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Vertebral end-plate fractures as a result of high rate pressure loading in the nucleus of the young adult porcine spine

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Abstract

In a healthy spine, end-plate fractures occur from excessive pressurization of the intervening nucleus. Younger spines are most susceptible to such type of injury due to the highly hydraulic nature of their intervertebral discs. The purpose of this paper was to confirm this fracture mechanism of the healthy spine through the pressurization of the nucleus in the absence of external compressive loading. Sixteen functional porcine spine units were dissected and both injection and pressure transducer needles were inserted into the nucleus of the intervertebral disc. Hydraulic fluid was rapidly injected into the nucleus until failure occurred. Peak pressure and rate of pressure development were monitored. Spine units were dissected to determine the type and location of fracture. Fifteen of the 16 spine units fractured (the remaining unit had a degenerated disc). Of the 15 fractures, 13 occurred at the posterior margin of the end-plate along the lines of the growth plates. A slightly exponential relationship was found between peak pressure and its rate of development ($R^2 = 0.544$). Also, in each of the growth-plate fractured specimens, nuclear material was forcefully emitted, during fracture, from the intervertebral disc into the vertebral foramen. The posterior end-plate fractures produced here are similar to those often seen in young adult humans. This provides insight into a mechanism of fracture development through pressurization of the nucleus that might be seen in older adolescents and younger adults during athletic events or mild trauma.

Keywords: Spine; End-plate fracture; Intervertebral disc; Hydrostatic pressure; Growth plate

1. Introduction

In a healthy spine, as vertebral bodies are compressed, the intervening nucleus pressurizes in order to transfer the load from one body to the adjacent body. Vertebral end-plate fractures appear to occur from tensile stresses that split the end-plate. Numerous studies have examined fracture development under compressive loading of individual spine units (Brinckmann et al., 1989; Gunning et al., 2001; Lundin et al., 1998; Yingling et al., 1997), and some have quantified pressure development within the nucleus during such loading (Ranu, 1990). In addition, Jayson et al. (1973) examined fracture development due to pressurizing the nucleus in the absence of external compressive load. These last authors were able to create fractures in the vertebral bodies similar to those observed due to compressive loading; however, they did not monitor the rate of pressure development and, due to the wide variability in their specimens, did not test the ability to consistently reproduce specific fracture types in a homogenous population.

Previous work has identified the growth plates to be the weakest area of the adolescent vertebral body in human (Aufdermaur, 1974; Karlsson et al., 1998), porcine (Lundin et al., 1998, 2000) and calf (Allan et al., 1990) specimens. Specifically, when compressed to failure in a neutral posture, fractures consistently occur along the growth line of the posterior margin of the end-plate. Similar types of fractures have been commonly identified in human adolescents and young adults (Aufdermaur, 1974; Molina et al., 2004; Takata et al., 1988), particularly those involved in athletic pursuits (Clark and Letts, 2001; Epstein and Epstein, 1991; Ikata et al., 1995). Because younger individuals tend to have healthier, and thus more hydrated

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intervertebral (IV) discs, the general consensus is that they are more susceptible to injuries caused by the transfer of load through the pressurizing of the IV disc and nucleus. Baranto et al. (2005) recently demonstrated that porcine spinal segments with degenerated IV discs require double the compressive load to produce end-plate fractures; this may be because degenerated discs lack the hydraulic nature necessary to sufficiently pressurize the nucleus and may thus lead to altered stress generation and distribution patterns acting on the end-plate. Work is needed to confirm that the types of end-plate fractures commonly diagnosed in a young human population are the result of stresses transmitted to the end-plates through its interface with the nucleus. Thus, the purpose of this brief report was to examine the effect of high pressures within the IV disc in the absence of compressive load on the development of end-plate fractures in a young adult porcine model. It was hypothesized that end-plate fractures would develop similar to those seen in young porcine spines exposed to acute compressive loading, as well as those frequently reported in young adult human spines.

