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Exposure of the porcine spine to mechanical compression: differences in injury pattern between adolescents and adults

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Abstract Recent studies of the spine in adolescents who have sustained trauma have shown injuries to the growth zone, whereas injuries to the vertebral body have been described in other studies of only adults. There are also reports on different clinical signs and radiological findings in adolescents with lumbar disc herniation when compared to adults. In order to find an explanation for these differences between adolescents and adults, this experimental study was performed. Six cadaveric lumbar motion segments (vertebral body-disc-vertebral body) obtained from three young male pigs and six lumbar motion segments obtained from three mature male pigs were tested in axial compression to failure. All units were examined with plain radiography and magnetic resonance imaging before and after compression. After the compression, his-

tological samples were taken from the injury site. In the adolescents, a fracture was consistently found in the endplate through the posterior part of the growth zone, displacing the annulus fibrosus with a bony fragment at the point of insertion to the vertebra. This type of injury could not be detected in any of the adults; instead, there was a fracture of the vertebra in four cases, and in two cases, a rupture of the annulus fibrosus without a bony fragment was seen. This study showed that, when compressed to failure, the weakest part of the lumbar spine of the adolescent pig differs from that of the mature pig in the same way that studies on human spinal units have shown.

Key words Biomechanical study · Compression forces · Injury patterns · Intervertebral disc · Porcine spine

Introduction

Lumbar disc herniation in children and adolescents is rare and accounts for only 0.5–3% of lumbar disc surgery [7, 9, 15, 17, 35, 37, 38]. Some authors have concluded that there is no difference between adolescent and adult lumbar disc disease [4, 7, 9, 11, 35], while others have shown that both the clinical presentation and the outcome do differ [6, 14, 15, 17, 28, 31, 37]. In some of these studies, a strong relation between trauma and disc injury has been reported in adolescents in contrast to adults [6, 7, 11, 20, 35, 37].

In adolescents and younger adults who have been diagnosed as having herniation of a lumbar disc, there are reports of fractures of the posterior margin of the vertebral body, found exclusively in this age group [13, 25, 43]. This injury has been regarded as a fracture of the posterior ring apophysis or separation of the posterior vertebral rim [3]. In a recently published study on adolescent porcine spine [33], we found a similar injury pattern when lumbar spinal units were compressed to failure. In all cases, there was a fracture of the posterior margin of the vertebral body, with annulus fibrosus anchored to the displaced fragment. Cadaveric studies on human spinal units have predominantly been done on adult spines [5, 19, 22, 34]. In these studies,

with the posterior elements intact, the weakest part of the vertebra was the vertebral endplate and the adjacent spongy bone. In one study on adolescent cadaveric spinal units exposed to compressive loads, the weakest part was the vertebral growth plate [29], similar to the findings in the adolescent porcine spines [33].

The aim of this study was to compare the injuries in the adolescent porcine spine to the injuries in the mature porcine spine when axially compressed to failure.

Materials and methods

Lumbar spines were obtained from three young male domestic pigs, 4 months old and weighing 55–58 kg, and three mature male domestic pigs, 2–3 years old and weighing 180–210 kg. The specimens were cleared of all musculature, placed in plastic bags to minimize dehydration and stored at -20°C until the time of testing. Prior to testing the specimens were thawed at room temperature for 24 h [27].

In the pig there is a great load on the dorsal structures of the spine, and the tissue responds to increasing weight during growth by osseous enlargement of the vertebral pedicles and facet joints. In the present study, an initial trial was performed where adult lumbar spinal units with intact posterior elements were compressed. However, it was not possible to compress the units to failure, due to the large posterior elements. Possible degenerative changes of the dorsal structures in the mature pig could also influence the mechanical properties of the motion segment. Therefore, and in order to compare the adolescent porcine spine with the mature porcine spine, the posterior elements were removed at the base of the pedicles in both groups, leaving the longitudinal ligaments intact.

