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ORIGINAL ARTICLE

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Fractures of the odontoid process in small children: biomechanical analysis and report of three cases

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Abstract Odontoid "fractures" in young children typically involve the cartilaginous plate (synchondrosis) that separates the odontoid process from the body of the axis; 58 cases have been described in the literature. We report two cases in which 2-year-old children were involved as back-seat passengers in head-on motor vehicle accidents, both were restrained by four-point child's seat harnesses. A biomechanical investigation was carried out using simulation in a real car crash test with a child dummy. This revealed that head-on collisions with a speed absorption of at least 40 km/h are the typical mechanism of injury in children under the age of 3 years involved in motor vehicle accidents. Shearing force is all that is necessary to explain the dens fracture. Both children were immediately symptomatic, and the diagnosis was obvious on radiographs. Neither child had neurological deficit, which correlates well with the literature, where neurological injuries were found only in conjunction with head injuries. After closed reduction, both cases were initially treated conservatively with halo and plaster vest for 12 weeks. In one case, in which the anterior dislocation was less than the diameter of the odontoid shaft, eventless healing occurred. In our second case, despite an anatomic reduction, the odontoid fracture failed to unite. After a temporary posterior fixation of C1/C2 we reamed the synchondrosis from anterior and performed autogenous bone grafting. The posterior fixation wire was removed after 5 months. In contrast to the literature, we do not recommend a permanent posterior fusion of C1/C2. Our two young patients were both followed-up for more than 3 years. Clinical and radiological examination at final follow-up was normal with no signs of atypical growth of the odontoid. In cases of major dislocation with greater instability we recommend primary open reduction and osteosynthesis with appropriate implants. This was done in a third case: a 1½-year-old boy who fell down the stairs and sustained a head injury and an unstable lesion of the odontoid with subtotal paraplegia. The odontoid was fixed with two screws.

Key words Odontoid fracture in children · Synchondrosis · Operative treatment · Follow-up · Biomechanics · Child seat restraint

Table 1 Overview of the literature concerning 75 odontoid "fractures" and our own three cases in children up to the age of 8 years (*av* average, *mva* motor vehicle accident, *chi* closed head injury)

Author	Year	*n*	Age (years)	Mechanism of injury	Dislocation upper cervical spine	Neurological deficit	Conservative/ operative therapy	Indication for surgery	Operative technique
Price [17]	1960	1	4	?	anterior	?	0/1	non-union	posterior fusion
Ewald [9]	1971	1	$1^7/_{12}$	?	?	?	1/0		
Anderson and d'Alonzo [1]	1974	5	3–6	?	1x anterior	no	4/1	?	post. cerclage and allogenic bone graft
Hubbard [13]	1974	1	2	fall	?	no	0/1	gross instability	fusion (?)
Gropper et al. [12]	1975	5	$1^4/_{12}$–5	?	?	no	5/0		
Barcat et al. [3]	1976	7	?	?	?	?	7/0		
Seimon [20]	1977	2	< 3	?	?	?	2/0		
Sherk et al. [21]	1978	11	< 7	9 × mva, 1 × fall 1 × birth trauma	anterior	only with a chi	11/0		
Stillwell and Fielding [22]	1978	1	7	fall	?	?	0/1	non-union	posterior fusion C1/C2
Ries and Ray [18]	1986	1	6	fall	posterior	no	2/0		
Taylor et al. [24]	1987	11	?	?	anterior	?	8/3	non-union	posterior fusion C1/C2
Diekema and Allen [7]	1988	11	av. 4	"nearly all high speed traffic accidents"	anterior	1x	10/1	?	posterior wiring
Fujii et al. [10]	1988	6	< 7	6 × mva	4 × anterior, 1 × posterior 1 × without	?	6/0		
Birney and Hanley [4]	1989	3	?	mva, falls	?	no	?		
Müller and Erdweg [16]	1989	1	$^6/_{12}$	?	anterior	no	1/0		
Dietz et al. [8]	1992	1	$3^6/_{12}$	mva	anterior	no	1/0		
Vining et al. [26]	1992	1	2	mva ejected	anterior	no	1/0		
Schwarz et al. [19]	1993	5	2–8	3 × mva 1 × jump into water 1 × struck by a box	?	no	5/0		
Junge et al. [14]	1994	1	3	mva (restraint in children's seat)	anterior	brain injury with partial tetraplegia	1/1	massive dislocation with instability and neurological deficit	anterior screw fixation
Blauth et al.		3		2 × mva (restraint in children's seat) 1 × fall	3 × anterior	2 × no 1 × subtotal tetraplegia	1/2	1 × non-union 1 × gross instability and neurol. deficit	1 × temp.post.fusion C1/C2 + anterior fusion without implant 1 × anterior screw fixation

