In vivo assessment of spinal cord elasticity using shear wave ultrasound in dogs

Amro Al-Habib, MD, FRCSC, MPH,¹ Abdulrahman Albakr, MD,¹ Abdullah Al Towim, MD,¹ Metab Alkubeyyer, MD,² Abdullah Abu Jamea, PhD,² Fahad Albadr, MD,² Abdelazeem A. Eldawlatly, MD,³ Tarek Kashour, MD,⁴ Hisham Alkhalidi, MD,⁵ and Tariq Alzahrani, MD³

¹Division of Neurosurgery, Department of Surgery, and Departments of ²Radiology, ³Anesthesia, ⁴Cardiac Sciences, and ⁵Pathology, College of Medicine, King Saud University, Riyadh, Saudi Arabia

OBJECTIVE Evaluation of living tissue elasticity has wide applications in disease characterization and prognosis prediction. Few previous ex vivo attempts have been made to characterize spinal cord elasticity (SCE). Recently, tissue elasticity assessment has been clinically feasible using ultrasound shear wave elastography (SWE). The current study aims to characterize SCE in healthy dogs, in vivo, utilizing SWE, and to address SCE changes during compression.

METHODS Ten Greyhound dogs (mean age 14 months; mean weight 14.3 kg) were anesthetized and tracheally intubated, with hemodynamic and neurological monitoring. A 3-level, midcervical laminectomy was performed. SCE was assessed at baseline. Next, 8- and 13-mm balloon compressions were sequentially applied ventral to the spinal cord.

RESULTS The mean SCE was 18.5 ± 7 kPa. Elasticity of the central canal, pia mater, and dura mater were 21.7 ± 9.6 kPa, 26.1 ± 14.8 kPa, and 63.2 ± 11.5 kPa, respectively. As expected, the spinal cord demonstrated less elasticity than the dura mater ($p < 0.0001$) and pia mater (trend toward significance $p = 0.08$). Notably, the 13-mm balloon compression resulted in a stiffer spinal cord than at baseline (233 ± 73 kPa versus 18.5 ± 7 kPa, $p < 0.0001$) and 8-mm balloon compression (233 ± 73 kPa versus 185 ± 68 kPa, $p < 0.048$).

CONCLUSIONS In vivo SCE evaluation using SWE is feasible and comparable to earlier reports, as demonstrated by physical sectioning of the spinal cord. The compressed spinal cord is stiffer than a free spinal cord, with a linear increase in SCE with increasing mechanical compression. Knowledge of the biomechanical properties of the spinal cord including SCE has potential implications for disease management and prognosis.

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KEYWORDS ultrasound; shear wave elastography; spinal cord compression

MECHANICAL properties of bodily tissues are altered by different disease processes.^{15,34} Recognition of such changes through organ palpation during examination is integral to medical diagnosis. The discovery of solid lesions may be suggestive of malignancy.⁴¹ In addition to the current imaging methods that visualize lesions based on their anatomical characteristics or contrast enhancement, hard and soft tissues can be differentiated using radiology, through tissue elasticity assessment.³³ Both ultrasound elastography (USE) and MR elastography (MRE) are currently used to assess the elasticity of superficial and deep tissues.^{31,41}

USE has wide applications as a diagnostic tool in different organs.³⁵ It is used to identify malignant breast lesions by defining the lesion's elasticity.^{4,13,38} A study has shown that USE for breast lesions is superior to B-mode ultrasound (US) and mammography, due to its greater sensitivity and specificity.¹⁹ Another study has suggested that USE, compared to conventional US, is more accurate and specific in assessing breast lesions. This could lead to a reduction in the number of unnecessary biopsies.²⁶ USE is also used in liver disease assessment for lesion evaluation and the grading of fibrosis; thus, possibly limiting the need for more invasive tests.³⁶ It is also used for monitoring the liver disease

ABBREVIATIONS MAP = mean arterial blood pressure; MEP = motor evoked potential; MRE = MR elastography; ROI = region of interest; SCE = spinal cord elasticity; SWE = shear wave elastography; USE = ultrasound elastography.