Plain radiographs were taken in anteroposterior and lateral views using the full-size technique. Magnetic resonance imaging (MRI) was performed on a 1.0-T Signa Advantage system (GE Medical System, Milwaukee, Wisc.) using an extremity coil. Sagittal T1 spin echo [repetition time (TR) 580; echo time (TE) 30] and T2 fast spin echo (TR 3020; TE 116) images were obtained before and after lumbar spine compression, using a field of view of 24×12 cm. Axial T1 spin echo (TR 500; TE 30) and T2 fast spin echo (TR 3460; TE 102) images were obtained before and after compression, using a field of view of 16×8 cm. A matrix of 512×384 and a slice thickness of 3 mm with a 0.5-mm gap were used in all sequences. MRI was also used to measure the transaxial area of the disc, by measuring the anteroposterior and transverse diameters of the disc. Disc area was estimated by an elliptical model, using the equation: anteroposterior diameter $\times$ transverse diameter $\times \pi/4$.

The six specimens were then divided into 12 lumbar motion segments, each consisting of two vertebral bodies (L2-L3 or L4-L5) and the intervening disc. The cranial part of the superior vertebra and the caudal part of the inferior vertebra were then mounted in a specially designed jig and stabilized with polyester putty (Loctite Sweden AB, Gothenburg, Sweden) to prevent sliding, torsion and rotation of the vertebral body. The vertebrae were mounted in such a way as to achieve parallel surfaces of the endplates, perpendicular to the compression axis. Axial compression was then performed in a hydraulic testing machine with force control. The load rate was kept constant at 1700–2500 N/s, and the force at failure was recorded. Failure was defined as a decrease in force, and in our study, was always accompanied by an audible crack.

After the compression test had been performed, the motion segments were re-examined radiographically and by MRI within 2 h. These examinations were performed in exactly the same manner as they had been performed before the compression. The motion segments were then frozen and stored at -20°C . After freezing, sagittal slices, 3–4 mm in width, were made through each specimen us-

ing a bench saw. Each slice was examined macroscopically and microscopically (magnification $\times 6$ –25). The slices were then decalcified, dehydrated, and fixed in paraffin. Samples of 4 μm were stained with Masson Tricrome, Alcian blue and haematoxylin-eosin solutions. Computer-generated photographs documented the microscopic and histologic findings. The radiographic films and MR images obtained before and after the compression testing were evaluated by a radiologist with no knowledge of the macroscopic, microscopic or histologic findings.

Statistical analysis

Adolescent and adult motion segments were compared with respect to ultimate force and stress (pressure) at failure by use of the unpaired *t*-test, two-tailed. Stress was calculated as ultimate force divided by disc area. A *P*-value of < 0.05 was considered statistically significant.

Results

The mean ultimate force at failure for the adolescent motion segments, at 9.4 kN (SD 0.9 kN), was significantly lower than that in the adult segments, at 25.3 kN (SD 0.7 kN), ($P < 0.001$). The mean cross-sectional area of the intervertebral discs in the adolescent group was 540 mm² (SD 40 mm²) and in the adult group 865 mm² (SD 88 mm²). The mean stress at failure in the adolescent group was 17.5 MPa (SD 2.2 MPa), and in the adult group 29.6 MPa (SD 3.5 MPa), a significant difference of $P < 0.001$.

Radiographic examination

There were no radiographic abnormalities in the vertebral bodies or disc spaces in any of the cases before the compression testing. After compression testing, an undisplaced fracture could be seen in one of the adolescent vertebrae affecting the caudal part of the cranial vertebra. This was visualized on the lateral view, where there was an oblique fracture line engaging a small fragment at the posterior corner. In three additional adolescent cases, a similar finding was suspected, but not regarded as definite.

