that this newer technique needs further study before widespread implementation.

Biomechanical Studies for Posterior Cervical Fixation

Dickman et al[59] compared the biomechanical characteristics of 4 different C1–C2 cable fixation and fusion techniques. The Sonntag interspinous wiring, the modified Brooks and Jenkins procedure, and 2 types of Gallie wiring methods were compared with each other and with both the intact and destabilized states. The authors also subjected each construct to several cycles of normal range of motion to induce fatigue on the constructs. They found that none of the cable techniques were rigid in all directions of movement. All techniques allowed considerable rotation and translation to occur even without induced fatigue. However, the modified Brooks and Jenkins and the Sonntag interspinous techniques provided better fixation than the 2 Gallie techniques. The modified Brooks and Jenkins and the Sonntag interspinous techniques were statistically similar except in lateral bending. The advantage of lateral bending of the Brooks and Jenkins technique was lost after the specimens were fatigued. All techniques showed significant loosening after subjected to cyclic torsional loads in the physiological range. The authors concluded that adjunctive fixation to supplement these C1–C2 wiring techniques, including use of a rigid cervical collar, the halo vest, or internal fixation in the form of transarticular screw fixation may be of greatest long-term benefit.

Naderi et al[60] evaluated the biomechanical features of different cable, graft, and screw fixation combinations. C1–C2 constructs using interspinous cable-graft alone, interspinous cable-graft with 1 transarticular screw, interspinous cable-graft with 2 transarticular screws, and transarticular screw fixation alone were compared with normal and destabilized cervical spinal specimens. The authors found the interspinous cable-graft provided superior restriction of the angular motion of flexion and extension, but provided limited rotational and lateral bending stabilization. The bilateral transarticular screw fixation technique provided the best rotational and lateral bending stabilization, but was not quite as effective in limiting flexion and extension movements. The most stable construct was the combination 3-point fixation model of C1–C2 interspinous cable-graft with bilateral transarticular screws.

Richter et al[61] compared the biomechanics of 6 different C1–C2 internal fixation and fusion constructs. The constructs included a Gallie wire construct, transarticular screws alone and in combination with a Gallie or atlas claw, C2 isthmic screws with atlas claw, and a C1 lateral mass–C2 isthmic screw-rod technique. The authors confirmed that 3-point fixation of C1–C2 provided the most stable construct. The transarticular screw technique combined with the atlas claw provided the best fixation of C1–C2. Of the constructs that did not involve transarticular screws, the C1–C2 screw-rod technique provided the most stability.

Claybrooks et al[62] compared the biomechanics of C1 lateral mass/C2 pedicle fixation with C1 lateral mass/C2 laminar fixation. Both techniques were equivalent in flexion-extension and anteroposterior translation. However, the C2 pedicle screw fixation demonstrated more stability with lateral bending and axial rotation. Gorek et al[63] found these 2 constructs to be statistically equivalent in their biomechanical assessment. Given these results, the authors favor bilateral C2 laminar screw fixation because of the reduced risk of vertebral artery injury.

Lapsiwala et al[64] performed biomechanical tests comparing 4 atlantoaxial fixation techniques: anterior transarticular, posterior transarticular, C1 lateral mass/C2 pedicle screws, and C1 lateral mass/C2 intralaminar screws. Posterior constructs were tested with and without a cable fixation augmentation. The authors reported that posterior transarticular fixation and C2 pedicle fixation constructs gained benefit from cable augmentation in flexion-extension. However, the benefit was only statistically significant with the posterior transarticular fixation. Anterior transarticular fixation was equivalent to the posterior transarticular fixation without cable augmentation. The disadvantage of the anterior technique is that it cannot be augmented by cable interlaminar fixation. When the 3 posterior techniques with cable augmentation were compared, there were no significant differences in axial rotation or flexion-extension. There was a statistically significant difference in lateral bending between posterior transarticular fixation with cable augmentation and C2 intralaminar screw fixation with cable augmentation. Despite this, the authors found that C2 intralaminar screw fixation with cable augmentation provided significant stability compared with the baseline intact spine.

Anterior Cervical Fixation

Posterior atlantoaxial fusion techniques achieve a high fusion rate, but the range of motion of the atlantoaxial joint is eliminated after such procedures, restricting head on neck rotation. White and Panjabi[65] described a reduction of 47 degrees of axial rotation and a reduction of 10 degrees of flexion and extension after posterior atlantoaxial internal fixation and fusion. Although posterior instrumentation and fusion do stabilize the segment, it does not reduce and directly aid in the fusion of the fracture itself. Maiman and Larson[27] described a fusion rate of only 35% across the fracture line after posterior fixation and fusion for C2 odontoid fractures. Odontoid screw fixation allows the surgeon to directly reduce and fixate the fracture itself, while maintaining atlantoaxial rotational mobility.

Odontoid Screw Fixation

Anterior screw fixation of odontoid fractures was first described independently by 2 surgeons in the 1980s. Böhler[34] is credited with initially describing the approach. It was the series of Aebi et al[66] and Apfelbaum et al[67] that demonstrated the clinical feasibility and utility of the technique for acute odontoid fractures that met specific criteria.

Most patients with an acute type II odontoid fracture and some with type III fractures are considered good candidates for odontoid screw fixation (Figures 11-13). Acute is defined by most authors as 6 months old or less. The integrity of the transverse ligament must be assessed before surgical decision making because disruption of the ligament is an absolute contraindication to odontoid screw fixation. Relative contraindications to the procedure are severe osteopenia, fractures that slope anteroinferiorly to posterosuperiorly, a fracture older than 6 months, and poor patient body habitus.

Julien et al[14] summarized a series of articles that described retrospective experiences with odontoid screw fixation.[15,21,34,68,69] The combined fusion rate of type II fractures treated in these series was 89% (112 of 126 patients). Patients with type III odontoid fractures had a 100% fusion rate (20 patients). Subach et al[70] managed 26 patients with odontoid screw fixation followed by 7 weeks of cervical collar immobilization. Fusion was achieved in 25 of 26 patients (96%). Jenkins et al[69] described a retrospective nonrandomized series of 42 patients undergoing odontoid screw fixation for type II odontoid fractures. The authors compared single-screw to 2-screw fixation. The rate of fusion was 81% and 85%, respectively. Apfelbaum et al[67] compared anterior screw fixation for recent and remote odontoid fractures at 2 institutions. A total of 147 patients underwent odontoid screw fixation for 138 type II fractures and 9 type III fractures. These patients underwent treatment either within 6 months of injury (129 patients) or more than 18 months after injury (18 patients). Fusion rates were 88% in the 6 months or less group and 25% in the remote injury group. Their experience suggests that anterior odontoid screw fixation is most effective when performed early after injury, but particularly within 6 months of injury. A positive correlation was identified between fusion and fractures oriented in the horizontal or posterior oblique planes. No effect of age, sex, number of screws, or degree of dens displacement was identified.