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progression and treatment response.³⁵ Moreover, elasticity assessment using USE and MRE has demonstrated promising diagnostic value for several other organs including thyroid, lymph nodes, heart, lung, muscles, spleen, kidneys, pancreas, uterus, and prostate.^{3,8,18,20–22,24,29,31,37}

The assessment of CNS elasticity has been a subject of developing research.^{10,12,22,25,29–31,37,40,42,43} Characterization of brain elasticity has shown potential diagnostic value for many diseases including normal pressure hydrocephalus, Parkinson's disease, dementia, multiple sclerosis, and brain tumors, and the noninvasive characterization of intracranial pressure.^{2,16,17,29,32,37,42} In one study, brain elasticity values measured using MRE were lower in Alzheimer's disease mice than in the control group, indicating that elasticity could be used as a biomarker for the diagnosis or grading the disease.²⁸ Brain elasticity assessment using MRE could predict brain tumor stiffness and correlates with the qualitative assessment of surgeons.²⁹ Integration of such assessments is important in planning surgical resections.²² Furthermore, intraoperative USE has also been used to identify and resect an epilepsy focus that was not apparent on preoperative MRI or intraoperative B-mode US.¹⁰

Current knowledge on spinal cord elasticity (SCE) is very limited. Elasticity of the spinal cord and pia mater was assessed previously in dogs by tissue sectioning and the application of tensile-loading method.⁴⁰ The study demonstrated that the sources of elasticity of the dura mater were both elastic and collagenous fibers.³⁹ Other studies have demonstrated that both pia mater and the dura mater are stiffer than the spinal cord.^{30,39,40} Overall, published studies on the subject are few and limited to physical experiments that were done *ex vivo*. They also lacked the demonstration of the effect of compression on SCE. Our current study aims at evaluating SCE *in vivo*. USE was utilized to assess the elasticity of the spinal cord, pia, and dura intraoperatively in anesthetized dogs after cervical laminectomy. The response of SCE during external compression was also assessed. The results of the current study may provide more insight into the biomechanical properties of the spinal cord and could have future implications for the diagnosis and prognosis of spinal cord diseases.

Methods

Experiment Preparation and Procedure

Ten Greyhound dogs weighing 8.6–20.0 kg (mean 14.3 kg), comprising 6 males and 4 females, with a mean age of 14 months, were included in the study. The Institutional Ethics Review board approved the study protocol.

General anesthesia was induced with intramuscular ketamine and xylazine (2 mg/kg each). Tracheal intubation was then performed and followed by connecting the dogs to the respirator for volume-controlled ventilation with oxygen and sevoflurane-maintenance anesthesia. The dogs were fully anesthetized during the procedure. An intravenous line was inserted to deliver the medications, and an infusion of Ringer's lactate was started. Continuous intraoperative monitoring of the heart rate, blood pressure, mean arterial blood pressure (MAP), and oxygen

saturation was performed. Intraoperative neurophysiological monitoring in the form of motor evoked potentials (MEPs) was used to assess the responses from both upper and lower limbs. Baseline MEPs were recorded prior to the beginning of the procedure.

The incision was done in the midline of the posterior neck area. After muscle dissection and posterior spine exposure, a 3-level midcervical laminectomy was performed, exposing the dura. US was then performed for anatomy and elasticity evaluation. At the end of the procedure, the animals were humanely euthanized, and mechanical ventilation was discontinued.

Elasticity Evaluation and Quantification

Elasticity of the spinal cord was studied using the SuperSonic Aixplorer ultrasound system (SuperSonic Imagine S.A.) coupled with a linear transducer array (4–15 MHz, SuperLinear 15–4).⁵ The SuperSonic US system measures tissue elasticity through the shear wave elastography (SWE) technique.⁴⁵ The probe sends mechanical waves that propagate through the tissues.⁴⁵ Shear waves are the transverse components of the transmitted waves. The speed of the waves is variable depending on tissue hardness. Therefore, measuring the speed of the shear waves provides an assessment of the tissue stiffness, presented in kilopascals.⁶ Since the probe, rather than the operator, is the source of the waves, SuperSonic SWE is less dependent on the operator, making the technique and results reproducible and quantitative.^{14,45}