In the adults, a vertical fracture of the cranial vertebra could be seen in two cases. One was visualized on the lateral view, situated in the centre of the vertebra and traversing through the entire height of the vertebra. One was visualized on the anteroposterior view at the most lateral part of the vertebra. In one additional case, a fracture line was suspected, but not regarded as definite, in retrospective analysis.

MRI examination

No abnormalities in the vertebral bodies or intervertebral discs could be seen on MRI before the compression testing. The nucleus pulposus was intact and showed high signal

Fig.1 Axial view of an adolescent lumbar motion segment on a T2-weighted magnetic resonance image, **A** before compression, centred in the disc, **B** after compression, centred in the disc, and **C** after compression, immediately above the disc. The fracture line in the posterior part of the vertebra is filled with nucleus material (arrows)

intensity on T2-weighted images in all cases. It was well-defined on both axial and sagittal T2-weighted images.

Adolescent group

In all adolescent cases, after the compression testing, a rupture of the nucleus pulposus was noted, evidenced by a reduction in the nucleus pulposus volume, partial loss of its high signal content and sometimes loss of its sharp demarcation (Fig. 1 A, B). In all six motion segments, abnormal MRI signal was found in either the cranial or the caudal vertebra surrounding the disc. Close to the disc, in the posterior part of the cranial vertebra in five cases and the caudal vertebra in one case, there was a localized region of abnormal signal of the same intensity as nucleus material, indicating the site of injury. This was evident on both axial (Fig. 1 C) and sagittal views. In two cases this signal intensity was linear in shape, compatible with a distinct fracture line, which extended through the posterior part of the endplate, traversing the growth zone, detaching the posterior bony corner of the vertebra.

Adult group

In the adult group, after the compression testing, rupture of the nucleus pulposus could be visualized in all but one case. In all six motion segments, abnormal MRI signal was found in the lower part of the cranial vertebra, while the caudal vertebra showed unchanged signal pattern in all cases. In three cases, there was a localized area of high signal in the most posterior part of the cranial vertebrae in close relation to the disc, indicating the injury site. In the other three cases a distinct fracture line in the vertebra could be identified, with horizontal as well as vertical extension traversing through the endplate. In the case with intact nucleus pulposus after compression, a fracture of the lower lateral part of the vertebra could be documented with MRI as well as plain radiography.

Pathoanatomic and histologic examination

The injury site seen on MRI was verified in all adolescent motion segments. In all cases a fracture line was seen at the posterior margin of the endplate, through the epiphyseal plate and through the growth zone dorsally (Fig. 2). The fracture involved a fragment from the corner of the vertebral body, where the anulus fibrosus was anchored at the most posterior part of the endplate. Histologic samples showed that the fracture site was filled with nucleus material in all but one case (Fig. 3).

In the adult motion segments, there was an irregularity of the posterior part of the anulus fibrosus in two cases, indicating a rupture (Fig. 4). In one of these, there was a min-

Fig. 2 Photomicrograph showing the microscopic appearance of an adolescent lumbar motion segment, sagittal section. *Arrow* indicates fracture line

Fig. 3 Photomicrograph showing a histological sample of an adolescent lumbar motion segment, stained with Masson trichrome solution. The fracture line, indicated by *arrow*, is filled with tissue from the nucleus pulposus

Fig. 4 Photomicrograph showing a histological sample of an adult lumbar motion segment, with rupture of the anulus fibrosus, stained with haematoxylin-eosin solution. *Arrow* indicate rupture site

imal bony fragment attached to the avulsed anulus fibrosus. The fractures of the vertebral bodies seen on MRI could be verified in all cases. As also indicated on MRI, the fracture line did not reach the disc in one case.

Discussion

The same type of injury in the adolescents was found with this experimental setup as in a previous study with intact posterior elements [33]. The injury was seen as a fracture line through the growth zone posteriorly, with anulus fibrosus still intact and anchored to a displaced bony fragment. Microscopic and histologic examinations demonstrated a fracture through the endplate and growth zone, as well as a rupture of the nucleus pulposus, in all cases, with leakage of nucleus material into the fracture line in all but one case. Several of these injuries could not be de-

tected by plain radiography. However, when using MRI, microscopic and histologic examinations, these injuries could be detected in all cases.