Introduction

Cervical spine injuries are rare events in childhood. Langwieder and Hummel [15] reported an incidence of 5–10%, independent of the mechanism of injury; severe cervical spine injuries with an abbreviated injury scale (AIS) 3–6 occur only in 0.12% of all cases. In young children in particular, unlike in adults, lesions are more common in the upper than in the lower cervical spine and most often the odontoid is concerned [16]. In children below the age of 7 years, 75% of all cervical spine lesions involve the odontoid process [21].

According to the literature (Table 1), lesions of the odontoid process in small children are usually treated conservatively. Sherk et al. [21] and Taylor et al. [24] have the largest reported series with 11 cases of odontoid fracture in children up to the age of 7 years. In case reports, surgical therapy is only described after the failure of conservative treatment. We found eight cases of posterior fusion of C1/C2 (see Table 1), and one case in which the anterior screw fixation described by Magerl and Böhler had been used [14].

The following study discusses odontoid fractures in children, describing three cases, one treated conservatively and two by operative therapy. Follow-up in two of the cases was more than 3 years, and in one case 1 year.

Since two children were involved in car accidents while secured with child seat restraint systems a biomechanical investigation of this condition could be of interest.

Anatomy and pathophysiology

Embryologically the odontoid represents the body of C1, and in infants the process in separated from the body of C2 by the synchondrosis. The synchondrosis is a cartilagenous plate comparable with the intervertebral disc; it does not have true characteristics of a growth plate. It is found in all children under the age of 3 years, but only in 50% by the age of 5 years. Rarely the synchondrosis can be found in adolescents, before a complete fusion of the odontoid process with the body of the second vertebra occurs [16]. Radiologically the synchondrosis appears as a small lucent line, often combined with a hyperdense rim. It may be misinterpreted as a fracture line. The ossification of the odontoid process starts in the 5th fetal month and has two centres. This explains the typical appearance of the odontoid process in the AP view.

The subdental synchondrosis is regarded as a very vulnerable area until the age of 10 years, the fracture line always stretches along this line [11, 23]. Beside synchondrosis between the dens and the body of C2, there exist two others between the dens and the neural arches and between the body and the neural arches (Bailey 1952). These synchondroses may be separated as well, and be visible in computerized tomography (Fig.7) [26].

The literature almost only demonstrates anterior dislocations comparable with a transdental dislocation of the lower cervical spine in the posterior direction (Table 1, Fig. 1).

Case reports

Case 1

A 23-month-old girl was involved in a car accident as a back-seat passenger wearing a four-point restraint system. The car was involved in a head-on collision with a stopping bus; the reported speed was approximately 50 km/h. The child immediately complained of neck pain and had a limited range of motion. Physical examination on admission demonstrated an isolated cervical spine injury without neurological deficits. Radiographs showed an anterior transdental dislocation of C1 at the level of the synchondrosis (Fig. 1). Examination under image intensification showed an extremely unstable injury, with even swallowing producing movement in the fracture line. Therapy consisted first of a minerva cast applied under general anaesthesia. Reduction could not be maintained (Fig. 1b); therefore, a halo fixator with a plaster cast was applied on the 1st day.

During the first 2 weeks, the child was sedated and nutrition was administered via a gastroduodenal tube (Fig. 2). Serial radiographs always showed an anatomic reduction of the fracture. The child was discharged in the halo fixator and 12 weeks after the injury the halo was removed. Flexion/extension radiographs at that time demonstrated persisting complete instability at the level of the synchondrosis.

It was therefore decided to proceed with open reduction and internal fixation. Intraoperatively, the patient's neck was placed in position with the halo ring and the help of an adult fixation device, routinely used in cervical spine surgery [5]. The odontoid position was controlled under image intensification (Fig. 3). Primarily, in prone position, a temporary posterior fusion of C1/C2 was performed with sublaminar wiring. In supine position, the synchondrosis was then debrided and filled with autologious bone graft (Fig. 3). The child was treated postoperatively for another 8 weeks with a halo fixator. Rehabilitation was uncomplicated. Removal of the wire was performed 5 months after the operation. Follow-up 1 year and 3 years after the operation revealed a child without complaints, and with free range of motion of the cervical spine. Radiographs demonstrated normal length of the odontoid process.