2. Methods

Sixteen functional spine units (FSUs) were dissected from young adult porcine cervical spines (approximate age at death 6 months and full body mass of 80 kg). Fourteen of the 16 (6 C3–4; 8 C5–6) units were stored frozen, thawed, and dissected prior to testing (referred to as fresh from here on); the other two units (C5–6) were stored frozen, thawed, dissected, re-frozen and re-thawed once before testing (referred to as re-frozen from here on). The posterior boney elements along with the posterior longitudinal and anterior longitudinal ligaments were removed to expose the IV disc from both the anterior and posterior directions.

In 13 of the 16 specimens (11 fresh and 2 re-frozen), a standard 2 mm diameter circular inflation needle was inserted through the anterior of the IV disc and into the nucleus (referred to as anterior injection). The needle was attached to a manually controlled hydraulic pump. A 1 mm diameter circular pressure transducer needle (range = 0–7.35 MPa, sensitivity = 4.52×10^{-6} MPa; OrthoAR, Medical Measurements Inc., Hackensack, NJ) was inserted into the nucleus through the posterior of the IV disc. In the other three specimens (all fresh; 1 C3–4, 2 C5–6), the injection needle was inserted through the posterior and the pressure needle through the anterior of the IV disc (referred to as posterior injection from here on). The injection needle and pressure sensor were both secured manually by an experimenter throughout the testing. Pressure data were amplified and A/D converted at 2000 Hz.

The two re-frozen and three posterior injection specimens were conducted to test the robustness of the fracture method.

Each FSU was set so that the end-plates of each vertebral body were oriented parallel to one another. The experimenter then manually secured both the upper and lower vertebral body while hydraulic fluid was slowly injected into the IV disc until full (as indicated by a significant resistance to further injection). At this point, another experimenter rapidly injected additional hydraulic fluid into the IV disc. An example nucleus pressure–time history of the fluid injection is shown in Fig. 1.

Failure was defined as a sudden drop in nucleus pressure, determined visually from inspection of nucleus pressure–time histories. Peak pressure and rate of pressurization were calculated for each FSU. The rate of pressurization was calculated as the slope of the line fit to the most linear set of sampled data points within 25 ms prior to the peak pressure (50 data points). These points were visually examined to ensure linearity; where the full 25 ms could not be used because of a deviation from linear, the maximum time period to ensure a linear fit was used (this period was never less than 17.5 ms or 35 data points).

Both needles were removed and the FSUs were further dissected to examine for damage to the end-plates, vertebral bodies and annular fibers.

3. Results

Distinct fractures were observed in 15 of the 16 FSUs. The one FSU which did not fracture (C5–6 fresh) was found to have a degenerated disc (Grade II according to grading scheme of Wilke et al. (2006)). This was first noted

