Published in final edited form as:

Spine Deform. 2020 October ; 8(5): 845–851. doi:10.1007/s43390-020-00139-9.

Quantifying the effect of posterior spinal instrumentation on the MRI signal of adjacent intervertebral discs

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Abstract

Study Design: *Ex vivo* porcine imaging study.

Objectives: Quantitatively evaluate change in MRI signal at the discs caudal to spinal fusion instrumentation.

Summary of Background Data: Individuals who receive posterior spinal instrumentation are at risk of developing accelerated disc degeneration at adjacent levels. Degeneration is associated with a loss of biochemical composition and mechanical integrity of the disc, which can be noninvasively assessed through quantitative T2* (qT2*) MRI techniques. However, qT2* is sensitive to magnetic susceptibility introduced by metal.

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Conflict of interest

Jutta Ellermann, Casey Johnson, and Arin Ellingson have received research grants from the National Institutes of Health. Arin Ellingson has received research grants from the Scoliosis Research Society. David Polly has received work royalties from Springer Textbook and a consultant at SI Bone, Inc. The remaining authors declare that they have no conflict of interest.

Methods: Nine *ex vivo* porcine lumbar specimens were imaged with 3T MRI. Fast spin-echo T2-weighted (T2w) images and gradient-echo qT2* maps were acquired, both without and with posterior spinal fusion instrumentation. Average T2* relaxation times of the nuclei pulposi (NP) were measured at the adjacent and sub-adjacent discs and measurements were compared using t-tests before and after instrumentation. The size of the signal void and metal artifact were determined (modified ASTM F2119–07) within the vertebral body and spinal cord for both MRI sequences. The relationship between T2* signal loss and distance from the instrumentation was evaluated using Pearson's correlation.

Results: There was no significant difference between adjacent and sub-adjacent NP T2* relaxation time prior to instrumentation ($p=0.86$). Following instrumentation, there was a significant decrease in the T2* relaxation time at the adjacent NP (average=20%, $p=0.02$), and no significant difference at the sub-adjacent NP (average=-3%, $p=0.30$). Furthermore, there was a significant negative correlation between signal loss and distance to disc ($r=-0.61$, $p<0.01$).

Conclusions: Spinal fusion instrumentation interferes with T2* relaxation time measurements at the adjacent disc but not at the sub-adjacent discs. However, there is sufficient signal at the adjacent disc to quantify changes in the T2* relaxation time following spinal fusion. Hence, baseline MRI scan following spinal fusion surgery are required to interpret and track changes in disc health at the caudal discs.

Level of Evidence: N/A

Introduction

Adjacent segment degeneration (ASD) is common following spinal fusion, and its prevalence increases with the length of the fusion[1]. Corrective surgeries for large deformities often span several levels, thus increasing the stress experienced at the adjacent levels, which tends to accelerate ASD and may lead to subsequent surgeries [1–4]. There is a clinical need to identify which levels are susceptible to ASD to guide treatment and surgical decision making (i.e., which levels to fuse). Additionally, as new biological therapies emerge, monitoring disc health adjacent to instrumentation is critical.

Disc degeneration presents initially as a loss of proteoglycan content, leading to decreased hydration and, ultimately, loss of mechanical integrity [5–7]. Clinical assessments of disc degeneration includes assessment using radiographs and magnetic resonance imaging (MRI) - the latter primarily uses T2-weighted imaging. With respect to disc degeneration, radiographs only evaluate change in disc height. T2-weighted imaging, which relates to disc hydration, provides a more complete grading of disc degeneration based on Pfirrmann classification, which qualitatively assesses disc height, nucleus pulposus (NP) signal, and distinction of the annulus fibrosus from the NP[8]. These degenerative findings do not always correlate with low back pain symptomology [9–11]. Additionally, Pfirrmann grading depends on subjective clinical assessment of disc health and lacks the ability to interpret disc health in an objective, biologically meaningful way. Though radiographs and T2-weighted images may have some clinical utility, they fall short in their ability to detect the early, subtle changes of disc degeneration (e.g., loss of proteoglycan content).