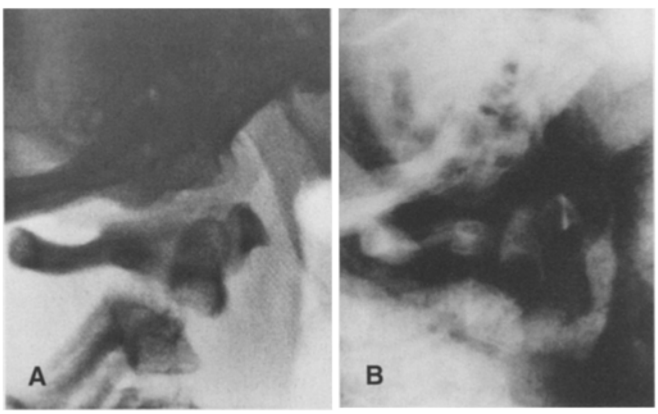


Fig. 1 A, B Case 1. **A** Unstable lesion of the subdental synchondrosis with transdental dislocation in a 23-month-old girl. **B** Inadaquate reduction in a plaster vest

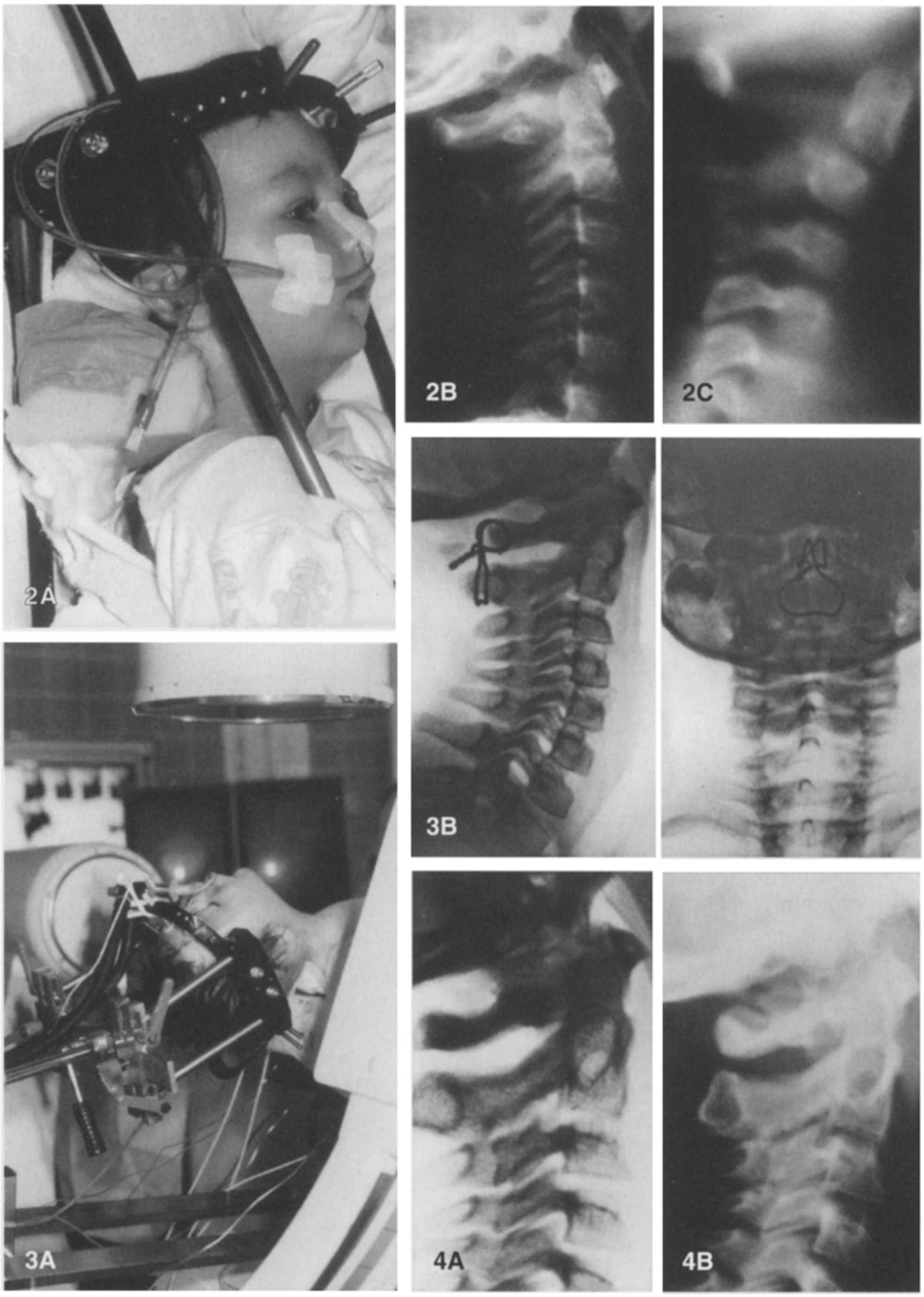


Fig. 2 **A, B** Reduction in a halo ring with a hypomochlion and a plaster vest. The child was sedated and nutrition administered through a gastroduodenal tube for 2 weeks after the operation because of the high degree of instability. **C** Tomography after 12 weeks. Flexion/extension radiographs under fluoroscopy (not shown here) demonstrated persistent instability at that time

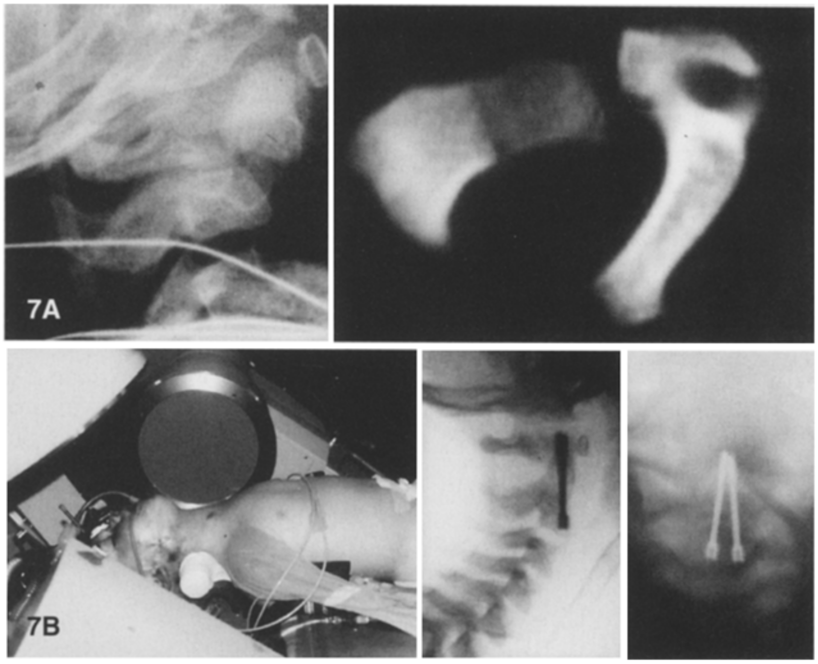
Fig. 3 **A** Intraoperative positioning with a halo ring, a special fixation device and two image intensifiers. **B** Reaming of the synchondrosis and autogenous bone grafting after temporary posterior fusion C1/C2, healing after 4 months

Fig. 4 Follow-up radiographs **A** after 1 year and **B** after 3 years show narrowing of the intervertebral disc C2/C3 with a slight kyphotic deformity and normal growth of the odontoid process

However, intervertebral disc height of C2/C3 was reduced, probably secondary to operative trauma. A slight kyphotic deformity could also be seen in the upper cervical spine. Residuals of surgery can be seen in tiny osteophytes on the ring of atlas (Fig. 4).

Case 2

A 22-month-old girl was involved in a head-on motor vehicle accident (Fig. 5), wearing a four-point restraint system as a back-seat passenger. Immediately, the father noted that the child was complaining of neck pain with extremely painful motion. At the local hospital no cervical spine injury on radiographs was noted. With persistent pain, 2 days later a tomogram of the upper cervical spine was performed showing an odontoid fracture at the level of the synchondrosis with anterior dislocation. The fracture line extended part way into the C2 body. After an emergency interhospital transfer the odontoid fracture was treated under general anaesthesia with closed reduction and halo fixation. Ten weeks after injury the halo was removed, 3 weeks later the child had no complaints and a



