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Mechanical yield of the lumbar annulus: a possible contributor to instability

Laboratory investigation

Brian D. Stemper, Ph.D.,[1,2] Jamie L. Baisden, M.D.,[1,2] Narayan Yoganandan, Ph.D.,[1,2] Barry S. Shender, Ph.D.,[3] and Dennis J. Maiman, M.D., Ph.D.[1,2]

[1]*Department of Neurosurgery, Medical College of Wisconsin;* [2]*Department of Veterans Affairs Medical Center, Milwaukee, Wisconsin; and* [3]*Naval Air Warfare Center, Aircraft Division, Patuxent River, Maryland*

Object. Segmental instability in the lumbar spine can result from a number of mechanisms including intervertebral disc degeneration and facet joint degradation. Under traumatic circumstances, elevated loading may lead to mechanical yield of the annular fibers, which can decrease load-carrying capacity and contribute to instability. The purpose of this study was to quantify the biomechanics of intervertebral annular yield during tensile loading with respect to spinal level and anatomical region within the intervertebral disc.

Methods. This laboratory-based study incorporated isolated lumbar spine annular specimens from younger and normal or mildly degenerated intervertebral discs. Specimens were quasi-statically distracted to failure in an environmentally controlled chamber. Stress and strain associated with yield and ultimate failure were quantified, as was stiffness in the elastic and postyield regions. Analysis of variance was used to determine statistically significant differences based on lumbar spine level, radial position, and anatomical region of the disc.

Results. Annular specimens demonstrated a nonlinear response consisting of the following: toe region, linear elastic region, yield point, postyield region, and ultimate failure point. Regional dependency was identified between deep and superficial fibers. Mechanical yield was evident prior to ultimate failure in 98% of the specimens and occurred at approximately 80% and 74% of the stress and strain, respectively, to ultimate failure. Fiber modulus decreased by 34% following yield.

Conclusions. Data in this study demonstrated that yielding of intervertebral disc fibers occurs relatively early in the mechanical response of the tissues and that stiffness is considerably decreased following yield. Therefore, yielding of annular fibers may result in decreased segmental stability, contributing to accelerated degeneration of bony components and possible idiopathic pain.
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Key Words • **biomechanics** • **annulus fibrosus** • **mechanical yield** • **instability** • **lumbar spine**

Lumbar spine instability refers to the decreased capability of an intervertebral segment to resist physiological loads, resulting in greater segmental motion for a given input.[16] Instability can lead to neural compromise under loading scenarios that would normally result in stable motion without pain. Under normal circumstances, healthy intervertebral discs and facet joints act in concert to maintain segmental stability. Injury or degeneration of one or more of these components contributes to instability. The role of the facet joint in contributing to unstable conditions, including degenerative spondylolisthesis, has been well defined.[8,18,20,21] With regard to the intervertebral disc, degenerative and traumatic mechanisms that may contribute to instability have been identified.[6,14] Disc degenerative changes involve dehydration of the nucleus pulposus and resultant loss of disc height. Given the constant length of annular fibers, lost disc height results in annular laxity that contributes to instability. Accordingly, graded degenerative changes of the intervertebral disc have been shown to affect kinematic properties of the segment.[11,19,27] Those studies have generally reported that greater segmental motion was associated with degenerative changes in the disc.

Under a traumatic mechanism, elevated single-cycle or repeated loading can injure annular fibers, affecting the integrity of the disc and its load-carrying capacity and contributing to instability. It was previously demonstrated that radial tears within the disc can destabilize the motion segment.[6] Other studies have also attributed segmental instability to annular tears.[30] Clinicians can use MRI of affected intervertebral discs as a tool to identify an-

Abbreviation used in this paper: PMHS = postmortem human subject.

nular tears that contribute to segmental instability and pain. However, patients presenting with idiopathic low-back pain remain common and, therefore, other mechanisms for lumbar spine instability may exist. Identifying and quantifying those mechanisms may lead to diagnostic protocols and targeted clinical treatment regimens.

