Correlation of cervical endplate strength with CT measured subchondral bone density

Nathaniel R. Ordway · Yen-Mou Lu · Xingkai Zhang ·
Chin-Chang Cheng · Huang Fang · Amir H. Fayyazi

Received: 19 August 2006 / Revised: 16 July 2007 / Accepted: 7 August 2007 / Published online: 22 August 2007
© Springer-Verlag 2007

Abstract Cervical interbody device subsidence can result in screw breakage, plate dislodgement, and/or kyphosis. Preoperative bone density measurement may be helpful in predicting the complications associated with anterior cervical surgery. This is especially important when a motion preserving device is implanted given the detrimental effect of subsidence on the postoperative segmental motion following disc replacement. To evaluate the structural properties of the cervical endplate and examine the correlation with CT measured trabecular bone density. Eight fresh human cadaver cervical spines (C2–T1) were CT scanned and the average trabecular bone densities of the vertebral bodies (C3–C7) were measured. Each endplate surface was biomechanically tested for regional yield load and stiffness using an indentation test method. Overall average density of the cervical vertebral body trabecular bone was $270 \pm 74 \text{ mg/cm}^3$. There was no significant difference between levels. The yield load and stiffness

from the indentation test of the endplate averaged $139 \pm 99 \text{ N}$ and $156 \pm 52 \text{ N/mm}$ across all cervical levels, endplate surfaces, and regional locations. The posterior aspect of the endplate had significantly higher yield load and stiffness in comparison to the anterior aspect and the lateral aspect had significantly higher yield load in comparison to the midline aspect. There was a significant correlation between the average yield load and stiffness of the cervical endplate and the trabecular bone density on regression analysis. Although there are significant regional variations in the endplate structural properties, the average of the endplate yield loads and stiffnesses correlated with the trabecular bone density. Given the morbidity associated with subsidence of interbody devices, a reliable and predictive method of measuring endplate strength in the cervical spine is required. Bone density measures may be used preoperatively to assist in the prediction of the strength of the vertebral endplate. A threshold density measure has yet to be established where the probability of endplate fracture outweighs the benefit of anterior cervical procedure.

N. R. Ordway · A. H. Fayyazi (✉)
Department of Orthopedics, SUNY Upstate Medical Center,
550 Harrison Street, Syracuse, NY 13202, USA
e-mail: amirfayyazi@yahoo.com

Y.-M. Lu
Department of Orthopedic Surgery,
Kaohsiung Medical University, Kaohsiung, Taiwan

C.-C. Cheng
Chang Gung Memorial Hospital, ChiaYi, Taiwan

X. Zhang
Institute of Orthopedics and Traumatology, Shanghai Jiaotong
University Medical College Ruijin Hospital, Shanghai, China

H. Fang
Tongji Medical College, Huazhong University of Science
and Technology, Wuhan, China

Keywords Indentation test · Biomechanics ·
Cervical spine · pQCT · Trabecular density

Introduction

Anterior cervical discectomy and fusion has been a reliable and safe procedure in treatment of cervical disc degeneration for the past 50 years [5, 7, 10]. The success of this procedure depends on the ability to reconstruct the anterior column and to obtain reliable fusion which can be accomplished through a structural allograft, a structural autograft, or an interbody cage packed with osteoinductive

or osteoconductive material. The addition of an anterior cervical plate can add additional stability to the construct and can potentially increase the fusion rate [15, 28, 31]. One of the side effects of using an anterior plate is loosening and dislodgement which is much more prevalent in multilevel procedures and is usually associated with loss of anterior column height which can be due to either graft remodeling, subsidence into the endplate, endplate fracture, or a combination of these effects [23, 30, 35]. Predicting the risk of subsidence is essential in preventing complications associated with anterior cervical surgery. This is especially important when evaluating patients for total disc replacement where device subsidence can have detrimental effects by altering the biomechanics of the spinal segment.