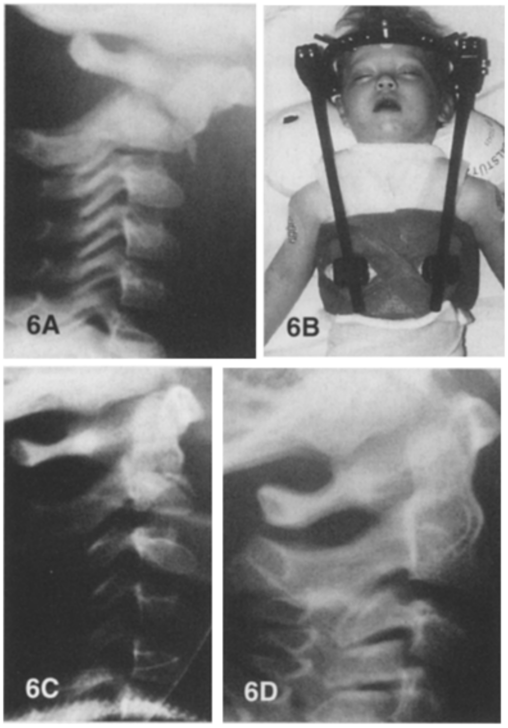


Fig. 5 Vehicle front deformation characteristic of a head-on collision with speed absorption during the collision of δv = 60 km/h (case 2)

Fig. 6 A–D Case 2. **A** Lesion of the synchondrosis in the dorsal part with a fracture line in the anterior part of the body of axis and a posterior transdental dislocation of the lower cervical spine in a 22-month-old girl. **B, C** Closed reduction and fixation in a halo with a plaster vest. **D** Follow-up 3 years after injury

Fig. 7 A–C Case 3. **A** Grossly unstable lesion of the synchondroses between dens and body as well as dens and the left arch of C2. **B** Intraoperative positioning and reduction for screw osteosynthesis. **C** Appearance of the child 7 months after the accident

free range of motion. There was no neurological deficit. Thirteen weeks after the injury, radiographs showed an anatomic reduction with signs of complete bone healing. Three years later a follow-up demonstrated slightly shortened odontoid length with a thickening in the former region of synchondrosis and normal findings at the adjacent levels (Fig. 6). The radiological appearance seems to be typical when compared to other children that have been followed-up for a longer period of time [27].

Case 3

An 18 month-old boy fell down the stairs and was at the same time hit by a scaffold. He sustained brain injury with fracture of the skull and a small epidural haematoma as well as a highly unstable lesion of the subdental synchondrosis of C2 and a fracture of the arch of C3. Initially we found a complete cord syndrome with quadriplegia; only the phrenic nerve on the right side seemed to be spared. After initial fixation with the halo fixator, early compression osteosynthesis was carried out with two Herbert screws using a standard anterior approach. Positioning of the small patient and intraoperative closed reduction in the same device as has been described in case 1 (Fig. 7). The postoperative course was uneventful. Follow-up revealed complete healing of the dens, proven by tomogram. Clinically, half a year after the accident the child showed active motion of all four extremities and has been mobilized in a wheel chair without mechanical ventilation.

Mechanism of injury

The two children involved in car accidents (cases 1 and 2) had been correctly fastened with belts in special seats as laid down by German law. This gave us cause to perform a biomechanical analysis of these two cases via reconstruction of the kinetics of the car, the car deformation and the type of safety-belt system used by the child. In view of lack of data concerning child protection, an accidentological and experimental study was carried out by specialists in an international task force [25]. The goals of this international research, involving experts from seven countries, were two-fold: on the one hand, to establish protection principles, gathering and analysing real crashes involving

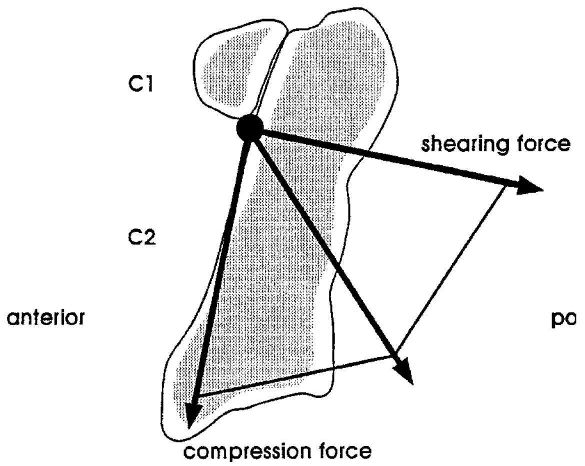


Fig. 8 Biomechanical analysis: anterior flexion of the cervical spine results in compression- and shearing-type forces on the atlas. In the typical mechanism of injury in children, shearing forces predominate as the resultant cause of injury