One of those mechanisms could involve yielding of annular fibers during subtraumatic loading. Axial compression of the intervertebral segment applies uniaxial loads to the incompressible nucleus pulposus, which then, according to Poisson's law, distributes that load equally in all directions to apply an outward and tensile load to the layers of the annulus. Basic biomechanical studies of soft tissue mechanics have defined the physiological and traumatic response of various soft tissues to tensile loading.[9,26,29] Excessive tensile loading beyond the physiological limit initiates the traumatic cascade, with tissue yielding eventually followed by rupture of the annular fibers. Yielding of the tissue is an irreversible event that fundamentally changes its mechanical response. The most notable postyield mechanical change is decreased stiffness. Therefore, decreased annular tension stiffness due to yielding could lead to segmental instability.

Whereas physiological and ultimate properties of annulus fibers have been well defined using a variety of experimental models,[1,2,4,5,7,13,24,25] the contribution of annular yield to biomechanical instability has not been investigated. Determining yield mechanics for the annulus may provide a possible explanation for lumbar spine segmental instability in the absence of remarkable intervertebral disc degeneration or obvious trauma. The purpose of this study was to investigate spinal level– and anatomical region–dependent elastic, yield, and failure properties of the lumbar intervertebral disc annulus.

Methods

Lumbar spines (T-12 to L-5) were obtained from postmortem human subjects (PMHSs) and stored at –70°C until testing. Normal or mildly degenerated (Thompson Grade I)[28] intervertebral discs were dissected away from the endplates at T12–L1 through L4–5. Test specimens consisted of a single layer of annular fibers, such that all fibers were oriented in a parallel direction (approximately 5.0 mm in length, 2.7 mm wide, and 0.8 mm thick). Specimens were obtained from superficial and deep layers of anterior and posterolateral (right and left) regions of each disc. Therefore, a total of 6 test specimens were obtained from each disc. Superficial specimens were obtained from layers of the disc closest to the periphery. Deep specimens were obtained from annular layers immediately adjacent to the nucleus. Specimens were periodically flushed in saline solution during dissection to prevent dehydration.

Once dissected, specimens were attached to test coupons, which consisted of a 30 × 20–mm sheet of Mylar film with a slit cut in the center measuring 4 mm long × 15 mm wide.[17] Glue was used to attach specimens to the coupons. Specimens were placed in a 0.15-mol/L NaCl bath approximately 5 minutes after mounting them to the test coupon, allowing sufficient time for the glue to solidify. Prior to testing, specimen length, width, and thickness were measured using digital images of anterior and lateral aspects.

Tensile testing was performed using an electrohydraulic testing system (MTS Systems Corp.; Fig. 1). The test coupon was attached to the piston clamps, and lateral edges were removed such that the annular specimen was the only connection between upper and lower sections of Mylar film. The specimen, coupon, and upper and lower fixations were then surrounded by an environmental chamber. Temperature was maintained within 1° of 37°C, and relative humidity was maintained between 91% and 96% during the entire test. A preload of 0.5 N was applied to the specimen, followed by preconditioning to 0.25 mm displacement for 5 cycles at a quasi-static rate of 0.005 mm/second. After preconditioning, specimens were returned to the preload level and allowed to relax for 5 minutes. Specimens were then distracted to failure at 0.005 mm/second. This rate was chosen to minimize viscoelastic effects of the collagen fibers.[25] Displacement of the piston was recorded at 5 Hz using a linear variable differential transformer (LVDT), and axial force was recorded at 5 Hz using a uniaxial load cell.

Axial stress was computed as axial force divided by cross-sectional area of the undeformed specimen. Strain was computed as vertical piston displacement divided by initial specimen length. Elastic modulus was computed as the slope of the linear region of the stress versus strain plot (Fig. 2). The yield point was defined as the point of initial decrease in the slope of the stress-strain curve following the linear elastic region. Elastic modulus, postyield modulus, yield stress, yield strain, ultimate stress, and ultimate strain were compared based on spinal level, anatomical region (anterior vs posterolateral), and radial position (superficial vs deep). Analysis of variance was used to determine statistically significant differences based on spinal level, anatomical location, and radial position. Linear regression was performed for each specimen in the elastic and postyield regions, and R^2 was used to quantify linearity.