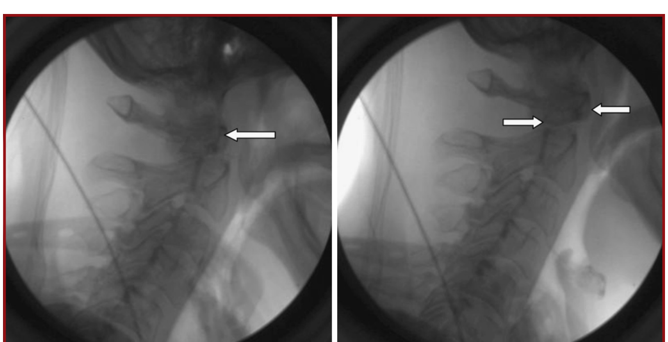

FIGURE 11. *Fluoroscopic images demonstrating the use of intraoperative imaging to assist with the reduction of a posteriorly displaced type II dens fracture in a 72-year-old woman. The patient was maintained in a halo device and underwent odontoid screw fixation.*

FIGURE 12. *Postoperative lateral view of a 52-year-old woman with a type II odontoid fracture after odontoid screw fixation. A lag screw provided good reduction compared with preoperative imaging of the dens fracture.*

FIGURE 13. *Postoperative anteroposterior view of the same patient after odontoid screw arthrodesis for a type II fracture.*

Anterior Atlantoaxial Facet Screw Fixation

This is a rarely used technique described by Feiz-Erfan et al[71] for failed posterior atlantoaxial fusion or for C1–C2 instability with destruction of the posterior elements of C1 and C2. The approach for this procedure is the same as that for odontoid screw fixation. The C1–C2 joint is identified bilaterally, and screws are placed in the anterior cortex of C2 and through the C1–C2 joint space at a 90-degree angle. The diameter of the screws ranged from 3.5 to 4.0 mm. The length varied between 22 and 25 mm. The authors do not recommend this procedure for patients with osteoporosis, fractures of the superior articular facets, vertebral body fracture of C2, or fracture of the lateral mass of C1.

Combination Atlas/Axis Fractures

In 1989, Dickman et al[72] reviewed their cases of cervical injuries over a 10-year period for the occurrence of combination atlas-axis fractures. The authors found that atlas-axis combination fractures represented 3% of their total population of acute cervical spine–injured patients. These combination fractures accounted for 43% of acute atlas fractures and 16% of axis fractures. Twelve percent of the C1–C2 combination fractures sustained an additional noncontiguous cervical spine fracture. Neurological deficit was found in 12% of C1–C2 combination fractures, a much higher incidence of deficit than when either of the fractures occurs in isolation. The C1–type II odontoid fracture was the most common C1–C2 combination fracture (40%).

Most of these fractures can be managed with external immobilization devices. The authors suggest that early surgery on patients with C1–C2 combination fractures should be based on the type of axis fracture present. The type of atlas fracture will determine the internal fixation and fusion technique to be used. If the atlas injury is such that it precludes its use in the C1–C2 fixation construct, then an occipital-cervical fusion should be performed. Only 1 patient treated with a halo vest, of the 20 patients with C1–C2 combination injuries treated by the authors with an external immobilization device, required internal fixation and fusion. Bony healing without subluxation on follow-up radiographic studies was obtained in all patients treated with open reduction, internal fixation, and fusion.

Odontoid Fracture Management in the Elderly

A number of studies have examined the circumstance of acute odontoid fracture in the older patient. Three series[1,73,74] argue against surgical fixation in the elderly patient. Ryan and Taylor[73] described 30 patients 60 years and older with type II odontoid fractures. The fusion success rate in patients older than 60 years treated with external immobilization was only 23%. However, the authors of this study thought that the high fracture nonunion rate was secondary to inadequate immobilization and delays in diagnosis in most cases. If these issues were eliminated, no significant difference in outcomes between surgical and nonsurgical management would have been demonstrated. Greene et al[1] reported no significant relationship between fracture nonunion and age using χ^2 analysis of C2 fractures in older patients.

Several case series favor surgical fixation of C2 fractures in older patients. The Lennarson et al[30] series mentioned earlier, a case-control study comparing outcome with age, provides class II medical evidence in support of surgery for patients 50 years and older. Patients 50 years and older with type II odontoid fractures had a 21 times higher rate of nonunion when treated with halo immobilization compared with those younger than 50 years. This is the most definitive, compelling evidence in the literature on this subject. All previous publications addressing age and outcome of traumatic type II odontoid fractures provides class III medical evidence on this issue.[18,74-81]

HANGMAN'S FRACTURE

Historical Overview

Bilateral fractures of the axis pars interarticularis was first described in 1866 by Haughton.[82] He reported this fracture dislocation in human subjects executed by hanging. Later in 1913, Wood-Jones[83] studied and reported the bony anatomy of individuals executed by hanging with the knot in the submental position. Grogono,[84] in 1954, published the first radiographs of an axis posterior arch fracture sustained in a motor vehicle accident and noted this injury to be similar to that sustained by judicial hanging. Garber[85] coined the term *traumatic spondylolisthesis* to describe this modern-day fracture. In 1965, Schneider et al[86] used the term "hangman's fracture" to describe this traumatic lesion of the axis caused by vehicle accidents or sudden deceleration accidents. Although these fractures are similar in appearance, they are different in mechanism of origin. The fracture resulting from hanging is caused by the submental knot position causing a hyperextension distraction injury. Most traumatic hangman's fractures are the result of falls and motor vehicle accidents. These injury mechanisms typically involve a hyperextension and compression insult that is less lethal because there is less disruption to ligament and the C2–C3 disc space. These features prompted modern investigators to classify hangman's injuries of C2 in a way that would assist with treatment (Figures 14 and 15).