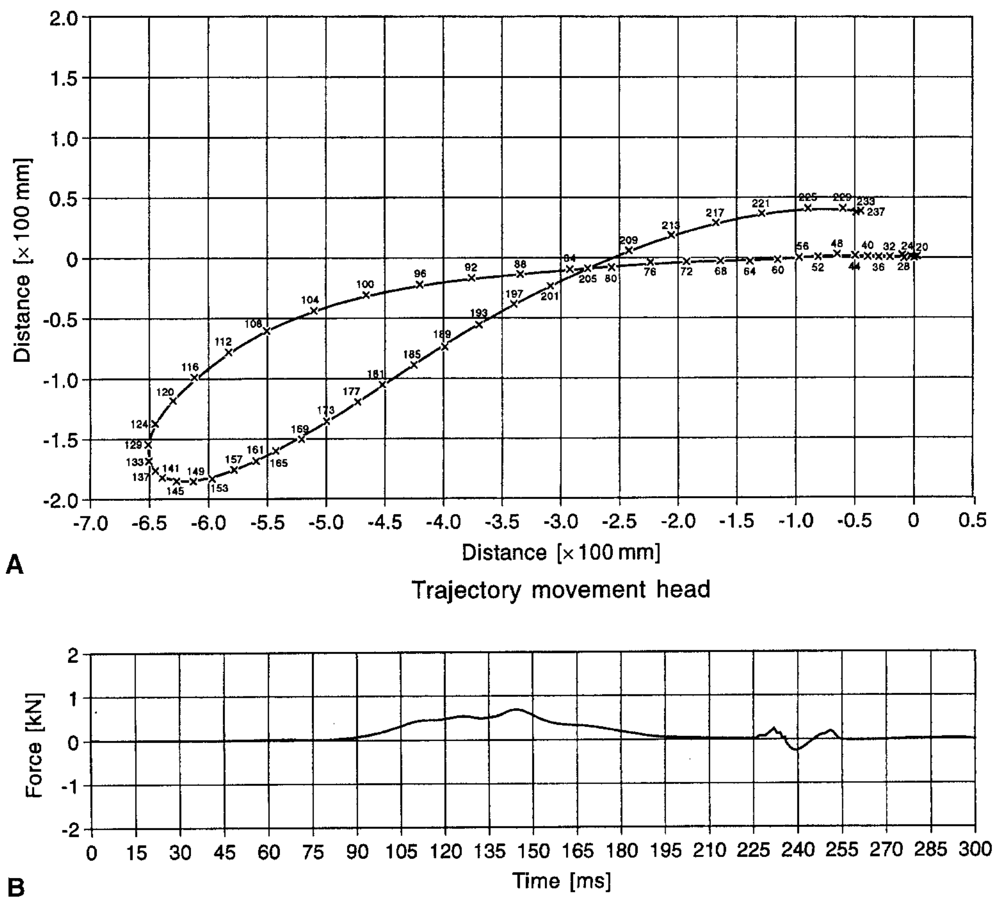
restrained children; on the other hand, to identify and quantify injury mechanisms in order to increase knowledge about child tolerances. To realize this second part, real crash reconstructions were performed in order to correlate observed injuries with recorded parameters on dummies. The two cases involving motor vehicle accidents were discussed in detail with this group.

According to these considerations, dislocation of the odontoid process must be caused by a bending force during accelerated flexion of the cervical spine. Without a cartilaginous segment between C1 and C2 as an elastic buffer, the resultant force could be the effect of force in *(X)* shearing or *(Z)* traction load, in these cases to be regarded as a shearing force resulting from the forward bending movement (Fig. 8). Other factors must be regarded as contributory biomechanical causes of this type of injury. First, the child's head is proportionally overlarge compared with the body, second, the synchondrosis does not posses the stiffness of a growth plate in shear [8].

A simulation of one of the two cases involved in motor vehicle accidents was performed in a real car crash test with the same vehicle model, the same child seat and the same estimated collision speed of 40 km/h. A dummy of a 3-year-old child was used ("CRABI") with a special neck transducer measuring forces and moments.

Biomechanical analysis of the accidents demonstrated that the injuries to the synchondrosis occur with the use of a child's four-point restraint system under shearing forces at the moment of maximal anterior flexion of the head.