Results

Specimens were obtained from 5 PMHSs with a mean age of 36 ± 6 years (mean ± standard deviation) at death. A total of 145 test specimens were obtained from 25 intervertebral discs (5 specimens were lost during preparation). Ultimate stress was significantly dependent on the radial position in the intervertebral disc ($p = 0.03$), not on the spinal level ($p = 0.36$) or anatomical position ($p = 0.92$). Superficial fibers had 46% greater ultimate stress than the deep fibers (Fig. 3). Ultimate strain was significantly dependent on the radial position in the intervertebral disc ($p = 0.02$), not on the spinal level ($p = 0.10$) or anatomical position ($p = 0.54$). Deeper fibers had 26% greater ultimate strain than the superficial fibers.

Yield occurred prior to ultimate failure in 98.5% of specimens. Yield stress occurred at an average of 79.9% ± 11.4% of ultimate stress, was significantly dependent on the radial position in the intervertebral disc ($p = 0.04$), and was not dependent on the spinal level ($p = 0.36$) or anatomical location ($p = 0.87$). Superficial fibers had 40%

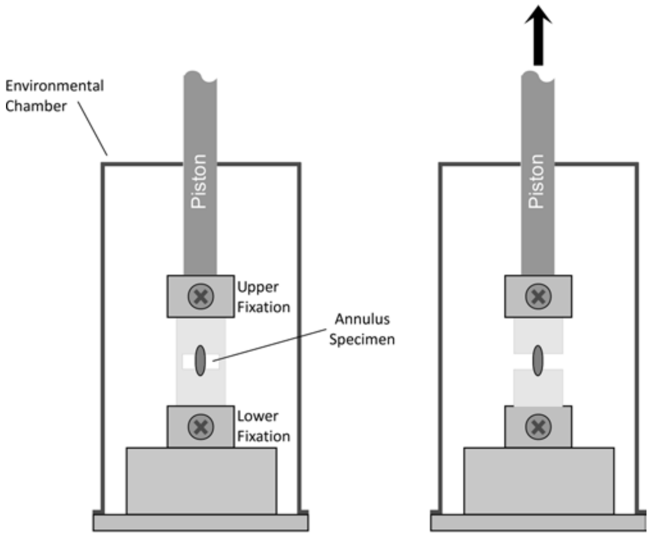

Fig. 1. Experimental setup with the test coupon intact **(left)** and after clipping the coupon edges **(right)**. All specimens were tested in quasi-static tension until failure, inside an environmental chamber that maintained temperature and humidity at in vivo conditions.

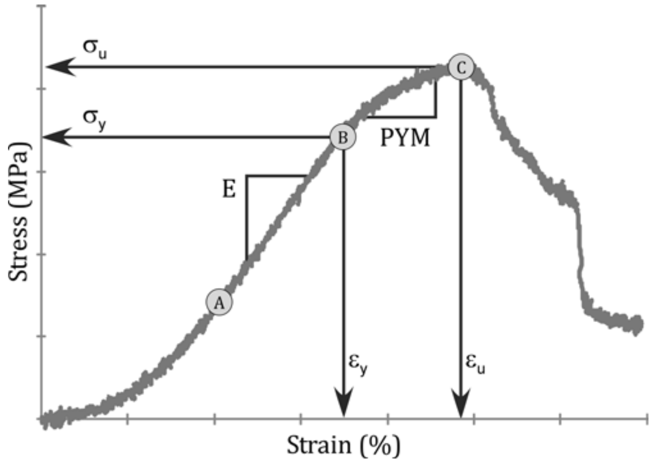

Fig. 2. Representative tensile stress versus strain response of annular specimens. Elastic (A–B) and postyield (B–C) regions are indicated, as are stress (σ) and strain (ε) at yield (y) and ultimate failure (u). E = elastic modulus; PYM = postyield modulus.

greater yield stress than the deeper fibers (Fig. 4). Yield strain occurred at an average of 73.9% ± 15.7% of ultimate strain, was significantly dependent on the region in the intervertebral disc (p = 0.01), and was not dependent on spinal level (p = 0.26) or anatomical location (p = 0.28). Deeper fibers had 27% greater yield strain than the superficial fibers.