Following laminectomy with the dura kept intact, the surgical field was filled with normal saline, avoiding air bubbles. The spinal cord and surrounding structures were assessed using the B-mode US (Fig. 1A). Subsequently, SCE assessment using SWE sequences was performed. During SWE image acquisition, it is necessary to avoid pressure by the US probe resulting in variability in elasticity results. SuperSonic US demonstrates if any pressure is applied by the probe, by measuring the elasticity in the extradural space where the irrigated fluid exists (Fig. 1).

Elasticity values were determined on the midline sagittal image for the spinal cord, central canal, pia mater, and dura mater. B-mode US imaging of the spinal cord was done in the sagittal midline plane showing the central canal (Fig. 1). The image was then immobilized by avoiding any movement for a few seconds, for SWE assessment. The image was then frozen and saved, and elasticity measurement was performed. Elasticity acquisition using SuperSonic SWE was performed, as previously described.⁴⁵ Tissue elasticity was superimposed on the B-mode US images as a color-scaled image; tissues exhibiting lower stiffness (lower values in kPa) were displayed in blue, while tissues with higher stiffness were displayed in red (higher values in kPa, Fig. 1).⁶ SCE quantification was determined on 3 sagittal SWE image acquisitions for each dog. Within each acquisition, 2 to 3 random points representing the region of interest (ROI) were specified (Fig. 1A). Each ROI was defined by a sizable circle (the so-called Q-Box) that is built into the system; the operator would place the ROI where elasticity measurement was desired. The values of the mean, maximum, minimum, and standard deviation relevant to the elasticity of the ROI (in kPa) would be dis-

FIG. 1. Sagittal-view US image (A) of the spinal cord showing the elasticity map obtained using SWE, superimposed on a B-mode US image (B). Summary of SWE information for the selected ROI called Q-Box is displayed on the right side of the image. Each Q-Box is labeled with a specific symbol that addresses a specific ROI. In this case, (+ Q-Box) represents dura mater, (x Q-Box) represents pia mater, and the other two Q-Boxes were selected randomly to represent the spinal cord. Data for each ROI are displayed on the screen, and they include the mean, maximum, minimum, and standard deviation of the measured elasticity. All the numbers are expressed in kilopascals (kPa). For accurate evaluation, each selected ROI was determined using the smallest Q-Box circle (1 mm) in size. CC = central canal; DM = dura mater; PM = pia mater; SC = spinal cord. Figure is available in color online only.

played accordingly. For accurate evaluation of elasticity, we selected the smallest Q-Box circle (1 mm) to isolate the location of interest and avoid inclusion of adjacent tissues (Fig. 1A).

Studying the Effect of Local Compression on the Elasticity of the Spinal Cord

The second part of the study involved addressing the SCE changes in response to compression. A balloon catheter was introduced anterior to the spinal cord during the laminectomy exposure. The compression was carried out in two steps, starting with gradual inflation of the balloon to 8 mm, followed by an increase to 13 mm of air with the assessment of SCE at each step of the compression (Fig. 2A–D). The balloon location was confirmed by B-mode US. SCE was assessed using the same SWE technique, at the maximum local site of compression, in addition to other points on the spinal cord distal to it (Fig. 3A and B).

During the entire procedure, neuromonitoring using MEPs in the upper and lower limbs indicated MEP levels at baseline prior to skin incision, after laminectomy, and before and after the compression.

Statistical Analysis

All statistical calculations, including Pearson correlation coefficients and paired-sample t-tests, were conducted using the Statistical Package for Social Science Software

(PC + version 19.0; SPSS, IBM). Descriptive statistics (mean $\pm$ SD, and 95% CI) were determined. A result was considered statistically significant if $p < 0.05$.