Recent work using quantitative T2* MRI has demonstrated a strong and significant correlation between T2* relaxation times and proteoglycan content, particularly in the NP ($r = 0.944$, $p < 0.001$) [12,13]. Additionally, characterizing the signal distribution within the disc has shown great promise in early detection of degeneration[14]. Specifically, very healthy discs have a highly centralized, discrete T2* relaxation time in the NP; and during the initial stages of degeneration, there is a diminished signal intensity accompanied by an expansion of the NP signal, resulting in an increased signal volume[14]. T2* relaxation times and signal distributions have also been shown to be correlated to local biomechanical properties of the disc[12] as well as functional mechanical properties of the spinal unit[15]. Therefore, quantitative T2* maps provide a significant advantage for noninvasively assessing the initial stages of disc degeneration [16] that occur soon after spinal fusion.

However, quantitative T2* mapping uses a gradient-echo sequence that is highly susceptible to magnetic field inhomogeneities such as those caused by metal instrumentation[17]. As a result, T2* images may be spatially distorted and have signal loss in the vicinity of metal instrumentation. Additionally, the size of the signal loss is dependent upon the orientation of the instrumentation relative to the main magnetic field; parallel minimizes and perpendicular maximizes the artifact [18,19]. Posterior spinal instrumentations are typically placed with rods parallel and pedicle screws perpendicular to the spine. Due to the inability to alter instrumentation orientation within the patient, quantifying signal loss with this orientation is desired to reliably interpret T2* relaxation times for evaluating changes in disc health properties for individuals with instrumentation.

Traditional artifact measurements aim to evaluate the size of the signal void and to qualitatively assess the effect of distorted signal on clinical interpretation [20–25]. Studies using T2-weighted imaging (a spin-echo sequence) found minimal to no effect on the interpretation at the adjacent disc due to spinal instrumentations, particularly when the instrumentation was composed of titanium alloy [20–25]. Quantitative analysis, in prior studies, evaluated signal void size by measuring the width of the void, showing an increase in the signal void in a gradient-echo sequence compared to a spin-echo sequence [23–27]. Previous work has shown clinical interpretation on T2-weighted images were not visually affected. However, quantitative T2* maps have not been investigated regarding the effect on quantitative interpretation via altered relaxation times - due to the nature of the gradient-echo sequence.

Our study aimed to quantify the impact of posterior spinal instrumentation on the T2* relaxation time of the disc - specifically, the nuclei pulposi adjacent to fusion. Additionally, we proposed to assess the size of the signal void and metal artifact generated by the spinal instrumentation for both T2-weighted images and quantitative T2* maps. The primary hypothesis was that, following fusion, T2* relaxation times would decrease in the NP adjacent to instrumentation and remain constant in the sub-adjacent NP. The secondary hypothesis was that there would be an increase in the signal void and metal artifact in the quantitative T2* maps compared to T2-weighted images.

Materials and Methods

Nine *ex vivo* immature porcine lumbar specimens were excised immediately post-mortem for analysis. Each specimen was imaged using a 3T MRI scanner (MAGNETOM Prisma; Siemens Healthcare; Erlangen, Germany) before and after implantation of non-ferrous posterior spinal instrumentation (Figure 1), which consisted of two multi-axial pedicle screws (5.5×30mm), two set screws (5.5/6.0mm), and two spinal rods (5.5mm-diameter). Rods and tulip of the pedicle screw were composed of cobalt chrome, while set screws and the shaft of the pedicle screw were composed of titanium alloy. Along with the 3T MRI scanner, a 64-channel head coil (Siemens Healthcare) was used to acquire co-registered sagittal images of T2-weighted and quantitative T2* mapping sequences (parameters are listed in Table 1). Images were resliced with OsiriX Imaging Software (Pixmeo; Geneva, Switzerland), with the three most-central mid-sagittal slices used for analysis.