Elastic modulus was significantly dependent on the radial position in the intervertebral disc (p = 0.004) and spinal level (p = 0.04), but not on the anatomical region (p = 0.96). Superficial fibers had 51% greater elastic modulus than the deeper fibers. Trends for elastic modulus with regard to spinal level were not as clear. Modulus was greatest at T12–L1 and L3–4, indicating a stiffer response at those levels, and was lowest at L1–2 and L4–5, indicating a more flexible response (Fig. 5). Postyield modulus was significantly dependent on the radial position in the intervertebral disc (p = 0.002), but not on the spinal level (p = 0.11) or anatomical region (p = 0.18), although trends with regard to radial position and spinal level were similar to those for elastic modulus. Linear regression was used to compute linearity of the postyield response. The average R^2 across all specimens was 0.847 ± 0.196, demonstrating a reasonably linear stress versus strain response of annular tissues in the postyield region. Postyield modulus was 66.5% ± 35.9% of elastic modulus, indicating a considerable decrease in annular fiber stiffness following yield.

Discussion

A focus of this study was to present properties associated with mechanical yield of the lumbar spine annulus using young, normal specimens. To that end, results demonstrated that yielding of the annulus in tension occurs somewhat early in the mechanical response (that is, 80% of the ultimate stress and 74% of the ultimate strain) and that stiffness of the tissues is considerably decreased following yield. It should be noted that 80% and 74% are relative to the total mechanical response of the tissues (that is, toe region, elastic region, and postyield region). Given some level of pre-stress in vivo, those percentages are likely to be much lower. Modulus of the postyield portion of the mechanical response was decreased by 34% compared with the linear elastic (that is, uninjured) portion. Decreased stiffness of the annular fibers following yield indicates a decreased ability to carry a load and may contribute to localized instability in the absence of annular tearing. In addition to localized instability, annular yielding may contribute to segmental degeneration due to increased load sharing of adjacent tissues as a result of decreased annular stiffness.

The clinical relevance of this work should not be minimized. There is little doubt that instability will promote certain types of mechanical back pain. Annular yielding as defined in this investigation can contribute to instability through two mechanisms. Decreased annular stiffness changes the localized load-sharing pattern, which con-

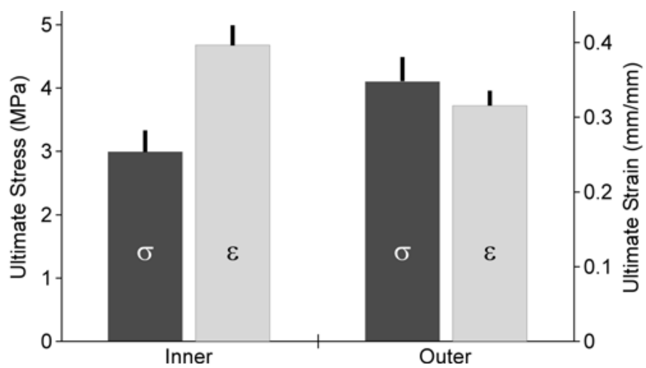

Fig. 3. Ultimate stress (σ, *dark bars*) and ultimate strain (ε, *light bars*) of isolated annular fibers under tensile loading. Ultimate stress (p = 0.03) and ultimate strain (p = 0.02) were significantly dependent on radial position in the disc. Data are presented as the mean ± standard error. Inner = deep; outer = superficial.

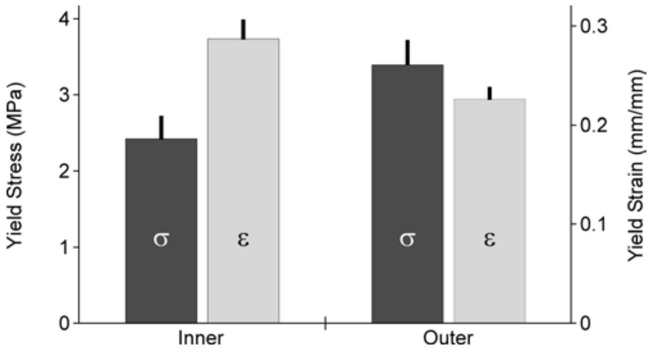

Fig. 4. Yield stress (σ, *dark bars*) and yield strain (ε, *light bars*) of isolated annular fibers under tensile loading. Yield stress (p = 0.04) and yield strain (p = 0.01) were significantly dependent on radial position in the disc. Data are presented as the mean ± standard error. Inner = deep; outer = superficial.

tributes to facet arthropathy and perhaps disc endplate ischemia through a largely degenerative process. However, changes in annular stiffness may also have a more direct and immediate effect of destabilizing the segment and stimulating noxious pain sensors via activity or inducing acute radiculopathic pain through transient foraminal stenosis resulting in nerve root impingement. These degenerative and pathological processes are potentially reversible with judicious surgical treatment. At a minimum, surgical fixation or conservative treatment, such as physical therapy, can halt the progressive cascade brought on by instability.