Results

Elasticity of the Spinal Cord, Central Canal, Pia Mater, and Dura Mater

Elasticity values of different tissues were demonstrated in Table 1. The spinal cord exhibited the least elasticity values, indicating that it is a softer structure compared to the dura mater, which is comparatively sturdier (Fig. 1, Table 1, $p < 0.0001$). Likewise, pia mater elasticity showed a higher value than that of the spinal cord; however, this difference demonstrated a trend toward significance ($p = 0.08$). Central canal elasticity did not exhibit a significant difference compared to the spinal cord ($p = 0.228$) or the pia mater ($p = 0.162$). There was no significant correlation between the subject's age, weight, heart rate, and SCE ($p = 0.307$, $p = 0.399$, $p = 0.906$, respectively).

During the procedure, the mean systolic blood pressure, diastolic blood pressure, and MAP were 115.7 mm Hg, 76 mm Hg, and 86.7 mm Hg respectively. Interestingly, SCE was negatively correlated with the mean systolic blood pressure ($r = -0.74$, $p = 0.013$), diastolic blood pressure ($r = -0.72$, $p = 0.018$), and MAP ($r = -0.74$, $p = 0.014$). This could be related to changes in the spinal cord fluid status with different hemodynamic values. It is well known that spinal cord blood flow changes with changing systemic blood pressure.²³ Tissue elasticity evaluation is subject to change when the tissue vascularity changes, as previously shown in the case of liver.²⁷ While recognizing that SCE changes with different hemodynamic values, it is beyond the scope of the current research to accurately define the fluid status of the spinal cord in response to changes in hemodynamic values and correlate that to SCE.

Quantitative Assessment of SCE With Compression

The local application of an 8-mm balloon compression on the spinal cord significantly increased the stiffness of the cord, as demonstrated by increased SCE values (mean 185 ± 68 kPa versus 18.5 ± 7 kPa, $p = 0.004$). Moreover, increasing the amount of balloon pressure to 13 mm led to an additional elevation in SCE values (mean 233 ± 73 kPa versus 18.5 ± 7 kPa, $p < 0.0001$). A 12-fold increase in the SCE value was demonstrated by the appearance of red color within the compressed area of the spinal cord on the SuperSonic SWE image (Fig. 3C). There was a significant difference between the results of SCE, considering the 2 levels of compression (233 ± 73 kPa with 13-mm balloon versus 185 ± 68 kPa with 8-mm balloon, $p < 0.048$) (Fig. 3C). The impact of the compression was not only limited to the site of compression. In fact, areas located distally, 1 to 2 cm in the cranial or caudal sides, were stiffer than the normal spinal cord (18.5 ± 7 kPa versus 88.1 ± 35.7 kPa, $p < 0.0001$) (Fig. 3A and B).

Neuromonitoring was used to evaluate baseline neural function during spinal cord compression, and otherwise. Among the 10 subjects in the study, MEPs were not obtainable from the lower limbs since the beginning, in 2 subjects, due to technical difficulties. The assessment of

FIG. 2. A and B: The spinal cord is exposed to local compression by a balloon to measure changes in elasticity. **C:** B-mode US image demonstrating local compression of the spinal cord due to the balloon (arrow) located ventral to the cord. Inflation of the balloon was done in 2 steps with different amounts of pressure. The first step started with inflating the balloon to 8 mm of air with the assessment of SCE afterward. **D:** Subsequently, the amount of pressure in the balloon is increased to 13 mm of air followed by the assessment of spinal cord elasticity. Figure is available in color online only.

MEP changes during compression, in the remaining 8 subjects, revealed either maintained or slight MEP changes in 5 subjects (62.5%) and complete loss of MEP signals in the remaining 3 subjects (37.5%). With spinal cord compression, SCE values were higher in subjects who lost the MEP signals compared to those who maintained or demonstrated slight MEP changes (mean 264.4 ± 61.5 kPa versus 188.2 ± 67.8 kPa, $p = 0.099$).