Extensive work has been directed to studying the graft endplate interface and the risk of subsidence. The regional anatomic and biomechanical variations of the endplates are very important and well understood [1, 18, 21, 29]. The effect of graft or device-endplate surface contact [16, 17, 32] and the effect of endplate removal [17, 19, 21, 22, 25, 32, 34] on the biomechanical properties are also well described. It has been shown that endplate failure is affected by patients bone quality [3, 4, 6, 14, 16, 21, 32, 34]. Osteoporosis and osteomalacia are quite common in the general population placing these patients at risk for this complication. However, it is difficult to determine the risk for a particular patient because the implant/graft interface plays an important role in the risk for subsidence. Currently, the structural properties of the cervical endplate isn't well understood other than in the context of a construct. To better understand the interface, a better understanding of the regional variation of the endplate is necessary. An indentation test technique is a well described method that can give insight into the regional variations in the endplate and has been previously described in evaluation of the cervical [19, 20], thoracic [22], and lumbar endplate strength [13, 14, 25].

It has been recommended that preoperative Dual Energy X-ray Absorptiometry (DEXA) scan be performed on all female patients older than 40 and all male patients older than 50 years old. Unfortunately, evaluation of cervical bone density with a DEXA scan is very difficult and lumbar bone density may not correlate well with the cervical endplate strength. Furthermore, there is no clear guideline on what is an unacceptable T- or Z-score for the cervical spine. Given these difficulties, CT scan measurement of cervical vertebral bone density may be very useful in preoperative evaluation of fracture risk of the endplate.

This study was designed to examine regional variations in the structural properties (average regional yield load and stiffness) of the cervical endplate in relation to where a bone graft or implant would be placed and test the hypothesis that the structural properties of the endplate

correlate with the trabecular bone density of the vertebral body.

Materials and methods

Eight fresh human cadaver cervical spines (C2–T1) were harvested en bloc and stored at -20°C until testing. The average ages of the specimens were 72 ± 6 years and five were females and three males. The cervical specimens were evaluated by X-ray to rule out bony deformities and severe degenerative conditions. Scanning was performed for determination of average trabecular density at each vertebral level (C3–C7). The scans were performed on a Stratec XCT-2000 peripheral Quantitative CT (pQCT) scanner. Trans-axial slices of 2.2 mm thickness were collected at each level. The voxel size was $0.4 \text{ mm} \times 0.4 \text{ mm} \times 2.2 \text{ mm}$ and there were 180 projections of each cross-section. The trabecular density of each cross-sectional slice was measured by selecting the vertebral body as the region of interest and removing the cortical edge in the image using a thresholding and edge detection algorithm within the Stratec XCT540 software. The bone edge detection threshold density was set to 169 mg/cm^3 and the trabecular apparent density was determined from within the central 50% of the outer vertebral body contour. This protocol was developed to have a consistent measurement technique between scans/specimens and to focus a trabecular measure on the centrum of the vertebral body. An example slice and density determination is shown in Fig. 1. The average trabecular bone density for each level was measured by averaging the scans between (not including) the endplates of the vertebral body in order to increase the precision and consistency of the measurements. Although it is possible to measure the bone density of the endplate, the contour and angle of the endplate would be difficult to capture within the pQCT slice thickness with

Fig. 1 Stratec XCT-2003 pQCT scan of a cervical vertebral body demonstrating the cross-sectional density of the specimen on the *left* and the area of the each vertebral body averaged for the trabecular bone density. The cortical edge is not included in the measurement

consistency and reliability. Focusing on the trabecular density will also be easier to implement clinically.

Levels C3–C7 were then dissected and cleaned of soft tissue. Eight cervical vertebrae during dissection had osteophytes or were fused and were not tested ($N = 32$). Care was taken to preserve the endplates of each vertebra. Each vertebra was partially embedded (approximately 1–2 mm) in a body filler mold to level the superior endplate surface for biomechanical testing of the endplate. Additionally, the specimens were not pressed into the body filler until the filler was partially cured (doughy consistency). The regional failure load of the endplate was determined using an indentation test method (2 mm diameter stainless steel hemispherical probe) on a MTS *Q*-test uniaxial testing machine. The location of each indentation test was defined by the dimensions of the individual endplates. A 2×3 matrix pattern was applied to the endplate which resulted in six tests per endplate (Fig. 2). Three equally spaced locations with respect to the width of the body and two equally spaced locations with respect to the depth of the body were determined for consistency between levels/specimens. The significance of these locations was representative of the load bearing surfaces following surgical cervical procedures involving bone graft or implants.