Changes due to instrumentation were evaluated by quantifying T2* relaxation times at the NP using customized Matlab scripts (The MathWorks, Inc.; Natick, MA). T2-weighted images were used to create masks of the NPs at the adjacent (one level caudal) and sub-adjacent (two levels caudal) discs across the three mid-sagittal slices using a manually set threshold. The masks were then applied to the co-registered quantitative T2* map to extract the T2* relaxation times of each pixel within each NP. A priori analysis (Tukey test) was done on four discs (prior to instrumentation) to evaluate normal ranges for the T2* relaxation times within the NP. If the T2* relaxation time at a given pixel was greater than two standard deviations from this sample population mean, then the pixel was considered an outlier and excluded from analysis. Average T2* relaxation times were calculated for the adjacent and sub-adjacent NP before and after instrumentation.

Distance measurements were acquired using OsiriX Imaging Software. Distances from the pedicle screw to the adjacent and sub-adjacent discs were measured on the T2-weighted images. To minimize the effect of the artifact on these measurements, the superior point was set to the center of the pedicle screw, which was determined by bisecting the pedicle screw in the sagittal view. “Disc distances” were measured in the sagittal plane from the superior point to the superior endplates of the adjacent and sub-adjacent discs.

To determine the signal void and metal artifact, the T2-weighted images and quantitative T2* maps were oriented such that they bisected the pedicle screw in the superior-inferior direction in an oblique sagittal plane. The signal void was then measured from edge to edge of the artifact within the vertebral body and spinal cord (Figure 2). The metal artifact was calculated (from the signal void measurement) based on the recommendation provided in the ASTM International F2119–07 standard[28] to superimpose the device at the center of the image with the largest void and assessed as measurement from the edge of the superimposed screw to the edge of the void.

Statistical Analysis:

A two-tailed unpaired t-test was used to assess the difference in T2* relaxation times between adjacent and sub-adjacent discs before instrumentation. To determine the difference in T2* relaxation times before and after spinal instrumentation, a two-tailed paired t-test was

employed for each level. Outlier analysis was performed by converting T2* relaxation time differences to a z-score and removing paired data beyond the 95% confidence interval.

The percent decrease in T2* relaxation times in the NP following implantation of instrumentation was calculated with respect to T2* relaxation time before instrumentation, for each specimen at adjacent and sub-adjacent discs. Outliers in the percent decrease data were removed based on an influential measurement analysis followed by a z-score outlier analysis. A Pearson's correlation analysis was used to determine the relationship between the percent decrease in T2* relaxation times and disc distance from the instrumentation.

All statistical tests were calculated using R: A language and environment for statistical computing (R version 3.5.3, R Foundation for Statistical Computing; Vienna, Austria) and the level of significance set to 0.05 [29–31] (outliers: Tests for outliers; xfun: Miscellaneous Functions by 'Yihui Xie').

Results:

No statistical difference was found when comparing T2* relaxation times at adjacent and sub-adjacent discs before introducing the spinal fusion instrumentation ($t = -0.18$, $df = 15.45$, $p = 0.86$; Figure 3). One specimen was a statistical outlier at the adjacent disc and was removed from paired analysis. A significant 20% ($\pm 17\%$) decrease in T2* relaxation times was observed at the adjacent disc following instrumentation ($t = 2.86$, $df = 7$, $p = 0.024$; Figure 3) with average T2* relaxation times of 111.67ms (± 17.78 ms) before and 90.07ms (± 32.31 ms) after instrumentation. There was a non-significant 3% ($\pm 12\%$) decrease in T2* relaxation times at the sub-adjacent disc due to instrumentation ($t = 1.11$, $df = 8$, $p = 0.30$; Figure 3) with an average T2* relaxation time of 116.19ms (± 22.44 ms) before and 112.11ms (± 23.30 ms) after instrumentation.

Signal void and metal artifact increased from anterior (vertebral body) to posterior (spinal cord) for both T2-weighted images and quantitative T2* maps (Table 2). The average signal void at the vertebral body was 3.91mm (± 0.95 mm) for the T2-weighted images and 10.73mm (± 2.60 mm) for the quantitative T2* maps. At the spinal cord, the average signal void was 7.88mm (± 2.52 mm) for the T2-weighted images and 18.52mm (± 7.60 mm) for the quantitative T2* maps.