Comparison of the present findings as regards annular tolerance with in vivo loading conditions in the human is complicated by a lack of human biomechanical data (that is, stress and strain) for everyday or traumatic situations. However, validated finite element models form a useful bridge between in vivo loading and material response of soft tissues. A recent finite element modeling study predicted tensile strains for annular tissues under pure and complex bending scenarios commonly incorporated as repeatable physiological substitutes during experimental testing.[22] Annular strains predicted by the finite element model were greatest in 7.5 Nm pure lateral bending and lateral bending combined with extension. Maximum strain magnitudes in those simulations (23%) approached yield tolerance (26%) but remained well below the ultimate failure magnitudes (36%) experimentally described here. However, a more recent study by the same group reported lower annular fiber maximum strain magnitudes (2.5%–7.5%) for loading scenarios simulating regular daily activities.[23] The relatively modest strain magnitudes for activities of daily living in comparison with the subtraumatic pure moment loading cases are probably the result of the limited repetitive load magnitudes (1600 N) applied in that study, whereas the pure bending protocols probably exercise the intervertebral disc closer to the physiological extents. Nonetheless, analysis of strain magnitudes in those studies provides a comparison of present yield tolerance levels and external load applications across a range of severities. Activities of daily living are probably well below the tolerance for annular strain, whereas more extreme single-cycle axial or bending loads can result in annular yield and contribute to segmental instability.

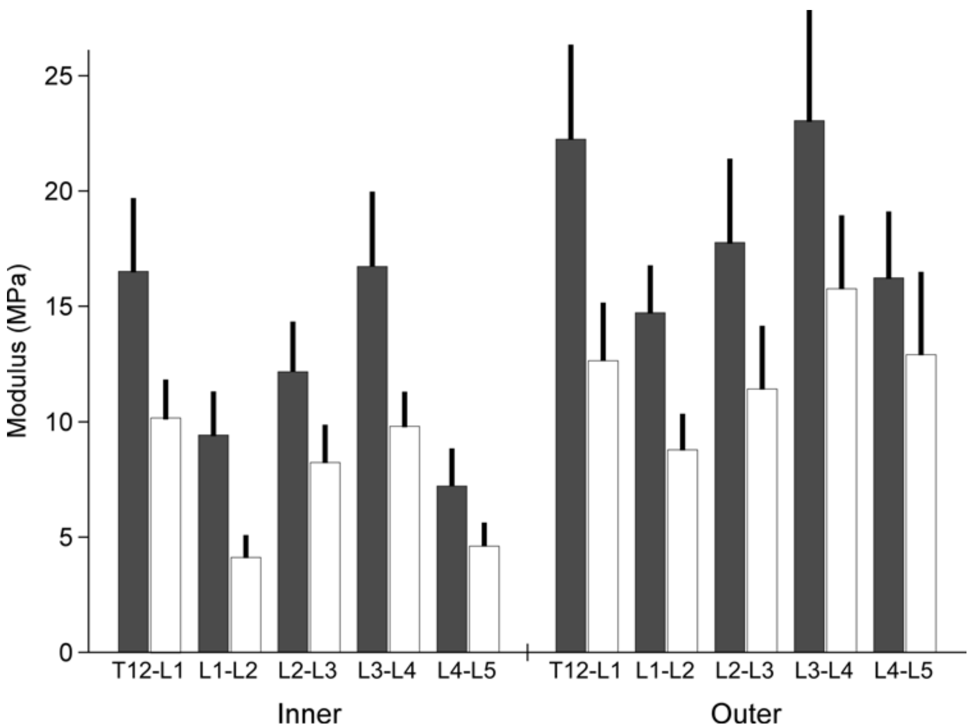

Fig. 5. Elastic modulus *(dark bars)* and postyield modulus *(light bars)* of isolated annular fibers under tensile loading. Elastic modulus was significantly dependent on radial position in the disc (p = 0.004) and spinal level (p = 0.04). Postyield modulus was significantly dependent on radial position in the disc (p = 0.002). Data are presented as the mean ± standard error. Inner = deep; outer = superficial.