In the mature motion segments, a fracture of the vertebral body was found in four cases. In the two other cases there was a true rupture of the anulus fibrosus dorsally. Two of the fractures could be detected using plain radiography.

These observed injuries are in accordance with the findings of Porter and co-workers [36]. In their cadaveric study using human lumbar spines compressed to failure, endplate fractures were the frequent injury pattern in specimens from individuals younger than 20 years of age, whereas in adult spines, vertebral body fractures were frequent.

In a study of cervical spine injuries in victims of traffic accidents, Jónsson and co-workers [26] found that the injury pattern in adolescent cases was different from that in adult cases. In the adults, a rupture of a disc or a vertebral body fracture was often found, whereas the adolescent

spines showed a partial or complete separation of the cartilaginous endplate from the bony endplate. Karlsson and co-workers [29] found, in a cadaveric study on adolescent spines compressed to failure, that the weakest part of the segment was the growth plate. This was in contrast to the findings of a similar study on adult spines by Granhed and co-workers [19]. They found a fracture in the center of the endplate, where an intact segment of the endplate was pressed into the underlying spongy bone, with trabecular fractures surrounding the fracture site. The Karlsson and Granhed studies also showed that the energy absorption capacity was almost three times greater in the adult group than in the adolescent group. This is in accordance with the findings of the present study, where there was a significant difference in the mean stress at failure in the adolescent as compared to the adult group.

The same type of injury as found in the present study among adolescent porcine spines has also been reported in studies of young individuals with back pain associated with symptoms of disc herniation [13, 25, 43]. Takata and co-workers [43] described a fracture of the posterior margin of the lumbar vertebral body in 29 adolescents and young adults with backache or sciatic pain. The injuries were graded into three different types. Type I was a simple separation of the posterior rim of the vertebra without an osseous defect, which was seen only in children less than 13 years of age. Type II was an avulsion fracture of the vertebral body, which was seen in somewhat older children. Type III was a localized fracture posterior to an irregularity in the cartilage of the endplate, which was seen in adolescents and younger adults. Epstein and co-workers [12] introduced a Type IV fracture, which spanned the entire length and breadth of the posterior vertebral body. Several authors have reported on these types of abnormalities among adolescents and young adults in varying numbers of cases [2, 8, 13, 21, 25, 30, 32]. Goldman and co-

workers [18] reported the cases of four patients, one of whom underwent a discogram where the contrast leaked between the vertebral body and the detached fragment. These injuries were regarded as a fracture of the posterior ring apophysis or separation of the posterior vertebral rim.

The same type of apophyseal abnormalities, but in the anterior part of the vertebra, has been seen in athletes with strenuous demands on their backs [24, 41, 42]. Swärd and co-workers [40] also followed the development of an acute apophyseal injury in two elite gymnasts. Alexander, in 1970 [1], defined this type of injury as "localized osteochondritis," and compared it to other types of changes affecting the growth zone and the disc, such as Schmorl's nodes and Scheuermann-like changes [23, 39, 41].

The present porcine study is a mechanical model of the vertebral bodies and the intervening disc when axially compressed to failure. With the posterior elements removed, the more complex biomechanical properties of the segment were not studied. The load was limited to one degree of freedom, in this case axial compression.

Conclusion

This study showed that the injury pattern of the adolescent porcine lumbar spine differed from that of the adult porcine spine when compressed to failure. This is in accordance with findings in the human spine. These injuries involve the growth plate and the apophyseal ring, and consequently the disc function may be altered if the immature spine is exposed to excessive loads. This may be a mechanism for disc herniation among adolescents, and for apophyseal injuries and development of early disc degeneration in elite athletes with strenuous demands on their spine.

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