A decrease in percent difference in T2* relaxation times at the NP was significantly correlated with increased disc distance from the spinal fusion instrumentation ($r = -0.61$, $p < 0.01$; Figure 4). The percent signal loss for one specimen at the adjacent disc was determined to be a statistical outlier and removed from correlation analysis; this was the same specimen removed from the paired data analysis.

Discussion:

Our results demonstrate that there is sufficient signal to quantify T2* relaxation times at discs adjacent to spinal fusion instrumentation, albeit diminished slightly. Furthermore, T2* relaxation times at the sub-adjacent disc are unaffected by the inclusion of the spinal

instrumentation. These findings support that quantitative T2* relaxation time mapping is a feasible method for evaluation of disc health in patients following spinal fusion surgery.

We found that metal artifacts were approximately double in size when using gradient-echo-based quantitative T2* mapping compared to clinical-standard T2-weighted spin-echo imaging. One reason for the increased artifact is due to the lack of a refocusing pulse in the gradient-echo sequence[32]. *Petersilge et al.* evaluated the artifact size produced from T2-weighted spin-echo imaging determining that the artifact was up to three-times the screw size[27]; thus the artifact on quantitative T2* maps can be expected to be about six-times the screw size. In comparison, another study assessed the artifact size created on a T2-weighted image by rods and found that artifact size around the rod was equivalent to the diameter and half the diameter for cobalt chrome and titanium, respectively[24]. In addition to the type of sequence the orientation of the instrumentation affects the size of the signal void and metal artifact. Our instrumentation was oriented to represent placement of surgical instrumentation *in vivo* for a posterior spinal fusion with pedicle screws perpendicular and rods parallel to the spine, and the spine was oriented parallel to the main magnetic field. This orientation produced maximum artifact for the pedicle screws and minimal artifact from rods[18].

Despite the sensitivity of T2* mapping to metal artifact, we found a potentially tolerable decrease in T2* relaxation times following inclusion of the spinal fusion instrumentation. T2* relaxation times decreased an average of 20% at the adjacent disc at an average disc distance of 2.25cm and decreased only 3% at the sub-adjacent disc with a disc distance of 5.9cm. As expected, we found that the percent decrease in T2* relaxation times was greater in discs that were closer to the instrumentation. The ASTM F2119–07 defines image artifact as when the signal changes 30% or more, comparing the reference image to the image with instrumentation[28]. This change in signal we observed at the adjacent disc, although significant, does not fall within the specifications for image artifact. Therefore, there is signal remaining at the adjacent disc to track and follow over time; providing researchers the ability to assess alterations in disc health following spinal fusion surgery in order to better understand the initial stages of ASD. By obtaining MRIs after surgery, the change in T2* relaxation time due to instrumentation can be used to help interpret disc health and monitor degenerative changes over time. Note that the percent decrease in T2* relaxation time is also a function of the echo times used to calculate T2*, since longer echo times in a gradient-echo sequence have greater signal loss[33]. Thus, in general, for T2* mapping near instrumentation it is advisable to use shorter echo times.

Our study has limitations. First, we used porcine specimens, which have anatomical differences from human discs and vertebrae. However, adjacent disc distances from the instrumentation were comparable to anatomical measurements from the center of the pedicle to the inferior endplate of the vertebral body; our measurements ranged 1.44cm to 2.69cm, while human cadaveric measurements ranged 1.31cm to 2.08cm [34–36]. Second, we only analyzed one specific instrumentation. Pedicle screw size was chosen for specimens based on pedicle and vertebral body size, similar to surgical practice. As anatomical features increase in size, either a longer or larger diameter pedicle screw is required. The signal void would likely increase with the diameter of the pedicle screw, while metal artifact (distortion of the signal beyond the edge of the pedicle screw) would remain constant[18]. Our study