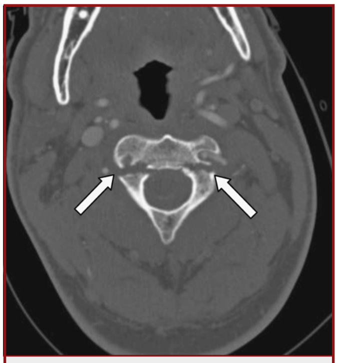

FIGURE 14. *Axial computed tomography depicting an acute traumatic C2 hangman's fracture.*

Classification

In 1981, 3 separate hangman's fracture classification schemes were proposed by different investigators. Pepin and Hawkins[87] published a 2-type classification scheme for hangman's fractures. Type I was described as a nondisplaced fracture of the posterior elements. Type II was a displaced fracture of the posterior elements and the body of the axis. This scheme never gained popularity, but the authors' ideas were included in a classification system produced by Francis et al[88] in the same year. Francis et al[88] pub-

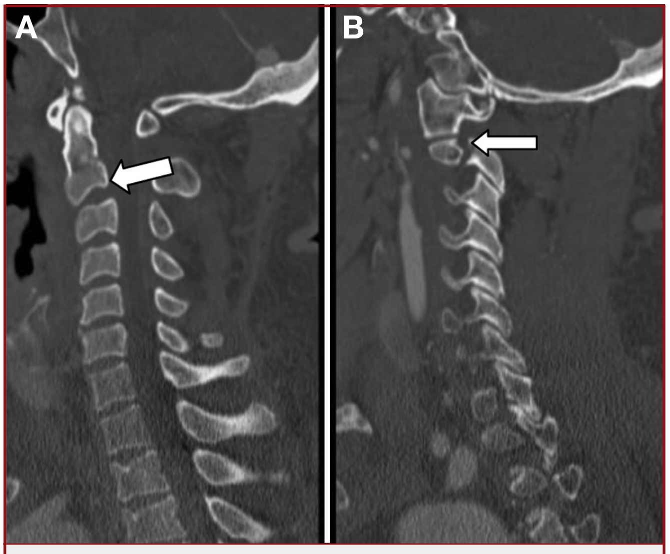

FIGURE 15. *Sagittal computed tomography of the same hangman's fracture shown in Figure 14 reveals angulation (**A**) at midline and the pars fracture laterally (**B**).*

lished collaborative experience with 123 patients with traumatic spondylolisthesis of the axis. Their system divided the injuries into 5 grades based on the amount of displacement and the degree of angulation of the axis on C3. Finally, Effendi et al[89] produced their own classification system, also in 1981, based on mechanism of injury. Levine and Edwards[90] modified the Effendi et al classification in 1985.

Starr and Eismont[54] reported an atypical traumatic spondylolisthesis of the axis in 6 of the 19 patients in their series. This fracture occurred through the posterior aspect of the vertebral body in continuity with the pedicle, causing a narrowing of the spinal canal as a result of the associated subluxation.

Incidence of Traumatic Spondylolisthesis

In the largest series of axis fractures described in the literature by Greene et al,[1] a total of 1820 cervical fractures were evaluated. Of these 1820 cervical fractures, 340 (19%) were fractures of the axis and 74 (4%) were hangman's fractures. The incidence of hangman's fractures of the axis was not addressed in either the Effendi et al or Francis et al reports. However, as mentioned previously, the incidence of specific subtypes was reported. In the Effendi et al[89] study of 131 hangman's fractures, the incidence of type I, II, and III fractures was 65%, 28%, and 7%, respectively. For the 123 fractures of the series of Francis et al[88], the incidence of grades I, II, III, IV, and V fractures was 15%, 7%, 38%, 34%, and 6%, respectively. The hangman's fractures in the Greene et al[1] study were classified according to both the Effendi et al and Francis et al classification systems. The most common hangman's fracture pattern identified in each system was the Effendi type I (72%) and the Francis grade I (65%). The investigators found a strong correlation and similarity between Effendi types I and III and Francis grades I and IV, respectively.

Burke and Harris[91] reviewed 165 acute injuries of the axis and found that 62 were hangman's fractures (38%). Using the Effendi system, they found 13 type I (21%), 35 type II (56%), and 3 type III fractures (5%). Of interest, 11 fractures (18%) had a fracture pattern not previously described in which 1 or both pedicle fractures involved a portion of the posterior cortex of the body of the axis. As mentioned earlier, Starr and Eismont[54] also described an atypical hangman's fracture in 1993.

Associated Injuries

The incidence of concomitant cervical fractures with hangman's type fractures is cited in the literature. Ryan and Henderson[92] studied 657 patients with cervical spine fractures. Hangman's type fractures occurred in isolation in 74% of their series. Only 9% were associated with fractures of the atlas. An additional 9% were associated with fractures of the subaxial cervical spine. Several other studies[89,90,93,94] reported that an incidence of 6% to 26% of hangman's type fractures have an associated atlas fracture. Francis et al[88] reported 39 of 123 (32%) hangman's type fractures were associated with other injuries of the cervical spine, with 94% of these occurring in the upper 3 cervical vertebrae. Greene et al[1] reported a 34% incidence of concomitant spinal injuries with their 340 axis fractures. Of these concomitant fractures, 99 of 117 were located in the cervical spine.

The incidence of spinal cord and nerve root injury as a result of hangman's type fracture is reportedly low. If a patient survives the initial injury, it has been proposed that the relatively spacious canal at the level of the axis affords some protection against spinal cord compromise.[95] In the Francis et al[88] series, only 8 of 123 (6.5%) hangman's type fractures were associated with a neurological deficit. All but 2 of these patients made a complete neurological recovery within 22 days. Effendi et al[89] noted with the exception of occipital neuralgia, permanent neurological signs were rare after a type I fracture. Nine of 85 patients (18%) with a type I fracture had transient neurological signs for a few weeks. Most had paresthesias of the extremities, one a sixth nerve palsy and one a transient hemiparesis related to a thrombosed vertebral artery. Seven of 37 patients (19%) with a type II fracture had transient deficit and 1 of 37 had a permanent deficit. The one permanent injury was quadriplegia that eventually was fatal. Transient deficits ranged from paresthesias of 2 extremities to quadriparesis. There were 9 patients with type III fractures. One experienced transient quadriparesis and 1 had permanent quadriplegia. Tan and Balanchandran[96] retrospectively reviewed 33 patients with hangman's fractures and found that 19 (57%) had neurological deficits ranging from quadriparesis to urinary retention. Mirvis et al[97] reported that 26% of 27 patients with hangman's fractures had an associated neurological deficit.

Treatment of Hangman's Fractures

Halo Immobilization

Most patients with traumatic hangman's fractures are treated with external cervical immobilization. Francis et al,[88] Effendi et al,[89] and Greene et al.[1] provide the three largest multi-institutional series on hangman's type fracture management. There have also been smaller series from Pepin and Hawkins,[87] as well as Levine and Edwards[90] that add to the literature on treatment of this fracture type.

Francis et al[88] managed 35 of 123 patients primarily in cervical or cervicothoracic supports and allowed early ambulation. Eighty-eight patients were treated initially with traction. After extended traction, the patients were placed in halo vests, Minerva casts, or cervicothoracic braces. Acceptable union occurred in 116 patients (94.5%) in less than 16 weeks regardless of the treatment plan or orthotic device. The average time to union was 11.5 weeks.