At each location, the indenter probe was pressed into the endplate to a depth of 3 mm at a rate of 12 mm/min. Following completion of the testing on the superior surface, each vertebra was removed from the potting material and repotted in order to test the inferior endplate surface. Prior to repotting, the endplates were visually inspected and were noted to be unaffected by the potting process. This was assured by keeping the specimens moist during the testing and preparation. The preparation and testing of the inferior endplate surface was the same as the superior endplate. The endplate yield load and stiffness of each location was determined by using the 0.1% offset method (TestWorksQT ver 2.03 software) from the load–

displacement curve. An example load–displacement curve during the indentation test is shown in Fig. 3.

Kolgorov–Smirnov tests were used to analyze the density, yield load and stiffness data for normality. The datasets were shown to be normally distributed. An ANOVA analysis was performed to examine differences in trabecular density between cervical levels and an ANCOVA analysis with density as the covariate was performed to examine differences in endplate structural properties (yield load and stiffness) between cervical levels. Paired *t*-test comparisons were used to examine regional differences in endplate structural properties based on endplate location (anterior vs. posterior and lateral vs. midline) and endplate surface (superior vs. inferior). A regression analysis was performed to examine the effect of cervical trabecular density on average regional endplate structural properties. The trabecular density for each vertebra was based on the average of the scans and the average regional endplate structural properties (yield load and stiffness) was calculated from the 12 locations (six superior, six inferior) of each vertebra. All tests were performed at a 95% level of significance.

Results

Overall average trabecular density of all vertebral specimens tested was $270 \pm 74 \text{ mg/cm}^3$. C5 had the highest density and C7 had the lowest density. There was no significant difference in trabecular bone density based on cervical level (Table 1).

The yield load of the endplate averaged $139 \pm 99 \text{ N}$ across all cervical levels and endplate surfaces. The C5 endplate exhibited the highest yield load in comparison to the adjacent levels; however this difference was not significant (Table 1). There were no significant differences in yield load between the superior endplate, $132 \pm 72 \text{ N}$, and inferior endplate, $145 \pm 83 \text{ N}$, $P = 0.30$. There was a

Fig. 2 The superior endplate of the vertebral body demonstrating the 2×3 indentation points

Fig. 3 Example of load–displacement curve from an indentation test

Table 1 Average values ($\pm$ SD) of trabecular density, endplate yield load, and endplate stiffness based on cervical level

	C3	C4	C5	C6	C7
Trabecular density in mg/cm^3	248 ± 76	281 ± 69	293 ± 73	287 ± 95	236 ± 58
Yield load in N	131 ± 24	138 ± 51	161 ± 84	142 ± 86	120 ± 62
Stiffness in N/mm	162 ± 35	159 ± 47	175 ± 66	154 ± 59	134 ± 47

significant difference between the yield load of the anterior endplate, 118 ± 65 N, when compared to the posterior endplate, 160 ± 74 N [$P < 0.001$, effect size (ES) = 0.60]. There was also a significant difference between the yield load of the lateral aspect of the endplate, 143 ± 65 N, when compared to the middle aspect of the endplate, 130 ± 72 N, ($P = 0.026$, ES = 0.17). Based on the ES, the significance of the posterior–anterior comparison was greater than the significance of the lateral–midline comparison.

The stiffness of the endplate averaged 156 ± 52 N/mm across all cervical levels and endplate surfaces and there were no significant differences between cervical levels (Table 1). There was a significant difference ($P < 0.001$, ES = 0.61) between the stiffness of the anterior endplate, 140 ± 50 N/mm, when compared to the posterior endplate, 173 ± 58 N/mm. There were no significant differences in stiffness between superior/inferior or the mid-sagittal/lateral regional locations (mean range of 153–161 N/mm).

There was a significant correlation ($P = 0.0002$, ES = 1.5) between the average endplate yield load and the trabecular bone density measured with the pQCT scanner on regression analysis with $R^2 = 0.37$ (Fig. 4). Therefore cervical trabecular density, as measured in this study, represents a 37% causal influence on endplate yield load as measured by an indentation test. Additional regression analyses were investigated to examine regional endplate yield load (anterior, posterior, lateral, and midline) and

trabecular density and the strength of the relationship was similar (R^2 ranged from 0.31 to 0.43). Similarly, there was a significant correlation ($P < 0.001$, ES = 1.7) between the endplate stiffness and the trabecular BMD on regression analysis with $R^2 = 0.42$ (Fig. 5).

