Validation of stress magnetic resonance imaging of the canine stifle joint with and without an intact cranial cruciate ligament

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Objective—To validate use of stress MRI for evaluation of stifle joints of dogs with an intact or deficient cranial cruciate ligament (CrCL).

Sample—10 cadaveric stifle joints from 10 dogs.

Procedures—A custom-made limb-holding device and a pulley system linked to a paw plate were used to apply axial compression across the stifle joint and induce cranial tibial translation with the joint in various degrees of flexion. By use of sagittal proton density–weighted MRI, CrCL-intact and deficient stifle joints were evaluated under conditions of loading stress simulating the tibial compression test or the cranial drawer test. Medial and lateral femorotibial subluxation following CrCL transection measured under a simulated tibial compression test and a cranial drawer test were compared.

Results—By use of tibial compression test MRI, the mean ± SD cranial tibial translations in the medial and lateral compartments were 9.6 ± 3.7 mm and 10 ± 4.1 mm, respectively. By use of cranial drawer test MRI, the mean ± SD cranial tibial translations in the medial and lateral compartments were 8.3 ± 3.3 mm and 9.5 ± 3.5 mm, respectively. No significant difference in femorotibial subluxation was found between stress MRI techniques. Femorotibial subluxation elicited by use of the cranial drawer test was greater in the lateral than in the medial compartment.

Conclusions and Clinical Relevance—Both stress techniques induced stifle joint subluxation following CrCL transection that was measurable by use of MRI, suggesting that both methods may be further evaluated for clinical use. (Am J Vet Res 2014;75:41–47)

Magnetic resonance imaging of the stifle joint in dogs has been described for evaluating intra- and periarticular structures.¹⁻³ The high contrast resolution inherent in MRI, compared with other imaging modalities, allows for superior evaluation of soft tissue structures such as ligaments and menisci. Magnetic resonance imaging has been investigated as an alternative diagnostic approach to arthrotomy or arthroscopy.⁴⁻⁹ However, conflicting reports exist on the benefit of MRI for diagnosis of intra-articular abnormalities such as meniscal lesions in dogs.⁶,¹⁰ Techniques for improving the diagnostic accuracy of stifle joint MRI in dogs may provide further understanding of joint disease and enhance characterization of soft tissue injuries in dogs with CrCL deficiency. Stress techniques that can simulate weight bearing have been used in traditional radiography¹¹,¹² and could be also used in stifle MRI to evaluate intra-articular structures such as menisci.

One of the advances in the field of MRI of the human knee joint is the development of open MRI that allows imaging the joint under a loading stress (ie, stress MRI).¹³⁻¹⁶ This technique allows for quantification of abnormal meniscal kinematics and improves the diagnosis of meniscal tears.¹⁷ In humans, meniscal displacement during stress MRI increases the sensitivity of detecting longitudinal, radial, or complex meniscal tears.¹⁸ Considering that dogs and humans may have a comparable mechanism of meniscal injury¹⁷,¹⁸ and a similar pattern of meniscal tears,¹⁹ stress MRI may be useful to increase the sensitivity of diagnosis of meniscal tears in dogs with MRI. Furthermore, in dogs, applying meniscal traction with the meniscal probe during arthroscopy or arthrotomy is an effective method to aid in the diagnosis of nondisplaced meniscal tears.²⁰

ABBREVIATIONS

<table>
<thead>
<tr>
<th>CDT</th>
<th>CrCl</th>
<th>TCT</th>
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<tr>
<td>Cranial drawer test</td>
<td>Cranial cruciate ligament</td>
<td>Tibial compression test</td>
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It follows, then, that displacement of the meniscus induced by stress MRI in dogs may be advantageous in the diagnosis of nondisplaced longitudinal or radial meniscal tears. Magnetic resonance imaging of the knee under loading stress can be obtained in an open MRI scanner with the human patient standing or in a closed scanner by applying an axial force to the limb to mimic weight bearing.22 Specific MRI-compatible loading devices have been developed for stress MRI of the knee and ankle in human patients.25–26 These devices consist of a footplate capable of sliding onto a board positioned on the MRI table.27 When a weight is applied to the end of the board, an axial force equal to the weight is exerted on the patient’s foot, simulating standing.23 In humans, another strategy for performing stress MRI is to simulate the Lachman test,28 which is similar to the CDT in dogs. The method consists of positioning the pelvic limb of a patient in a custom-made jig to create a cranial displacement of the tibia relative to the femur.28

An effective stress MRI technique for diagnosis of meniscal tears is expected to cause femorotibial subluxation in CrCL-deficient stifle joints.29,30 It is possible that femorotibial subluxation will deform an abnormal meniscus in a manner that improves the ability to visualize meniscal tears via MRI. Therefore, a reasonable approach to validate the new technique of stress MRI is to compare femorotibial subluxation between intact and CrCL-deficient stifle joints. The purpose of the study reported here was to develop a method for obtaining MRI images of the canine stifle joint under physiologically substantial loading with a custom MRI-compatible jig by comparing the magnitude of femorotibial subluxation elicited by 2 techniques in intact and CrCL-deficient stifle joints. We hypothesized that 2 stress MRI techniques (MRI-TCT11 or MRI-CDT12,28) would induce cranial tibial subluxation in CrCL-deficient stifle joints that is detectable with high-field MRI.

**Materials and Methods**

**Specimens**—Ten cadavers of adult dogs of various breeds with body weight ranging from 20 to 35 kg were collected within 12 hours following euthanasia. Dogs were euthanized for reasons unrelated to this study. Palpation of each pelvic limb and orthogonal radiographs of the stifle joint were performed to ensure the absence of orthopedic disease. The cadavers were stored at −20°C until testing. In preparation for testing, the cadavers were thawed to room temperature (approx 25°C). The study was approved by the institution’s animal care and use committee.