Seven patients were treated operatively for nonunion or malunion of a hangman's fracture. The authors thought that primary surgical treatment for hangman's type fractures is not warranted. All patients should be assessed with follow-up examinations, with heightened awareness for nonunion in grade II and V fracture patients.

Effendi et al[89] treated 62 of 85 type I fractures with an external orthosis. The authors reported that they were too aggressive with the operative management of both type I and II hangman's fractures. They mentioned that most of the surgically treated lesions probably would have healed in an external orthosis. The authors concluded that surgical treatment should be reserved for unusual type III fractures and fractures that fail to heal despite 3 months of treatment in a halo device.

Greene et al[11] treated 65 of 74 patients with hangman's type fractures nonoperatively with an external orthosis for a median of 12 weeks. Seven patients required early surgical stabilization for inability to maintain fracture alignment in the halo device. Union was achieved in all 7 patients without evidence of instability. Greene et al,[1] like the previous series, concluded that external immobilization should be the initial treatment in virtually every patient with a hangman's type fracture. Early surgical stabilization should be reserved for unstable injuries that are not effectively immobilized in a halo-vest device.

Smaller series[87,90,98] have confirmed that halo-vest immobilization should be the initial treatment of hangman's fractures and that internal fixation should be reserved for fusion failures and those fractures that are either irreducible or repeatedly unstable during initial bracing.

Cervical Collar

Grady et al[99] reported a series of 27 patients with hangman's type fractures. Sixteen were managed in halo vest, 8 in a Philadelphia collar, and 3 with bed rest only. Union was achieved in all cases. Govender and Charles[100] prospectively assessed 39 patients with hangman's fractures. All patients were successfully treated with collar immobilization.

Surgical Management

The surgical treatment of unstable hangman's fractures or those in which external immobilization fails include C2–C3 anterior cervical discectomy and fusion (Figure 16) and dorsal C1–C3 fusion procedures. Effendi et al[89] managed 42 of 131 hangman's fractures and Francis et al[88] managed 7 fractures surgically. Fusion was obtained in all surgically treated patients. Two smaller series[101,102] report the surgical management of patients with acute hangman's fractures without associated morbidity.

Verheggen and Jansen[103] argued that patients with Effendi type II and III fractures should be managed surgically from the outset. The authors used screw fixation of the posterior arch of the axis, as described by Judet et al,[104] and argued that this fixation technique resulted in better long-term functional results when compared with historical controls. Despite favable outcomes in all patients, this series did not receive general acceptance.[105-107] Borne et al[108] described a technique of bilateral posterior screw fixation that achieved a 100% fusion rate. Their technique did not gain widespread acceptance either.

Fractures of the Axis Body

A third general type of axis fracture is the traumatic injury to the C2 body. These fractures do not involve the odontoid process and do not involve a fracture through the pars interarticularis of the axis. Axis body fractures include fractures of the body, pedicle, superior articulating process (lateral mass), and transverse foramen (Figure 17). These fractures have been referred to by many names. They have been labeled as axis body fractures, nonodontoid and nonhangman's fractures, and miscellaneous fractures of the axis.[1,109-111] The Anderson and D'Alonzo type III odontoid fracture is actually an axis body fracture.

FIGURE 16. *Postoperative sagittal computed tomography after a C2–C3 anterior cervical discectomy internal fixation and fusion for stabilization of an unstable C2 hangman's fracture.*

FIGURE 17. *Sagittal computed tomography of a stable C2 anteroinferior vertebral body fracture.*

Benzel et al[110] classified axis body factures into 3 types based on a 15-patient series. The fractures were classified according to orientation of the fracture along with subtypes in each group. There are 2 types of vertically arranged fractures and 1 type of horizontally arranged fracture. Type I C2 body fractures are vertical and coronally oriented (Figure 18). Type II C2 body fractures are vertical and sagittally oriented fractures (Figure 19). Type III C2 body fractures are transverse, axially (horizontally) oriented injuries. Type I and II C2 body fractures can be acquired by a variety of mechanisms that result in a number of subtypes. These subtypes are delineated in Benzel's[109] biomechanics article. The original Benzel et al[110] report of 15 patients suggested a mechanism of injury for each C2 body fracture but made no comments on treatment or outcome.

German et al[112] performed a retrospective analysis of 21 patients with type I and II vertical C2 body fractures. Sixteen fractures (76%) were type I fractures and 5 were type II C2 axis body fractures. None of these patients had a neurological injury that was attributed to the axis fracture. Eighteen patients were available for follow-up. Thirteen were treated with a Minerva brace, 4 with a cervical collar, and 1 with a halo device followed by a Minerva vest. The average length of treatment for type I and II fractures was 3.4 months and 3.75 months, respectively. All these patients demonstrated radiological and clinical evidence of fusion after treatment.

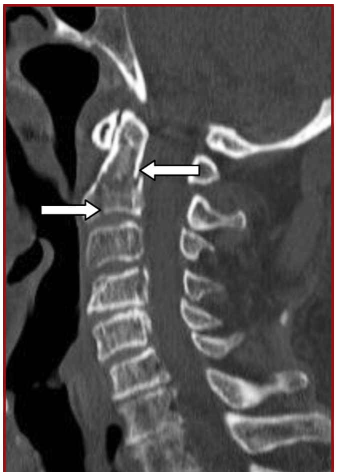

FIGURE 18. *Sagittal computed tomography of a complex C2 body fracture. Note the multiple fractures within the corpus of the axis.*

FIGURE 19. *Coronal computed tomography of a C2 body lateral mass fracture that extends into the vertebral body.*

In the Greene et al[1] series, 20% of axis fractures were classified as miscellaneous fractures of the axis. Most of these traumatic injuries involved the vertebral body or lateral mass. One patient with a C2 lateral mass fracture was managed with early surgical fusion because of a 5-mm subluxation of C2 on C3. The remaining miscellaneous axis fractures were managed with an external orthosis. Only 1 of these patients required late surgical intervention despite initial treatment with a halo immobilization device.

Fujimura et al[113] classified 31 axis body fractures on the basis of their radiographic injury pattern: avulsion, transverse, burst, or sagittal. In their series, all 9 cases of avulsion fractures and 2 cases of transverse fractures fused in external orthosis. Two of the 3 C2 burst fractures were treated with C2–C3 anterior interbody fusion and the third with an external orthosis. Union was obtained in all 3 fractures. Fifteen of 17 sagittal fractures were successfully treated with an external orthosis. Two required operative treatment; the authors chose a transoral atlantoaxial fusion. Of the sagittal fractures, 8 patients had nuchal pain caused by osteoarthrosis of the atlantoaxial joint. The authors recommended initial nonoperative treatment for C2 axis body fractures, but suggested it may be appropriate to use atlantoaxial fusion when severe malalignment of the atlantoaxial joint is recognized.