Fig. 9 A, B Crash simulation with the CRABI dummy. **A** Two-dimensional trajectory movement *(X, Z)* of the head. **B** Neck force behaviour related to time duration



The head of the child accelerates more rapidly than the rest of the body, which is restrained by the security belts. The acceleration of the seat itself is also delayed because of the belts keeping it attached to the seat of the car. Therefore, the maximum shearing force affects the cervical spine when it is bent forward at its maximum. Simulation with dummies of head-on collisions with speed absorption during the collision of $\delta v = 40$ km/h demonstrated shearing forces of 600 N (Fig. 9). This resulted in an anterior shift of the head of 650 mm and a deceleration of 130 g (1 g = 9.81 m/s^2). Collision of the head with the front seats was not observed.

Discussion

Fracture of the synchondrosis of the odontoid is a rare but typical injury in childhood. Even more interesting, not only are there typical lesions of the synchondrosis comparable with epiphysiolysis, but associated teardrop-like fractures of the anterior-inferior part of the body and lesions of the arch of C2, as described in this paper, can also be found (cases 2 and 3). According to our knowledge, such a combined lesion has so far only been reported by Vining et al. [26]. The authors stress the importance of computerized tomography to detect lesions not only of the synchondrosis between the ossification centres of the dens and body but also between the dens and neural arches.

A review of 75 lesions of the synchondrosis in children under the age of 8 years reveals some common features that could be confirmed in our cases:

1. The atlas and the odontoid dislocate anteriorly; there are only two cases of posterior dislocations reported.
2. Motor vehicle accidents are the main mechanism of injury, followed by falls.
3. Spinal cord injuries are only reported in conjunction with closed head injuries [21].

All authors advocate conservative therapy. Closed reduction under anaesthesia was followed by retention in a Minverva plaster or by extension in a Glisson traction, Crutchfield extension or halo fixation. We prefer halo fixation in conjunction with a plaster cast; closed reduction with a hypomochlion in the neck is helpful in some cases.

Reduction was achieved in our two cases using this method without complications or repeated corrections. Local pin infections can be easily treated.

The cause of non-union is inadequate immobilization, according to the reports of Taylor et al. [24] and Stillwell and Fielding [22]. Taylor et al., in their three cases of non-union, primarily applied a Minerva plaster cast, Schwarz et al. [19] in one reported case also used a Minerva cast. Only in one reported case of non-union was a soft collar used. In other reports of non-union, the type of immobilization is not described.

In our first case, adequate immobilization of the upper cervical spine was achieved. Follow-up radiographs showed continued good reduction. Interesting, in case 1, was the degree of instability. Retention in a Minerva plaster cast was not possible in this case. Though there are no reports in the literature about the degree of primary instability, we do recommend operative therapy in cases of dislocation of the odontoid process with more than a width of the diameter of the odontoid and marked instability when examined under image intensification.

In summary, we found nine reports, excluding our own, describing reduction and stabilization. Only in one case [14] was a direct fusion performed; all the other cases were treated by indirect posterior fusion sacrificing the motion segment C1/C2. Though children can compensate for limitation of rotation in the upper cervical spine, direct osteosynthesis is to be preferred. Though our treatment of case 1 can be regarded as successful, today we prefer internal fixation with adequate small implants as shown in case 3. The approach and technique of direct screw fixation does not differ from the technique described for adult odontoid fractures [6]. Of utmost importance is correct positioning of the patient and preoperative closed reduction. For this purpose we found our specially designed traction and positioning device in conjunction with the halo ring to be extremely helpful [5].

Our experience also demonstrates the importance of assessing stability under image intensification following conservative treatment.

With operative therapy, iatrogenic lesions of the intervertebral disc should be avoided. We found growth of the odontoid process to be unaffected up to 3 years after trauma.

The first biomechanical analysis of odontoid fracture mechanisms in small children has been performed. Shearing forces of 600 N produce this pattern of injury. The shearing force is all that is necessary to explain the dens fracture. It affects the cervical spine of a child in a restraint seat at the moment of maximum flexion. From the biomechanical point of view, options to avoid or minimize the risk of these injuries would be to use rearward facing systems for as long as possible during infancy [7] or children's seat systems that are integrated with the seat of the car – so-called "isofix systems". Analysis of further reconstructions is needed in order to reach reliable definitions of the forces that lead to injury and limits of tolerance.

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