Discussion

Given the morbidity associated with subsidence of cervical interbody devices, a reliable and predictive method of endplate fracture risk is required. A DEXA scan is currently the most commonly used method for measuring bone density and has been shown to be a reliable method. There are other methods of measuring bone density in vivo. These include pQCT of distal radius, single energy QCT of the axial skeleton, or dual energy QCT. Each of these methods have been shown to be highly predictive of vertebral body strength [9], however, there are marked differences between these methods [2, 11, 12, 26, 33] with the QCT scan being the most sensitive method for evaluation of axial skeletal in vivo [2, 12].

The pQCT method used in the current study was useful in measuring the trabecular bone density in the cervical specimens tested. Although there were no significant differences in trabecular density between levels (C3–C7), there was considerable variability between cervical spine specimens. The age range of the specimens tested was 64–82 years and

Fig. 4 Regression analysis of vertebral bone density and endplate yield load demonstrated a significant correlation ($P = 0.0002$, ES = 1.5)

Fig. 5 Regression analysis of vertebral bone density and endplate stiffness demonstrated a significant correlation ($P = 0.0001$, ES = 1.7)

the trabecular bone mineral density ranged from 123 to 411 mg/cm³. To the author's knowledge, these are the first reported values in the cervical spine by this method. Guglielmi et al. have reported a mean value of 187 mg/cm³ for trabecular bone mineral density in the distal radius of 126 postmenopausal white women by pQCT. However, since values between different anatomical locations do not necessarily correlate and pQCT measures in the spine are not possible *in vivo*, further protocols and comparisons using clinical scanners will be necessary in the cervical spine to establish normative values.

A number of authors have evaluated the correlation of cervical, thoracic, and lumbar vertebral structural properties with measured bone density. Closkey et al. has evaluated QCT and has demonstrated it to be predictive of thoracic vertebral strength [8]. DEXA scan measurements of bone mass has been used by Lim et al. [21], Parkinson et al. [27], Grant et al. [14]. QCT and DEXA measurement of lumbar vertebral bodies were used by Hasegawa et al. for testing of lumbar cages demonstrating the greater significance of the QCT scan [16]. Biggemann et al. has demonstrated the effectiveness of QCT scan bone density measurement in predicting the lumbar compressive strength and the risk of lumbar insufficiency fractures [3, 4, 6]. In this study, a peripheral QCT scanner was chosen to directly measure the cancellous bone mineral density given the greater sensitivity of QCT in predicting bone composition both *in vivo* and *in vitro* and the difficulty in performing DEXA scan. Using this device, this study was able to demonstrate a significant correlation between cervical trabecular bone density and average regional endplate yield load and stiffness.

In our study, there was no significant difference in endplate structural properties (yield load and stiffness) between cervical levels, nor was there a significant difference in structural properties between the superior and the inferior endplates. However, regional differences were noted on the endplates with the posterior and the lateral aspect having higher yield load than the anterior or the midline aspects, respectively. In addition, the posterior endplate had a higher stiffness than the anterior endplate. This regional difference has been demonstrated anatomically [1, 21, 29] and biomechanically in the cervical [19], thoracic [22], and the lumbar spine [13, 14]. It may be advantageous to place the interbody device as far posterior as possible and to choose a device that covers the lateral aspects of the endplate to prevent subsidence.

The measured endplate yield load and stiffness obtained in this study may not have a clinical significance to the majority of the population receiving cervical surgery given the elderly age of the specimens; however, there is great potential for the use of this technique in predicting the risk of endplate fracture or device subsidence. Although this

study has shown statistically significant regional variations and a relationship with cervical trabecular density, in order for there to be clinical significance there needs to be the establishment of a bone density threshold.

The endplate yield load and stiffness measures can serve as baseline values for comparisons when examining physiologic loads following placement of cervical grafts and plates or disc implants. These comparisons will be useful for avoiding cases resulting in catastrophic failure. Even though this study did not examine the fatigue properties of the endplate, knowing the endplate structural properties and the relationship to bone density will serve as the foundation to understanding the fatigue characteristics. The endplate yield load and trabecular bone density relationship also has potential to lead to the establishment of a threshold value where the probability of endplate fracture or subsidence outweighs the potential benefit of the cervical procedure.