Craig and Hodgson[114] followed 9 patients with axis body fractures that involved the superior articular facet. An odontoid fracture accompanied 7 of these 9 facet fractures. The authors recommended immobilization for nondisplaced fractures and surgical consideration for patients with fractures that were not able to be reduced.

Kores et al[115] followed 14 patients with avulsion or "teardrop" fractures of the anterior inferior axis body. All 14 of these avulsion type fractures were successfully managed with cervical immobilization.

SUMMARY

Odontoid Fractures

Fractures of the second cervical vertebra are common. Odontoid fractures are the most prevalent C2 fracture subtype. Type I odontoid fractures are unusual and are universally managed with an external orthosis. These fractures have an essentially100% fusion rate regardless of the type of external immobilization used. Type III odontoid fractures have a high associated fusion rate with external immobilization (approximately 85%) and have a nearly 100% fusion rate with internal fixation and fusion, ventral or dorsal. Common practice is to externally immobilize the patient with a type III fracture as initial treatment and to withhold surgical treatment for failures of union. However, based on patient and fracture characteristics and surgeon experience, initial treatment with surgical fixation may be the treatment of choice in selected patients. A type III fracture with displacement of 5 mm or more may influence the surgeon to consider early internal fixation and fusion.

The treatment of type II odontoid fractures is not as straightforward. These are the most common fractures of the dens and are the most variable. Many are effectively managed in an external orthosis, but certain patient or fracture characteristics should influence treatment toward internal fixation and fusion. Class II medical evidence supports early surgical stabilization and fusion for patients 50 years of age or older with a type II odontoid fracture. External immobilization for type IIA fractures caused by fracture comminution at the base of the dens is highly likely to fail, and these fractures should also be considered for early surgical fixation. A dens displacement of 5 mm and greater or significant posterior displacement of the type II fracture are other features that support early surgical fixation. If the transverse ligament is intact and the type II fracture line is transverse or anterosuperior to posteroinferior and patient habitus is favorable, anterior screw fixation with postoperative collar immobilization seems to be the treatment of choice (approximately 90% fusion rate). A compromised transverse ligament, comminuted fracture line, or anteroinferior to posterosuperior type II fracture line requires a posterior approach to atlantoaxial fixation and fusion. All methods of posterior fixation have a high rate of fusion; therefore, surgeon familiarity, experience, and patient anatomy dictate the method of fixation. Transarticular screw fixation and polyaxial screw-rod constructs with dorsal fusion offer the greatest stability.

Hangman's Fractures

A hangman's fracture or bilateral traumatic spondylolisthesis of the dorsal arch of the axis is the second most common C2 fracture subtype. There is an abundance of class III medical evidence that support the use of 12 weeks of external orthosis immobilization for most hangman's fractures. Surgical stabilization should be considered in cases of severe angulation (Francis types II and

IV, Effendi type II), disruption of the C2–C3 disc space (Francis type V, Effendi type III) or the inability to obtain and/or maintain alignment in a halo-vest orthosis.

Fractures of the Axis Body

These are unusual and mixed fractures of the second cervical vertebra. Class III medical evidence supports individualized treatment of axis body fractures. The use of external immobilization is advocated as initial treatment for these fracture injuries.