Data in the current study revealed consistent differences in biomechanical metrics as a function of radial position in the intervertebral disc. These differences were evident primarily between superficial and deep fibers for ultimate and yield stress and strain, as well as for elastic and postyield moduli. Greater ultimate and yield stress and elastic modulus indicate stronger tissue fibers in the superficial regions of the disc. Conversely, greater failure strain and lower elastic modulus in deeper regions demonstrate more elastic deep fibers of the intervertebral disc. Trends with regard to ultimate metrics and physiological properties were consistent with those in previous experimental studies.[1,7,13,25] These regional trends in biomechanical metrics indicate a primary role of the superficial fibers in maintaining integrity of the disc, whereas the deep fibers provide a higher level of elasticity. Trends with regard to anterior and posterolateral regions of the disc were not evident in this study, although other studies have identified stronger fibers in anterior regions.[7] However, that study indicated stronger trends for superficial versus deep than for anterior versus posterolateral fibers.

Studies of lumbar spine components for material property determinations have traditionally used PMHSs of various ages. Some of these studies have tested specimens in the 9th decade or older.[1,3,10,15] In contrast, the present study used specimens younger than 50 years, and hence it is expected that age-based variations are minimal for this relatively narrow sample. From this perspective, the present data can be used as a normative set for investigating the biomechanical properties of young and normal spines. These data indicate that the mechanical properties of the human lumbar annuli are radially and, in some cases, level dependent. Furthermore, the degree of dependency is controlled by the specific variable. This initial observation may have implications for the intrinsic load-sharing behavior of the intervertebral disc, as disorders such as disc herniation are region specific. It is possible to use finite element models incorporating these region- and level-specific properties to quantify internal load sharing and delineate the mechanism of herniation.

Tension testing conditions for annular layers were outlined by Galante.[12] That study also outlined the effects of donor age and intervertebral disc degeneration on tensile properties of annular specimens. Normal or minimally degenerated annular specimens obtained from donors between 26 and 70+ years demonstrated consistent mechanical properties without regard to age. In other words, increasing age in the absence of degeneration did not affect annular mechanics. However, comparison of normal and minimally degenerated with more severely degenerated specimens yielded two significant findings. Firstly, severely degenerated specimens failed early, indicating decreased tension tolerance in degenerated annular tissues. Secondly, annular flexibility considerably increased in specimens with higher levels of degeneration. This finding is in line with the present findings of yielded annulus specimens demonstrating decreased stiffness (that is, higher flexibility). In essence, annular yield and intervertebral disc degeneration had the same biomechanical effect of decreasing tensile stiffness, which can contribute to segmental instability in the patient.

Conclusions

In the present study we quantified physiological, ultimate, and mechanical yield properties of isolated intervertebral disc annulus specimens obtained from younger and normal or minimally degenerated human lumbar spines. Radial location dependency was identified between deep and superficial fibers. Mechanical yield was evident prior to ultimate failure in 98.5% of specimens tested and occurred at approximately 80% and 74% of the stress and strain, respectively, to ultimate failure. Fiber modulus decreased by 34% following yield. This finding indicates that yielding of intervertebral disc fibers occurs relatively early in the mechanical response of the tissues and that stiffness is considerably decreased following yield. Therefore, yielding of annular fibers may result in decreased segmental stability contributing to accelerated degeneration of bony components and possible idiopathic pain.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper. This research was supported in part by the Office of Naval Research through Naval Air Warfare Center Aircraft Division Contract N00421-10-C-0049 and the Department of Veterans Affairs Medical Research.

Author contributions to the study and manuscript preparation include the following. Conception and design: Stemper, Baisden, Shender, Maiman. Acquisition of data: Stemper. Analysis and interpretation of data: Stemper, Baisden, Yoganandan, Maiman. Drafting the article: Stemper. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Stemper. Statistical analysis: Stemper. Administrative/technical/material support: Stemper, Baisden, Shender. Study supervision: Stemper, Shender.

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Address correspondence to: Brian D. Stemper, Ph.D., Department of Neurosurgery, Medical College of Wisconsin, 9200 W. Wisconsin Ave., Milwaukee, WI 53226. email: bstemper@mcw.edu.