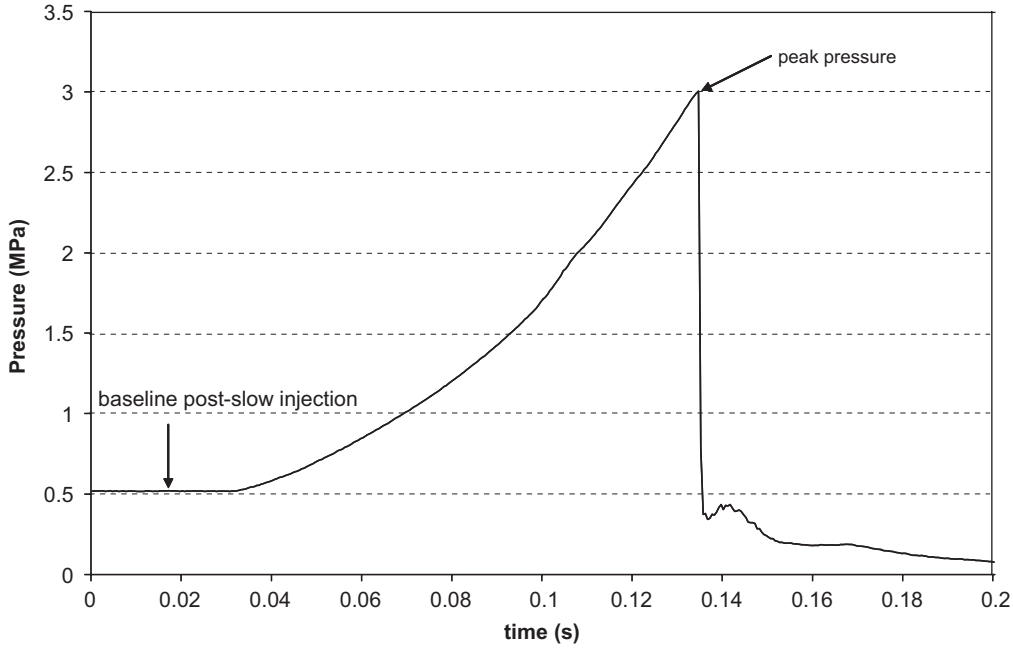

Fig. 1. Example of the nucleus pressure-time history during injection of hydraulic fluid, beginning post-slow fluid injection, continuing through peak pressure (point of failure) to post-failure stage.

as a severely reduced disc height while encountering difficulty in attempting to insert the needles into the nucleus of the IV disc. Thirteen of the remaining 15 FSUs (including the 2 re-frozen specimens and 2 of the 3 posterior injection specimens) fractured in the posterior margin of the endplate along the growth plate (Fig. 2) (12 fractured on the end-plate of the superior vertebral body, 1 on the inferior end-plate). The final two FSUs (both C5–6 fresh; one injected anteriorly, the other injected posteriorly) fractured in the mid-lateral region of the end-plate of the inferior vertebral body.

In each of the growth-plate fractures, the cartilaginous end-plate was completely separated from the spongy bone at the posterior margin of the vertebral body, through to the posterior of the end-plate, and maintained attachment to the rest of the vertebral body only through fixation to fibers of the annulus. Fig. 3 displays the removal of the bone fragment once the annular fibers were cut.

Peak and rates of pressure for each specimen are displayed in Table 1 and Fig. 4. Both linear and exponential relationships were tested for the relationship between the two variables; the exponential relationship was found to be slightly stronger ($R^2 = 0.544$ ($y = 26.012e^{0.214x}$) to $R^2 = 0.502$ ($y = 15.606x - 0.247$)).

4. Discussion

This study documented vertebral fractures of the young adult porcine cervical spine exposed to rapid pressure increases within the nucleus. The original hypothesis that end-plate fractures would develop similar to those seen in young porcine spines exposed to acute compressive loading as well as those often reported as occurring in the spines of young human adults was confirmed. Specifically, 13 of the 16 specimens fractured along the growth plates at the posterior of the end-plate (12 superior end-plate; 1 inferior end-plate). Two other specimens fractured towards the mid-lateral portion of the end-plate of the inferior vertebrae. The final specimen did not fracture (degenerated disc). This indicates that end-plate fractures, in healthy FSUs, result from pressure increase within the nucleus acting on the adjacent end-plates. This provides insight into the mechanism of load transfer, leading to potential end-plate damage, from external load to adjacent vertebral bodies through the pressurization of the intervening nucleus.