used cobalt chrome and titanium alloys, which are the most common materials used in spinal fusions. Although cobalt chrome alloys are more susceptible to metal artifacts than titanium alloys, *Ahmad et al.* found that there was an average metal artifact increased from cobalt chrome to titanium 2.75mm in T2-weighted images[24] and gradient-echo sequences have up to 35% greater voids than spin-echo sequences[37]. Hence, additional metal artifact created by a cobalt chrome alloy pedicle screw would not encroach upon the adjacent disc space - as it would be less than the vertebral body height. As thus, the change in screw size or material is unlikely to have a drastic effect on T2* relaxation times within the NP. Although the signal void was quantified in the spinal canal, changes in the T2* relaxation time was not quantified in the spinal cord because of the excised nature of the specimen, the spinal cord did not always remain intact. Future work will aim to assess the impact of instrumentation on spinal cord imaging.

In conclusion, it is potentially feasible to use quantitative T2* mapping to track changes in disc health due to ASD following spinal fusion, but a baseline scan is required post-operatively to establish the baseline health. This method may thus be useful to assess biochemical and biomechanical changes in the disc near metallic instrumentation. Future work will aim to optimize the quantitative T2* mapping technique to minimize artifacts created by the instrumentation and assess this technique *in vivo* following spinal fusion surgery.

Acknowledgements

Porcine specimen donated from the University of Minnesota's Visible Heart Lab.

Funding

The work was supported by the Scoliosis Research Society and the National Institutes of Health [K12 HD073945, K01 AR070894, 1S10OD017974, and P41 EB015894].

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Key Points

- Signal voids are larger in gradient-echo sequences (quantitative T2*) than in spin-echo sequences (fast spine-echo T2-weighted)
- Although there is a loss in T2* signal (20%) at the disc adjacent to spinal fusion instrumentation, there is signal remaining that may be used to assess and track early signs of disc degeneration
- Signal at the sub-adjacent disc is not affected by the spinal fusion instrumentation
- To use quantitative T2* MRI maps to assess disc degeneration, imaging following surgery needs to be done to determine base line and track changes due to degeneration, and not due to the inclusion of instrumentation within the MRI.

Fig. 1. Representative T2-weighted images and quantitative T2* maps of a porcine lumbar specimen before and after posterior spinal instrumentation with the adjacent (red) and sub-adjacent (green) nucleus pulposus region of interest highlighted

Fig. 2.
Representative images of measurements taken of the signal void within the vertebral body (VB) and spinal cord (SC) using (A) T2-weighted images and (B) quantitative T2* map

Fig. 3. Average T2* relaxation time ($\pm$ standard deviation) of the adjacent and sub-adjacent nucleus pulposus before and after spinal instrumentation. Note: * indicates $p < 0.05$

Fig. 4.

Signal loss (percent decrease in T2* relaxation time, %) with respect to the disc distance (distance from center of screw to edge endplate, cm), correlation coefficient and p-value. Hollow circle represents the outlier data that was excluded from the analysis

Table 1

MRI sequence parameters for sagittal acquired T2-weighted images and quantitative T2* maps

	T2-weighted Images	Quantitative T2* Maps
TR (ms)	3220	500
TE (ms)	91	4.18, 11.32, 18.46, 25.60, 32.74, 39.88
Flip Angle (deg)	160	60
Pixel Size (mm)	0.47x0.47	0.47x0.47
Slice Thickness (mm)	3	3
Field of View (mm)	180 x 180	180 x 180
Bandwidth (kHz)	255	260
Slices	33	33
Matrix Size	288 x 384	384 x 384
Inter-Slice Gap (mm)	3	3

Table 2.

Average ($\pm$ standard deviation) size of the signal void (mm) and metal artifact (mm) for T2-weighted and quantitative T2* maps

	Vertebral Body, mm	Spinal Cord, mm
T2-weighted		
Signal Void	3.91($\pm$ 0.95)	7.88($\pm$ 2.52)
Metal Artifact	-0.80($\pm$ 0.47)	1.19($\pm$ 1.26)
Quantitative T2* Maps		
Signal Void	10.73($\pm$ 2.60)	18.52($\pm$ 7.60)
Metal Artifact	2.62($\pm$ 1.30)	6.51($\pm$ 3.80)