One of the dogs had a different focal area of higher echogenicity within the spinal cord, particularly in the area of the gray matter, as found using B-mode US (Fig. 4A–C). Elasticity evaluation revealed that these abnormal focal areas were stiffer compared to the adjacent normal-looking spinal cord, in the same dog (mean 64 kPa versus 29 kPa; $p = 0.04$). Histopathological examination of that segment, including the areas of increased echogenicity, showed mild edema of spinal cord tissue and foci of recent hemorrhage within the gray matter. No evidence of well-defined cyst or tumor was present. The findings could be related to inadvertent surgical trauma.

Discussion

The Current Study

The current study is the first to demonstrate SCE in

vivo. In 1978, Tunturi published one of the earliest studies on measuring SCE in dogs, using the uniaxial tensile test. The elastic moduli of the spinal cord was estimated to be 16.8 kPa and 11.9 kPa at different loading modes.⁴⁰ Two decades later, Ozawa et al. examined the mechanical properties of the spinal cord in rabbits using the tensile test and presented unique findings.³⁰ In their report, the spinal cord with an intact pia had an elasticity value of 16 kPa, while it was 5 kPa when the pia was removed.³⁰ Therefore, they concluded that the pia mater tripled the elastic modulus, making the spinal cord stiffer. Furthermore, the pia mater was found to enhance the restoration of the cross-sectional shape of the spinal cord after the removal of compression.³⁰ Our findings are in agreement with the findings of Tunturi and Ozawa et al., as a mean SCE value of 18.5 kPa was found in our study, in addition to the result that the pia mater is stiffer than the spinal cord. Moreover, our elasticity measurements were performed while the animals were alive and the spinal cord was under normal physiological conditions, as evaluated by real-time neuromonitoring. This indicates that the current work is more relevant, and the results are more applicable due to the in vivo nature of experimentation. The current study was also the first to demonstrate an increased stiffness of the spinal cord with increasing

FIG. 3. Changes in SCE in response to spinal cord compression. **A:** Summary of SWE values for the selected ROI at the compression site (+ Q-Box) is displayed on the right side of the image. The mean elasticity value for the compressed ROI is 262 kPa, as compared to the normal (free) spinal cord mean elasticity value of 18 kPa. **B:** Elasticity image of the compressed spinal cord with color-scale presentation. The compressed site demonstrates a red color, indicating increased stiffness (SCE 240 to 300 kPa) as presented in the scale at the right side of the image. Tissues located adjacent to the area of maximum compression exhibit an increased stiffness as demonstrated in blue (SCE 100 kPa). **C:** A linear relationship is demonstrated as increased SCE values with increasing degree of compression. Figure is available in color online only.

compression. Such a finding exhibits both diagnostic and prognostic significance in the assessment of different disease conditions affecting the spinal cord.

Physics of Elasticity

Elasticity is the inherent ability of the object to return to its original shape and size after deformation.⁴¹ The relationship between the applied force (stress or σ) and the resulting deformation (strain or ϵ) is presented as Young's modulus E ($E = \sigma/\epsilon$). The methods of tissue elasticity as-

TABLE 1. Elasticity values of different regions of the spinal cord using the SuperSonic SWE

Location	Elasticity Values (kPa)			
	Mean	SD	Minimum	Maximum
Spinal cord	18.5	7	5.4	36.1
Central canal	21.7	9.6	11.1	55.2
Pia mater	26.1	14.8	14.1	69.3
Dura mater	63.2	11.5	36.8	107
Compressed spinal cord*	185	68	110	203
Compressed spinal cord†	233	73	178	300

* Inflating the balloon with 8 mm of air.

† Inflating the balloon with 13 mm of air.

essment using US depend on either strain or shear wave techniques.^{35,41} The strain method assesses elasticity by repeated manual compression from the transducer, measuring the amount of deformation relative to the normal surrounding tissue.¹¹ Using the "strain elastography" technique, Chakraborty et al. differentiated tumors from normal brain tissue by applying gentle pressure from the transducer on the brain to generate strain.⁹ A drawback of this technique, however, is the use of external force to generate strain. The produced force is not uniform and is subject to interoperator variability.¹¹