REFERENCES

1. Greene KA, Dickman CA, Marciano FF, Drabier JB, Hadley MN, Sonntag VK. Acute axis fractures: analysis of management and outcome in 340 consecutive cases. *Spine (Phila Pa 1976)*. 1997;22(16):1843-1852.
2. Alker GJ Jr, OH YS, Leslie EV. High cervical spine and craniocervical junction injuries in fatal traffic accidents: a radiological study. *Orthop Clin North Am*. 1978;9(4):1003-1010.
3. Bucholz RW, Burkhead WZ, Graham W, Petty C. Occult cervical spine injuries in fatal traffic accidents. *J Trauma*. 1979;19(10):768-771.
4. Hadley MN, Sonntag VK, Grahm TW, Masferrer R, Browner C. Axis fractures resulting from motor vehicle accidents. The need for occupant restraints. *Spine (Phila Pa 1976)*. 1986;11(9):861-864.
5. Huelke DF, O'Day J, Mendelsohn RA. Cervical injuries suffered in automobile crashes. *J Neurosurg*. 1981;54(3):316-322.
6. Hadley MN, Browner C, Sonntag VK. Axis fractures: a comprehensive review of management and treatment in 107 cases. *Neurosurgery*. 1985;17(2):281-290.
7. Mixter SJ, Osgood RB. IV. Traumatic lesions of the atlas and axis. *Ann Surg*. 1910;51(2):193-207.
8. Osgood RB, Lund CC. Fractures of the odontoid process. *N Engl J Med*. 198:61-72.
9. Anderson LD, D'Alonzo RT. Fractures of the odontoid process of the axis. *J Bone Joint Surg Am*. 1974;56(8):1663-1674.
10. Hadley MN, Browner CM, Liu SS, Sonntag VK. New subtype of acute odontoid fractures (Type IIA). *Neurosurgery*. 1988;22(1 Pt 1):67-71.
11. Grauer JN, Shafi, B, Hilibrand AS, et al. Proposal of a modified, treatment-oriented classification of odontoid fractures. *Spine J*. 2005;5(2):123-129.
12. Clark CR, White AA 3rd. Fractures of the dens: a multicenter study. *J Bone Joint Surg Am*. 1985;67(9):1340-1348.
13. Traynelis VC. Evidence-based management of type II odontoid fractures. *Clin Neurosurg*. 1997;44:41-49.
14. Julien TD, Frankel B, Traynelis VC, Ryken TC. Evidence-based analysis of odontoid fracture management. *Neurosurg Focus*. 2000;8(6):e1.
15. Chiba K, Fujimura Y, Toyama Y, Fujii E, Nakanishi T, Hirabayashi K. Treatment protocols for fractures of the odontoid process. *J Spinal Disord*. 1996;9(4):267-276.
16. Govender S, Grootboom M. Fractures of the dens—the results of non-rigid immobilization. *Injury*. 1988;19(3):165-167.
17. Marar BC, Tay CK. Fracture of the odontoid process. *Aust N Z J Surg*. 1976;46(3):231-236.
18. Pepin JW, Bourne RB, Hawkins RJ. Odontoid fractures, with special reference to the elderly patient. *Clin Orthop*. 1985;193:178-183.
19. Polin RS, Szabo T, Bogaev CV, Replogle RE, Jane JA. Nonoperative management of types II and III odontoid fractures: the Philadelphia collar versus the halo vest. *Neurosurgery*. 1996;38(3):450-457.
20. Wang GJ, Mabie KN, Whitehill R, Stamp WG. The nonsurgical management of odontoid fractures in adults. *Spine (Phila Pa 1976)*. 1984;9(3):229-230.
21. Fuji E, Kobayashi K, Hirabayashi K. Treatment in fractures of the odontoid process. *Spine (Phila Pa 1976)*. 1988;13(6):604-609.
22. Ryan MD, Taylor TK. Odontoid fractures. A rational approach to treatment. *J Bone Joint Surg Br*. 1982;64(4):416-421.
23. Bucholz RD, Cheung KC. Halo vest versus spinal fusion for cervical injury: evidence from an outcome study. *J Neurosurg*. 1989;70(6):884-892.
24. Dunn ME, Seljeskog EL. Experience in the management of odontoid process injuries: an analysis of 128 cases. *Neurosurgery*. 1986;18(3):306-310.
25. Ekong CE, Schwartz ML, Tator CH, Rowed DW, Edmonds VE. Odontoid fracture: management with early mobilization using the halo device. *Neurosurgery*. 1981;9(6):631-637.
26. Lind B, Nordwall A, Sihlbom H. Odontoid fractures treated with halo-vest. *Spine (Phila Pa 1976)*. 1987;12(2):173-177.
27. Maiman DJ, Larson SJ. Management of odontoid fractures. *Neurosurgery*. 1982;11(4):471-476.
28. Schiff DC, Park WW. The arterial supply of the odontoid process. *J Bone Joint Surg Am*. 1973;55(7):1450-1456.
29. Apuzzo ML, Heiden JS, Weiss MH, Ackerson TT, Harvey JP, Kurze T. Acute fractures of the odontoid process. An analysis of 45 cases. *J Neurosurg*. 1978;48(1):85-91.
30. Lennarson PJ, Mostafavi H, Traynelis VC, Walters BC. Management of type II dens fractures: a case control study. *Spine (Phila Pa 1976)*. 2000;25(10):1234-1237.
31. Gallie WE. Fractures and dislocations of the cervical spine. *Am J Surg*. 1939;46:495-499.
32. Tucker HH. Technical report: method of fixation of subluxed or dislocated cervical spine below C1-C2. *Can J Neurol Sci*. 1975;2(4):381-382.
33. Magerl F, Seeman PS. Stable posterior fusion of the atlas by transarticular screw fixation. In: Kehr P, Weidner A, eds. *Cervical Spine I*. New York, NY: Springer-Verlag; 1987.
34. Böhler J. Screw-osteosynthesis of fractures of the dens axis (author's translation) [in German]. *Unfallheilkunde*. 1981;84(6):221-223.
35. Goel A, Desai KI, Muzumdar DP. Atlantoaxial fixation plate and screw method: a report of 160 treated patients. *Neurosurgery*. 2002;51(6):1351-1357.
36. Harms J, Melcher RP. Posterior C1-C2 fusion with polyaxial screw and rod fixation. *Spine (Phila Pa 1976)*. 2001;26(22):2467-2471.
37. Wright NM. Posterior C2 fixation using bilateral, crossing C2 laminar screws: case series and technical note. *J Spinal Disord Tech*. 2004;17:158-162.
38. Dickman CA, Marciano FF. C1-C2 Wiring Techniques. *Tech Neurosurg*. 1995;1:96-101.
39. Brooks AL, Jenkins EB. Atlanto-axial arthrodesis by the wedge compression method. *J Bone Joint Surg Am*. 1978;60(3):279-284.
40. Griswold DM, Albright JA, Schiffman E, Johnson R, Southwick WO. Atlanto-axial fusion for instability. *J Bone Joint Surg Am*. 1978;60(3):285-292.
41. Dickman CA, Sonntag VK, Papadopoulos SM, Hadley MN. The interspinous method of posterior atlantoaxial arthrodesis. *J Neurosurg*. 1991;74(2):190-198.
42. Coyne TJ, Fehlings MG, Wallace MC, Berstein M, Tator CH. C1-C2 posterior cervical fusion: long-term evaluation of results and efficacy. *Neurosurgery*. 1995;37(4):688-693.
43. Waddell JP, Reardon GP. Atlantoaxial arthrodesis to treat odontoid fractures. *Can J Surg*. 1983;26(3):255-257, 260.
44. Statham P, O'Sullivan M, Russell T. The Halifax interlaminar clamp for posterior cervical fusion: initial experience in the United Kingdom. *Neurosurgery*. 1993;32(3):396-399.
45. Huang CI, Chen IH. Atlantoaxial arthrodesis using Halifax interlaminae clamps reinforced by vest immobilization: a long-term follow up experience. *Neurosurgery*. 1996;38(6):1153-1157.
46. Paramore CG, Dickman CA, Sonntag VK. The anatomic C1-C2 suitability of the C1-C2 complex for transarticular screw fixation. *J Neurosurg*. 1996;85(2):221-224.
47. Dickman CA, Sonntag VK. Posterior C1-C2 screw fixation for atlanto-axial arthrodesis. *Neurosurgery*. 1998;43(2):275-281.
48. Grob D, Jeanneret B, Aebi M, Markwalder TM. Atlanto-axial fusion with transarticular screw fixation. *J Bone Joint Surg Br*. 1991;73(6):972-976.
49. Grob D, Crisco JJ 3rd, Panjabi M, Wang P, Dvorak J. Biomechanical evaluation of four different posterior atlanto-axial fixation techniques. *Spine (Phila Pa 1976)*. 1992;17(5):480-490.
50. Jeanneret B, Magerl F. Primary posterior fusion C1/2 in odontoid fractures: indications, technique, and results of transarticular screw fixation. *J Spinal Disord*. 1992;5(4):464-475.
51. Jeanneret B. Posterior transarticular screw fixation of C1-C2. *Tech Orthop*. 1994; 1:49-59.
52. Suchomel P, Stutlík J, Klézl Z, et al. Transarticular fixation of C1-C2: a multicenter retrospective study [in Czech]. *Acta Chir Orthop Traumatol Cech*. 2004;71(1):6-12.
53. Stulik J, Vyskocil T, Sebesta P, Kryl J. Atlanto axial fixation using the polyaxial screw-rod system. *Eur Spine J*. 2007;16(4):479-484.