In each specimen that fractured along the posterior growth plate, it appeared that the boney fragment

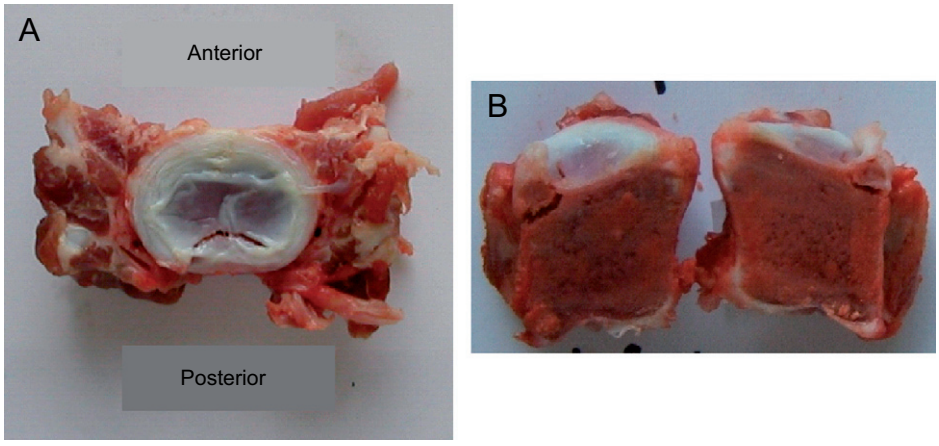

Fig. 2. (A) View of the inferior end-plate of superior vertebral body that has fractured along its growth plate. Anterior and posterior orientations of the vertebrae are labeled. (B) Sagittal cut through the vertebral body of a specimen that has a posterior fracture along its growth plate.

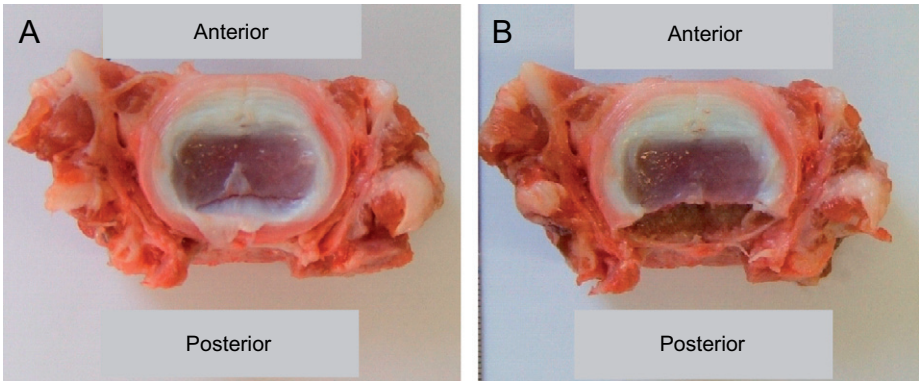

Fig. 3. View of the inferior end-plate of superior vertebral body that has fractured along its growth plate. (A) the annulus intact; (B) the annular fibers cut and the bone fragment removed by the investigator. Anterior and posterior orientations of the vertebrae are labeled.

remained attached to the vertebrae only by annular fiber fixation. Once these annular fibers were dissected away, the boney fragment came free. The boney fractures underlying the end-plate appeared to always follow the edges of the growth plates, where the horizontal growth plate underlying the end-plate meets the vertically oriented growth plate located in the posterior third of the vertebral body.

Table 1
Peaks and rates of pressure and force (acting over the nucleus area of the end-plate) for each of the 15 fractured specimens

Specimen	Peak pressure (MPa)	Rate of pressure (MPa/s)	Peak force (N)	Rate of force (N/s)	Fracture
1	4.4	56.7	1072.5	13880.6	GP C3
2	6.1	104.5	1432.1	24389.5	GP C3
3	5.4	71.0	1190.8	15796.9	GP C3
4	5.2	94.6	1189.6	21543.2	GP C3
5	2.9	48.2	581.7	9844.3	GP C3
6	5.4	64.0	1400.4	16026.3	GP C5
7	4.9	56.8	1054.0	12167.3	GP C5
8	3.5	76.1	646.9	13980.7	GP C5
9	6.6	135.2	1195.9	24418.6	GP C5
10	5.0	64.1	992.9	12739.5	EP C6
11	4.1	66.5	851.7	13778.0	GP C5
12	5.9	76.4	1126.3	14449.1	GP C6
13	3.4	53.4	751.1	11862.4	GP C3
14	4.6	68.8	1251.2	18646.4	EP C6
15	5.7	129.5	1277.4	29248.4	GP C5