In contrast, the shear wave technique does not produce deformation. SWE was first reported in 1998 as a new diagnostic method based on measuring the speed of travel of remotely induced shear acoustic waves through tissues.^{33,41} The shear waves are produced by a focused US beam and an ultrafast imaging approach at a very high frame rate (up to 5000 frames/sec), which allows quantitative elasticity assessment of biological tissues in a single ultrasonic sequence.^{6,38} The measurement of the velocity of the shear wave propagation speed in soft tissues enables the creation of an elasticity map.⁶ A stiffness map is extracted through Young's modulus (E), or elasticity, in relation to shear wave speed (c) by the equation $E = 3\rho c^2$, where ρ is the tissue density (kg/m^3).^{18,35} The speed of the shear waves is variable depending on the hardness of the tissues.⁴ Stiff tissues tend to have high speeds of shear waves producing higher elasticity values (in kPa). For instance, it was demonstrated that malignant breast lesions, which exhibit higher tissue stiffness, show higher mean elasticity values on SWE US examination.⁴⁵ Since SWE does not require tissue deformation, it is more suitable for elasticity assessment of the brain and the spinal cord, where tissue deformation is undesirable.⁷

Quantification of Tissue Elasticity

Analogous to palpation in clinical assessment, SWE can differentiate tissues based on their stiffness. Moreover, since the velocity of the shear waves (m/sec) can be measured, quantification of tissue elasticity, or Young's modulus (kPa), is possible.⁴⁴ Quantification of elasticity is performed by selecting small circular areas (ROIs; 1 mm in the current research) in the target area and in several other locations for comparison. The displayed colors and

FIG. 4. B-mode US image (A), sagittal view, of a single dog demonstrating small rounded focal areas within the spinal cord exhibiting higher SWE values compared to image (B) of the more rostral areas of the spinal cord (41.8–103.4 kPa versus 25.2–31.2 kPa). C: Axial US image of the spinal cord showing focal areas of increased echogenicity within the gray matter area. Figure is available in color online only.

elasticity values indicate differences in elasticity of the lesion compared to that of other tissues. The elasticity value is provided in kPa.⁴⁴ Quantification of elasticity was useful in the current study where SCE demonstrated different values with variable degrees of balloon compression (Fig. 3).

Elasticity Assessments of the Spinal Cord

While US has been widely used in spine surgery for several decades,¹ there is no previous report regarding its use to assess SCE. Furthermore, little is known about the mechanical properties of the spinal cord. Most available research has been conducted on ex vivo specimens.^{30,39,40} Such previous work has eliminated many factors that contribute to tissue stiffness in vivo, such as spinal cord vascularity and its fluid status. The current study addressed SCE in living and monitored subjects using USE for the first time. The agreement between the current results (SCE mean 18.5 kPa) and those of previous studies using physical sectioning of the cord is in favor of the utility of USE in such assessment. Together, these results are ideal for expanding the use of USE for SCE measurement in the future.^{30,39,40}

The use of other imaging modalities for SCE measurement has been limited. Only a single report looked at the elasticity of the spinal cord using MRE in volunteers.²⁵ Their findings demonstrated elasticity values of the superior portion of the spinal cord to be 12.1 kPa.²⁵

Previous research on the mechanical properties of the pia and dura mater resulted in significant variations in reported elasticity values. The variability was in part related to the methods of the study, leading to different conclusions on the actual elasticity values of the pia and dura mater. For instance, in one study, the elastic modulus of the pia mater was estimated to be 2300 kPa, whereas another study reported the elasticity value of the dura mater to start from 400 kPa.^{30,39} In the current study, the dura mater was about twice as stiff as the pia mater. This finding corresponds well with the knowledge about the consistency of neuronal tissues.

Tissue compression changes the elastic properties of tissues. This was clearly demonstrated in the current study as a linear increase in the stiffness of the spinal cord with increasing spinal cord compression. In our study, the elasticity of the spinal cord increased in stiffness, 12 times, under the influence of compression. Our findings may underestimate the maximum effect of compression on SCE since the stiffness values in some cases reached the upper limit of the USE machine (300 kPa). On the other hand, it is necessary to correlate SCE values, with and without compression, to the neurological status of the subject. Some of the animals in the current study had preserved MEPs in the upper and lower limbs during compression. This corresponds to the clinical observation that some patients may have a preserved neurological status while undergoing spinal cord compression, as detected on MRI. However, it is necessary for future studies to evaluate whether quantifying SCE could predict future clinical deterioration. In the present work, we have shown the feasibility of USE for SCE evaluation. However, future work is needed for clinical correlation in order to validate the usefulness of this imaging technique and to demonstrate its clinical value.