There are limitations to the use of a pQCT scanner in measuring cervical bone mineral density. A pQCT scanner cannot be employed in the clinical setting given the special dimension of the device. We elected not to use a QCT scanner given the difficulties associated with transporting and preservation of the pre-dissected specimens and the cost associated with obtaining QCT measurement of the cadaveric cervical spines. The biomechanical limitations of the study include the size and the shape of the indenter, the rate of the compression, the dissection and the potting procedure. The yield load and stiffness of the endplate is dependent on the size and the shape of the indenter in addition to the rate of the loading of the endplate [24]. The shape and rate of the indenter used in this study was consistent with other studies. Although using a hemispherical probe could technically result in a stress singularity, it is unlikely due to the uneven nature of the endplate and therefore has advantages over a cylindrical probe with a flat surface.

Conclusions

CT measurement of trabecular bone density has the potential to predict the fracture risk of the cervical endplate and can be used to predict the risk of endplate fracture prior to anterior cervical interbody device placement. Further correlation and protocol development on clinical CT scanners will be necessary to verify the trabecular density and fracture risk relationship over a broader age range. In our study, there was no significant difference between the yield load or stiffness of the superior and the inferior endplate of the cervical vertebrae. And although the lateral and the posterior aspect of the cervical vertebral endplate was significantly different than the anterior and the middle aspect of the endplate,

there was no regional differences in yield load or bone density between the levels.

Acknowledgment Partial research funding for this study was provided by Synthes Spine.