Specimens 1–5 are C3–4 fresh. Specimens 6–10 are C5–6 fresh. Specimens 11 and 12 are C5–6 frozen. Specimen 13 is C3–4 and specimens 14 and 15 are C5–6 (all fresh) with the oil injected through the posterior of the intervertebral disc. Fracture location is indicated: GP, fracture along the growth plate; EP, fracture of the end-plate (not through the growth plate). *Note*: Specimen 16 is not shown as it did not fracture (attributed to a grade II degenerated disc).

Also, in each specimen that fractured along the posterior growth plate, nuclear material (mixed with hydraulic fluid) was forcefully emitted, during fracture, from the vertebral body in the posterior direction, into the vertebral foramen. Subsequent tests with slow fluid injections post-fracture showed fluid leaking from the fracture line as well as through the venous and arterial foramina. This mechanism highlights the potential for damage to neural structures (spinal cord, spinal nerves) from such forceful contact with the nuclear material. In the current experiment, bone fragments were never emitted in a forceful manner. It is also interesting to note that the direction of fluid injection (anterior versus posterior) and/or the re-freezing of the specimen did not appear to affect the location, type and mechanism of fracture development (Table 1, Fig. 4).

The type of growth-plate fracture documented in the current study has been commonly identified in adolescents and young adults (Aufdermaur, 1974; Molina et al., 2004; Takata et al., 1998), especially those participating in athletics (Clark and Letts, 2001; Epstein and Epstein, 1991; Ikata et al., 1995). These fractures have also been consistently induced in adolescent porcine spines exposed to mechanical compression (Lundin et al., 1998, 2000). The rates of pressure used in the current study ranged from 48.2 to 135.2 MPa/s, which correspond to compressive force rates of approximately 9844.3 to 24418.6 N/s acting over the nucleus area of the end-plates. These loading rates represent those potential seen in athletic events or during mild acute trauma.

The best fit relationship between pressure rate and failure pressure was found to be exponential ($R^2 = 0.544$) (Fig. 4). Yingling et al. (1997) found no relationship between failure loads and compressive rates between 1000 and 16,000 N/s in porcine FSUs, while Elias et al. (2006)

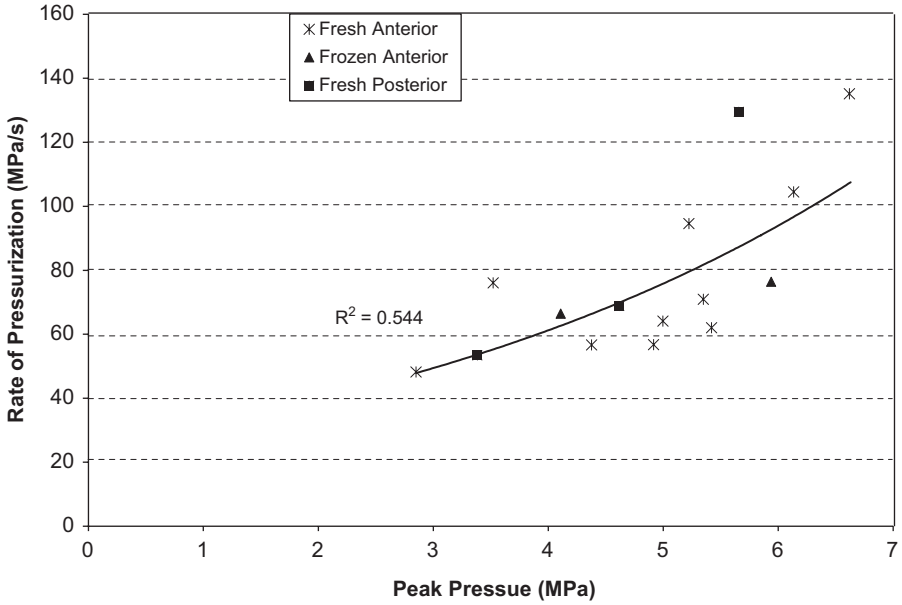

Fig. 4. Relationship between peak pressure (MPa) and rate of pressure development (MPa/s) in the 15 fractured specimens. The exponential line of best fit and corresponding R^2 value are shown.