The current study should be interpreted within existing limitations. A larger sample size could provide more insight into understanding SCE. In the current study, we aspired to utilize many random areas of the spinal cord for precise elasticity evaluation. Within each subject, we obtained 3 different US-image acquisitions. Within each acquisition, we selected 2 to 3 random ROIs for elasticity evaluation, resulting in a minimum of 8 ROI points for measuring the SCE. An important limitation to note is regarding the generalizability of the results of animal studies to humans. Furthermore, the upper limit available in the SuperSonic SWE US machine is 300 kPa; some of the compressed SCE values reached the upper limit of 300 kPa. We expect that these values could have been higher, although this could not be demonstrated in the US machine. While SCE measurement is possible using SWE US examination, USE requires the removal of bony and ligamentous structures. It is also possible that the remaining bone and ligament structures interfere with the sensitivity of the elasticity measurements. The need for bone removal such as in cases of compressive spinal pathology could affect the sensitivity of USE by freeing the spinal cord and, as a result, limiting the actual impact of compression on SCE values. More studies could be done to address SCE using MRE. Additionally, the current study did not address the white and gray matter of the spinal cord separately. Thus, it is necessary to conduct further experiments with a distinct evaluation of gray matter and white matter using USE. The current study also assessed the effect of acute compression on SCE. Future studies could develop methods to assess the effect of chronic compression on SCE.

Conclusions

The current study enhances the understanding of the biomechanical properties of the spinal cord. Using USE, normal SCE values were identified in dogs. Our results agree with basic anatomical knowledge that the dura mater has the highest elasticity, followed by the pia mater, and, lastly, the spinal cord. The central canal of the spinal cord did not exhibit a significant difference in elasticity compared to the spinal cord or pia mater. Moreover, the current study demonstrates significant changes in the spinal cord stiffness following the application of compression. The compressed spinal cord was much stiffer than the noncompressed cord. This should prompt future studies to utilize imaging techniques to provide reference values of SCE in humans. Currently, no modality other than USE is capable of defining tissue elasticity, in real time and intraoperatively. It is, however, limited by the surrounding bone and ligamentous structures.

The portable and economic features of this technique may exhibit potential future diagnostic and prognostic implications in various pathologies involving spinal cord compression. For example, evaluating SCE values in patients with cervical myelopathy or spinal cord injury may predict the functional outcome and the extent of recovery following surgery. Finally, USE may assist neurosurgeons during spinal surgery by accurately defining the region of interest. It may aid in detection, characterization, and definition of the boundaries of different spinal tumors,

intraoperatively, thereby facilitating safer surgery. To our knowledge, this study is the first to confirm the feasibility of this technique for spinal cord evaluation. It, thus, supports future work to address technical issues and challenges associated with USE in the spinal cord, in addition to determining USE values that specify spinal cord biomechanical properties.

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Disclosures

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Supplemental Information

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Author Contributions

Conception and design: Al-Habib, Albakr, Abu Jamea, Albadr, Eldawlatly, Kashour. Acquisition of data: all authors. Analysis and interpretation of data: all authors. Drafting the article: Al-Habib, Albakr. Critically revising the article: Al-Habib, Albakr,

Alkubeyyer, Eldawlatly, Kashour, Alkhalidi. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Al-Habib. Statistical analysis: Albakr. Administrative/technical/material support: Al-Habib, Albakr, Al Towim, Alkubeyyer, Abu Jamea, Eldawlatly, Kashour. Study supervision: Al-Habib.

Correspondence

Amro F. Al-Habib: College of Medicine, King Saud University, Riyadh, Saudi Arabia. amro.alhabib@gmail.com.