References

- Amstutz HC, Sissons HA (1969) The structure of the vertebral spongiosa. *J Bone Joint Surg Br* 51:540–550
- Bergot C, Laval-Jeantet AM, Hutchinson K, Dautraix I, Caulin F, Genant HK (2001) A comparison of spinal quantitative computed tomography with dual energy X-ray absorptiometry in European women with vertebral and nonvertebral fractures. *Calcif Tissue Int* 68:74–82
- Biggemann M, Hilweg D, Brinckmann P (1988) Prediction of the compressive strength of vertebral bodies of the lumbar spine by quantitative computed tomography. *Skeletal Radiol* 17:264–269
- Biggemann M, Hilweg D, Seidel S, Horst M, Brinckmann P (1991) Risk of vertebral insufficiency fractures in relation to compressive strength predicted by quantitative computed tomography. *Eur J Radiol* 13:6–10
- Bohlman HH, Emery SE, Goodfellow DB, Jones PK (1993) Robinson anterior cervical discectomy and arthrodesis for cervical radiculopathy. Long-term follow-up of one hundred and twenty-two patients. *J Bone Joint Surg Am* 75:1298–1307
- Brinckmann P, Biggemann M, Hilweg D (1989) Prediction of the compressive strength of human lumbar vertebrae. *Spine* 14:606–610
- Brodke DS, Zdeblick TA (1992) Modified Smith–Robinson procedure for anterior cervical discectomy and fusion. *Spine* 17:S427–S430
- Closkey RF, Parsons JR, Lee CK, Blacksin MF, Zimmerman MC (1993) Mechanics of interbody spinal fusion. Analysis of critical bone graft area. *Spine* 18:1011–1015
- Ebbesen EN, Thomsen JS, Beck-Nielsen H, Nepper-Rasmussen HJ, Mosekilde L (1999) Lumbar vertebral body compressive strength evaluated by dual-energy X-ray absorptiometry, quantitative computed tomography, and ashing. *Bone* 25:713–724
- Emery SE, Bolesta MJ, Banks MA, Jones PK (1994) Robinson anterior cervical fusion comparison of the standard and modified techniques. *Spine* 19:660–663
- Formica CA, Nieves JW, Cosman F, Garrett P, Lindsay R (1998) Comparative assessment of bone mineral measurements using dual X-ray absorptiometry and peripheral quantitative computed tomography. *Osteoporos Int* 8:460–467
- Grampp S, Jergas M, Lang P, Steiner E, Fuerst T, Gluer CC, Mathur A, Genant HK (1996) Quantitative CT assessment of the lumbar spine and radius in patients with osteoporosis. *Am J Roentgenol* 167:133–140
- Grant JP, Oxland TR, Dvorak MF (2001) Mapping the structural properties of the lumbosacral vertebral endplates. *Spine* 26:889–896
- Grant JP, Oxland TR, Dvorak MF, Fisher CG (2002) The effects of bone density and disc degeneration on the structural property distributions in the lower lumbar vertebral endplates. *J Orthop Res* 20:1115–1120
- Grubb MR, Currier BL, Shih JS, Bonin V, Grabowski JJ, Chao EY (1998) Biomechanical evaluation of anterior cervical spine stabilization. *Spine* 23:886–892
- Hasegawa K, Abe M, Washio T, Hara T (2001) An experimental study on the interface strength between titanium mesh cage and vertebra in reference to vertebral bone mineral density. *Spine* 26:957–963
- Hollowell JP, Vollmer DG, Wilson CR, Pinter FA, Yoganandan N (1996) Biomechanical analysis of thoracolumbar interbody constructs. How important is the endplate? *Spine* 21:1032–1036
- Keller TS, Hansson TH, Abram AC, Spengler DM, Panjabi MM (1989) Regional variations in the compressive properties of lumbar vertebral trabeculae. Effects of disc degeneration. *Spine* 14:1012–1019
- Li JY, Zhu QA, Yuan L, Zhao WD, Lin LJ, Zhang MC, Huang WH (2003) Role of the biomechanical property of the endplate in anterior cervical fusion. *Di Yi Jun Yi Da Xue Xue Bao* 23:402–408
- Li JY, Zhao WD, Zhu QA, Yuan L, Li M, Lin LJ, Zhang MC (2004) [The effect of disc degeneration on the structural property distributions in the cervical vertebral endplates.]. *Zhonghua Wai Ke Za Zhi* 42:1330–1332
- Lim TH, Kwon H, Jeon CH, Kim JG, Sokolowski M, Natarajan R, An HS, Andersson GB (2001) Effect of endplate conditions and bone mineral density on the compressive strength of the graft-endplate interface in anterior cervical spine fusion. *Spine* 26:951–956
- Lowe TG, Hashim S, Wilson LA, O'Brien MF, Smith DA, Diekmann MJ, Trommter J (2004) A biomechanical study of regional endplate strength and cage morphology as it relates to structural interbody support. *Spine* 29:2389–2394
- Macdonald RL, Fehlings MG, Tator CH, Lozano A, Fleming JR, Gentili F, Bernstein M, Wallace MC, Tasker RR (1997) Multi-level anterior cervical corpectomy and fibular allograft fusion for cervical myelopathy. *J Neurosurg* 86:990–997
- Ochia RS, Tencer AF, Ching RP (2003) Effect of loading rate on endplate and vertebral body strength in human lumbar vertebrae. *J Biomech* 36:1875–1881
- Oxland TR, Grant JP, Dvorak MF, Fisher CG (2003) Effects of endplate removal on the structural properties of the lower lumbar vertebral bodies. *Spine* 28:771–777
- Pacifici R, Susman N, Carr PL, Birge SJ, Avioli LV (1987) Single and dual energy tomographic analysis of spinal trabecular bone: a comparative study in normal and osteoporotic women. *J Clin Endocrinol Metab* 64:209–214
- Parkinson RJ, Durkin JL, Callaghan JP (2005) Estimating the compressive strength of the porcine cervical spine: an examination of the utility of DXA. *Spine* 30:E492–E498
- Rapoff AJ, Conrad BP, Johnson WM, Cordista A, Rehtine GR (2003) Load sharing in Premier and Zephir anterior cervical plates. *Spine* 28:2648–2650; discussion 2651
- Roberts S, McCall IW, Menage J, Haddaway MJ, Eisenstein SM (1997) Does the thickness of the vertebral subchondral bone reflect the composition of the intervertebral disc? *Eur Spine J* 6:385–389
- Sasso RC, Ruggiero RA Jr, Reilly TM, Hall PV (2003) Early reconstruction failures after multilevel cervical corpectomy. *Spine* 28:140–142
- Spivak JM, Chen D, Kummer FJ (1999) The effect of locking fixation screws on the stability of anterior cervical plating. *Spine* 24:334–338
- Steffen T, Tsantrizos A, Aebi M (2000) Effect of implant design and endplate preparation on the compressive strength of interbody fusion constructs. *Spine* 25:1077–1084
- Thickman D, Nodine C, Iddenden D (1990) Quantitative CT of the spine. Significance of intervertebral body variability. *Invest Radiol* 25:19–23
- Truumees E, Demetropoulos CK, Yang KH, Herkowitz HN (2003) Failure of human cervical endplates: a cadaveric experimental model. *Spine* 28:2204–2208
- Vaccaro AR, Falatyn SP, Scuderi GJ, Eismont FJ, McGuire RA, Singh K, Garfin SR (1998) Early failure of long segment anterior cervical plate fixation. *J Spinal Disord* 11:410–415