54. Starr JK, Eismont FJ. Atypical hangman's fracture. *Spine (Phila Pa 1976)*. 1993;18(14):1954-1957.
55. Goel A, Laheri V. Plate and screw fixation for atlanto-axial subluxation. *Acta Neurochir (Wien)*. 1994;129(1-2):47-53.
56. Resnick DK, Benzel EC. C1-C2 pedicle screw fixation with rigid cantilever beam construct: case report and technical note. *Neurosurgery*. 2002;50(2):426-428.
57. Aryan HE, Newman CB, Nottmeier EW, Acosta FL Jr, Wang VY, Ames CP. Stabilization of the atlantoaxial complex via C1 lateral mass and C2 pedicle screw fixation in a multicenter clinical experience in 102 patients: modification of the Hams and Goel technique. *J Neurosurg Spine*. 2008;8(3):222-229.
58. Menendez JA, Wright, NM. Techniques of posterior C1-C2 stabilization. *Neurosurgery*. 2007;60(1 Suppl 1):S103-S111.
59. Dickman CA, Crawford NR, Paramore CG. Biomechanical characteristics of C1–2 cable fixations. *J Neurosurg*. 1996;85(2):316-322.
60. Naderi S, Crawford NH, Song GS, Sonntag VK, Dickman CA. Biomechanical comparison of C1–2 posterior fixations: cable, graft, and screw combinations. *Spine (Phila Pa 1976)*. 1998;23(18):1946-1956.
61. Richter M, Schmidt R, Claes L, Puhl W, Wilke HJ. Posterior atlantoaxial fixation: biomechanical in vitro comparison of six different techniques. *Spine (Phila Pa 1976)*. 2002;27(16):1724-1732.
62. Claybrooks R, Kayanja M, Milks R, Benzel E. Atlantoaxial fusion: a biomechanical analysis of two C1-C2 fusion techniques. *Spine J*. 2007;7(6):682-688.
63. Gorek J, Acaroglu E, Berven S, Yousef A, Puttlitz CM. Constructs incorporating intralaminar C2 screws provide rigid stability for atlantoaxial fixation. *Spine (Phila Pa 1976)*. 2005;30(13):1513-1518.
64. Lapsiwala SB, Anderson PA, Oza A, Resnick DK. Biomechanical comparison of four C1 to C2 rigid fixative techniques: anterior transarticular, posterior transarticular, C1 to C2 pedicle and C1 to C2 intralaminar screws. *Neurosurgery*. 2006;58(3):516-521.
65. White AA, Panjabi MM. *Clinical Biomechanics of the Spine*. 2nd ed. Philadelphia, PA: JB Lippincott; 1990.
66. Aebi M, Etter C, Coscia M. Fractures of the odontoid process. Treatment with anterior screw fixation. *Spine (Phila Pa 1976)*. 1989;14(10):1065-1070.
67. Apfelbaum RI, Lonser RR, Veres R, Casey A. Direct anterior screw fixation for recent and remote odontoid fractures. *J Neurosurg*. 2000;93(2 Suppl):227-236.
68. Dickman CA, Sonntag VK. Surgical management of atlantoaxial nonunions. *J Neurosurg*. 1995;83(2):248-253.
69. Jenkins JD, Coric D, Branch CL Jr. A clinical comparison of one and two screw odontoid fixation. *J Neurosurg*. 1998;89(3):366-370.
70. Subach BR, Morone MA, Haid RW Jr, McLaughlin MR, Rodts, GR, Comey CH. Management of acute odontoid fractures with single-screw anterior fixation. *Neurosurgery*. 1999;45(4):812-820.
71. Feiz-Erfan I, Klopfenstein JD, Vougioukas VI, Dickman CA. Surgical therapy for fractures and dislocations of the craniocervical junction and upper cervical spine. In: Kim DH, Henn JS, Vaccaro AR, Dickman CA, eds. *Surgical Anatomy & Techniques to the Spine.* Philadelphia, PA: WB Saunders; 2006:328.
72. Dickman CA, Hadley MN, Browner C, Sonntag VK. Neurosurgical management of acute atlas-axis combination fractures: a review of 25 cases. *J Neurosurg*. 1989;70(1):45-49.
73. Ryan MD, Taylor TK. Odontoid fractures in the elderly. *J Spinal Disord*. 1993;6(5):397-401.
74. Seybold EA, Bayley JC. Functional outcome of surgically and conservatively managed dens fractures. *Spine (Phila Pa 1976)*. 1998;23(17):1837-1846.
75. Andresson S, Rodrigues M, Olerud C. Odontoid fractures: high complication rate associated with anterior screw fixation in the elderly. *Eur Spine J*. 2000;9(1):56-59.
76. Bednar DA, Parikh J, Hummel J. Management of type II odontoid process fractures in geriatric patients: a prospective study of sequential cohorts with attention to survivorship. *J Spinal Disord*. 1995;8(2):166-169.
77. Berlemann U, Schwarzenbach O. Dens fractures in the elderly: results of anterior screw fixation in 19 patients. *Acta Orthop Scand*. 1997;68(4):319-324.
78. Börm W, Kast E, Richter HP, Mohr K. Anterior screw fixation in type II odontoid fractures: is there a difference in outcome between age groups? *Neurosurgery*. 2003;52(5):1089-1094.
79. Campanelli M, Kattner KA, Stroink A, Gupta K, West S. Posterior C1-C2 transarticular screw fixation in the treatment of displaced type II odontoid fractures in the geriatric population-review of seven cases. *Surg Neurol*. 1999;51(6):596-601.
80. Hanigan WC, Powell FC, Elwood PW, Henderson JP. Odontoid fractures in elderly patients. *J Neurosurg*. 1993;78(1):32-35.
81. Pitzen T, Caspar W, Steudel WI, Barbier D. Dens fracture in elderly patients and surgical management [in German]. *Aktuelle Traumatol*. 1994;24(2):56-59.
82. Haughton S. On hanging, considered from a mechanical and physiological point of view. *London, Edinburgh and Dublin Philosophical Magazine and Journal of Science.* 1866;32(4):23-34.
83. Wood-Jones F. The ideal lesion produced by judicial hanging. *Lancet*. 1913;i:53.
84. Grogono BJ. Injuries to the atlas and axis. *J Bone Joint Surg Br*. 1954;36:397-410.
85. Garber J. Abnormalities of the atlas and axis vertebrae—congenital and traumatic. *J Bone Joint Surgery Am*. 1964;46:1782-1791.
86. Schneider RC, Livingston KE, Cave AJ, Hamilton G. "Hangman's fracture" of the cervical spine. *J Neurosurg*. 1965;22:141-154.
87. Pepin JW, Hawkins RJ. Traumatic spondylolisthesis of the axis: hangman's fracture. *Clin Orthop Relat Res*. 1981;157:133-138.
88. Francis WR, Fielding JW, Hawkins RJ, Pepin J, Hensinger R. Traumatic spondylolisthesis of the axis. *J Bone Joint Surg Br*. 1981;63-B(3):313-318.
89. Effendi B, Roy D, Cornish B, Dussault RG, Laurin CA. Fractures of the ring of the axis: a classification based on the analysis of 131 cases. *J Bone Joint Surg Br*. 1981;63B(3):319-327.
90. Levine AM, Edwards CC. The management of traumatic spondylolisthesis of the axis. *J Bone Joint Surg Am*. 1985;67(2):217-226.
91. Burke JT, Harris JH Jr. Acute injuries of the axis vertebra. *Skeletal Radiol*. 1989;18(5):335-346.
92. Ryan MD, Henderson JJ. The epidemiology of fractures and fracture-dislocations of the cervical spine. *Injury*. 1992;23(1):38-40.
93. Fielding JW, Francis WR Jr, Hawkins RJ, Pepin J, Hensinger R. Traumatic spondylolisthesis of the axis. *Clin Orthop Relat Res*. 1989;239:47-52.
94. Müller EJ, Wick M, Muhr G. Traumatic spondylolisthesis of the axis: treatment rationale based on the stability of the different fracture types. *Eur Spine J*. 2000;9(2):123-128.
95. Mollan RA, Watt PC. Hangman's fracture. *Injury*. 1982;14(3):265-267.
96. Tan ES, Balanchandra N. Hangman's fracture in Singapore (1975–1988). *Paraplegia*. 1992;30(3):160-164.
97. Mirvis SE, Young JW, Lim C, Greenberg J. Hangman's fracture: radiological assessment in 27 cases. *Radiology*. 1987;163(3):713-717.
98. Mestdagh H, Letendart J, Sensey JJ, Duquennoy A. Treatment of fractures of the posterior arch axial arch. Results of 41 cases[in French]. *Rev Chir Orthop Reparatrice Appar Mot*. 1984;70(1):21-28..
99. Grady MS, Howard MA, Jane JA, Persing JA. Use of Philadelphia collar as alternative to the halo-vest in patients with C2, C3 fractures. *Neurosurgery*. 1986;18(2):151-156.
100. Govender S, Charles RW. Traumatic spondylolisthesis of the axis. *Injury*. 1987;18(5):333-335.
101. McLaurin RL, Vernal R, Salmon JH. Treatment of fractures of the atlas and axis by wiring without fusion. *J Neurosurg*. 1972;36(6):773-780.
102. Salmon JH. Fractures of the second cervical vertebra: internal fixation by interlaminar wiring. *Neurosurgery*. 1977;1(2):125-127.
103. Verheggen R, Jansen J. Hangman's fractures: arguments in favor of surgical therapy of type II and III according to Edwards and Levine. *Surg Neurol*. 1998;49(3):253-262.
104. Judet R, Roy-Camille R, Saillant G. Fractures du raches cervical. Actualities de *Chirurgie orthopedique de l'hopital Raymond-Poincare*. 1970;8:174-195.
105. Pagni CA. Hangman's fractures: arguments in favor of surgical therapy of type II and III according to Edwards and Levine. *Surg Neurol*. 1998;49:253-262.
106. Sonntag VK. Hangman's fractures: arguments in favor of surgical therapy of type II and III according to Edwards and Levine. *Surg Neurol.* 1998;49:253-262.
107. Sypert GW. Hangman's fractures: arguments in favor of surgical therapy of type II and III according to Edwards and Levine. *Surg Neurol*. 1998;49:253-262.
108. Borne GM, Bedou GL, Pinaudeau M. Treatment of pedicular fractures of the axis: a clinical study and screw fixation technique. *J Neurosurg*. 1984;60(1):88-93.
109. Benzel EC. *Biomechanics of Spine Stabilization.* New York, NY: Thieme; 2001.
110. Benzel EC, Hart BL, Ball PA, Baldwin NG, Orrison WW, Espinosa MC. Fractures of the C-2 vertebral body. *J Neurosurg*. 1994;81(2):206-212.
111. Hadley MN, Dickman CA, Browner CM, Sonntag VK. Acute axis fractures: a review of 229 cases. *J Neurosurg*. 1989;71(5 Pt 1):642-647.