found a significant positive correlation between failure loads and displacement rates between 5 and 5000 mm/s (corresponding to approximately 2000 and 3,250,000 N/s, respectively) in adolescent baboon FSUs. However, Elias et al. (2006) found no significant differences between the displacement rate groups in terms of failure load and therefore concluded the relationship between load rate and failure load to be relatively weak. The association seen in the current study indicates that the failure loads created through a hydrostatic pressure mechanism in young porcine spines are partially related to the rate of load development, at least for the range of load rates examined here.

The average failure pressures documented by Ranu (1990) during slow (0.13 mm/s) compressive loading of human cadaveric lumbar spine FSUs was 3.02 MPa; and by Jayson et al. (1973) during oil injection into human lumbar FSU discs ranged from 2.07 to >6.89 MPa (transducer only capable of recording up to 6.89 MPa). The mean in the current study was 4.87 MPa (SD 1.07). Pressure rates were not reported in Jayson et al. (1973)'s paper, but the rates in the current study are much higher (again simulating acute injury events) than those in the study by Ranu (1990), and most likely explain the higher failure pressures seen here. This suggests an apparent tissue stiffening/strengthening effect, similar to that seen in many previous biomechanical studies, as a result of high load and/or pressurization rates.

The mechanism utilized in the current study to increase pressure within the nucleus (increased fluid volume) does not represent a common "physiologic" mechanism. More commonly, compressive loads applied to the spinal unit result in an increased fluid pressure within the nucleus. However, the fractures detailed in the current study have also been consistently produced through compressive loading protocols, indicating that the stress concentrations produced by each of the methodologies are similar in nature. Thus, the benefit of the current method of increasing fluid volume in the absence of compressive load is that it has isolated the rise in pressure as the probable mode of fracture.

The current study utilized younger cervical porcine spines as a correlate for adolescent or young adult lumbar human spines. Previous work has documented the similar anatomical and mechanical characteristics between the two spine types (Oxland et al., 1991; Yingling et al., 1999). Further, the animal model used here allowed for control over the age, diet, activity level and health of the specimens, which are not possible using human donors. Finally, as mentioned previously, the types of fractures seen here are similar to those often documented in adolescents and young adults reporting spine fractures (Aufdermaur, 1974; Molina et al., 2004; Takata et al., 1988; Clark and Letts, 2001; Epstein and Epstein, 1991; Ikata et al., 1995). Therefore, it is thought that the young porcine model appears to provide a useful model for investigating the development of such types of vertebral injury. However, caution should be taken in applying evidence obtained from a porcine model directly to the human.

5. Conclusions

Posterior end-plate fractures similar to those often seen in young humans were consistently produced through the high rate injection of hydraulic fluid into the IV disc of adjacent porcine vertebral bodies. This confirms the possibility of the real-life mechanism of fracture occurring through the following steps: load applied to the spine causes the nucleus to pressurize thereby causing tensile stresses to develop on the end-plate with subsequent end-plate splitting and boney fracture along the lines of the horizontal and vertical growth plates. This fluid injection simulated pressure increases that would occur within a healthy nucleus resulting from a rapidly applied compressive force, such that might occur during athletic activity, an unexpected fall, or an event related to mild yet rapid trauma to the spine. A second potential mechanism of injury was identified, as nuclear material was forcefully emitted posteriorly into the vertebral foramen where it would have the potential to contact neural structures such as the spinal cord and nerve roots.

Conflict of interest

None of the authors have any affiliations that have influenced the content of this work.

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