112. German JW, Hart BL, Benzel EC. Nonoperative management of vertical C2 body fractures. *Neurosurgery*. 2005;56(3):516-521.
113. Fujimura Y, Nishi Y, Kobayashi K. Classification and treatment of axis body fractures. *J Orthop Trauma*. 1996;10(8):536-540.
114. Craig JB, Hodgson BF. Superior facet fractures of the axis vertebra. *Spine (Phila Pa 1976)*. 1991;16(8):875-877.
115. Korres DS, Zoubos AB, Kavadias K, Babis GC, Balalis K. The "tear drop" (or avulsed) fracture of the anterior inferior angle of the axis. *Eur Spine J*. 1994;3(3):151-154.
116. Fowler JL, Sandhu A, Fraser RD. Review of fractures of the atlas vertebra. *J Spinal Disord*. 1990;3(1):19-24.
117. Gleizes VV, Jacquot FP, Signoret F, Feron JM. Combined injuries in the upper cervical spine: clinical and epidemiological data over a 14-year period. *Eur Spine J*. 2000;9(5):386-392.
118. Hanssen AD, Cabanela ME. Fractures of the dens in adult patients. *J Trauma*. 1987;27(8):928-934.
119. Henry AD, Bohly J, Grosse A. Fixture of odontoid fractures by an anterior screw. *J Bone Joint Surg Br*. 1999;81(3):472-477.
120. Lee TT, Green BA, Petrin DR. Treatment of stable burst fractures of the atlas (Jefferson fracture) with rigid cervical collar. *Spine (Phila Pa 1976)*. 1998;23(18):1963-1967.
121. Levine AM, Edwards CC. Fractures of the atlas. *J Bone Joint Surg Am*. 1991;73(5):680-691.
122. Montesano PX, Anderson PA, Schlehr F, Thalgott JS, Lowrey G. Odontoid fractures treated with anterior odontoid screw fixation. *Spine (Phila Pa 1976)*. 1991;16(3 Suppl):S33-S37.
123. Morandi X, Hanna A, Hamlat A, Brassier G. Anterior screw fixation of odontoid fractures. *Surg Neurol*. 1999;51(3):236-240.
124. Stulik J, Krbec M. Magerl's technique of C1-C2 fixation. *Acta Chir Orthop Traumatol Cech*. 2000;67(2):93-99.
125. Wright NM, Lauryssen C. Vertebral artery injury in C1–2 transarticular screw fixation: results of a survey of the AANS/CNS section on disorders of spine and peripheral nerves. *J Neurosurg*. 1998;88(4):634-640.
126. Zavanone M, Guerra P, Rampini P, Crotti F, Vaccari U. Traumatic fractures of the craniovertebral junction. Management of 23 cases. *J Neurosurg Sci*. 1991;35(1):17-22.