**Limb preparation**—One of the pelvic limbs in each dog was randomly selected for testing. Randomization was performed by flipping a coin. After thawing, the hair was clipped from the mid-diaphysis of the femur to the mid-diaphysis of the tibia. A 3-cm lateral stiffe arthroscopy was performed to allow transection of the CrCL during testing without removing the cadaver from the positioning jig. Two 3.5-mm tibial tunnels were drilled. These tunnels were used to define the sagittal and dorsal plane for the orientation of the MRI sagittal and dorsal slices. To allow for consistent position of the tibial tunnels, 2 Kirschner wires were placed with fluoroscopic guidance and were used as guide wires for drilling. The first wire was inserted 10 mm distal to the tibial tuberosity, in the craniocaudal direction, parallel to the tibial plateau. The second wire was inserted in the mediolateral direction, perpendicular to the first wire. By use of the guide wires, tibial tunnels were drilled with a 3.5-mm cannulated drill bit. One tibial tunnel was made in a craniocaudal orientation parallel to the tibial plateau, which was defined on the basis of radiographic landmarks. The second tunnel was made in a mediolateral orientation perpendicular to the first tunnel. The wires were removed prior to performance of MRI.

**MRI-compatible stifle-loading jig**—A polyoxymethylene loading device that was compatible with MRI and fit into a 1.5-T commercial MRI unit was built (Figure 1). The device consisted of 2 adjustable boards connected with a hinge mechanism, to allow the positioning of the stifle joint at a desired flexion angle. The proximal board, where the femur was located, had 2 slots on the lateral and medial side where belts were inserted to strap the thigh, securing the femur. The distal board, used for the tibia, had on its distal part 2 rectangular blocks to accommodate the hock joint, which helped maintain the crus in a vertical orientation. The presence of a strap positioned on the distal portion of the tibia allowed avoiding its displacement when the limb was weighted. Both parts of the jig were extendable, making possible the use of the jig for different-sized dogs. Foam sponges were packed around the hock and around the femur to minimize excessive rotation and to keep the entire limb oriented dorsally when it was loaded. Positioning of the dog in the jig was considered appropriate when the sagittal plane of the pelvic limb was deemed to be perfectly vertical.

The design allowed for axial compression and cranial tibial translation across the stifle joint in various degrees of flexion, however, for this study, only...
compression at 135° was used. The weighting apparatus consisted of a pulley system linked to a paw plate. One-gallon plastic bottles filled with sand were used to deliver a force equal to 20% of body weight, which approximately corresponds to a single pelvic limb load during standing.\textsuperscript{31}

When performing MRI-TCT, the paw plate was attached to the pulley system (Figures 2 and 3). For MRI-CDT, no load was applied to the paw. The weight of the dog and the compression of the caudal aspect of the crus against the jig were used to induce femorotibial subluxation, as described in humans.\textsuperscript{28}

MRI—With each specimen mounted to the stress MRI jig, lateral radiography of the limb was performed. A plastic goniometer was used to measure stifle joint flexion angles by aligning each arm with anatomic landmarks on the tibia and femur (lateral and medial malleolus and femoral greater trochanter). Stifle joint flexion angle was measured on each radiograph to ensure the acquired image was within 5° of the targeted angle.\textsuperscript{32} Following radiography, the cadaver was positioned in the MRI unit, and images were acquired by use of a circular surface receive-only coil. Localizer images were acquired in 3 planes, and the tibial tunnels were identified. Images in the sagittal plane were planned such that the image axis was perpendicular to the long axis of the mediolateral tibial tunnel and parallel to the long axis of the craniocaudal tibial tunnel. Images in the dorsal plane were planned such that the image axis was perpendicular to the long axis of the craniocaudal tibial tunnel and parallel to the long axis of the mediolateral tibial tunnel. Images in the transverse plane were planned such that the image axis was parallel to the long axes of both tibial tunnels. Stifle joints were imaged before and after transection of the CrCL. The CrCL was transected via the cranio medial arthroty site. Different sequences were tested to determine which protocol would provide optimal visualization of the menisci and ligaments, with the best balance of contrast resolution and spatial resolution. The sequences included a proton density sequence (repetition time, 3,008 milliseconds; echo time, 18 milliseconds; flip angle, 90°; slice thickness, 2 mm; matrix, 304 X 320), a 3-D steady-state free precession sequence (repetition time, 14.7 milliseconds; echo time, 7.2 milliseconds; flip angle, 20°; slice thickness, 1 mm; matrix, 256 X 256), and an isotropic 3-D fast field echo (repetition time, 12 milliseconds; echo time, 5 milliseconds; flip angle, 20°; slice thickness, 1 mm; matrix, 256 X 256). All images were stored in a picture archive and communication system in Digital Imaging and Communications in Medicine (ie, DICOM) format.

Figure 2—Illustration of a dog in an MRI scanner during an MRI-TCT (A). A weight is suspended behind the dog, and a set of pulleys transfer the force into compressive load. B—Illustration of a dog in an MRI-CDT. The position of the limb in the jig and the weight of the dog create a cranial displacement of the tibia relative to the femur.

Figure 3—Photograph of a dog positioned for a simulated MRI-TCT. Notice the loading setup, the limb-holding jig, and the weight suspended behind the dog (white arrow). The straps and the foam padding are used to hold the limb in the desired position.
Stress MRI analysis—To test the ability of MRI-TCT and MRI-CDT to simulate femorotibial subluxation expected in CrCL-deficient stifle joints, femorotibial subluxation was measured for the medial and lateral compartments with a method modified from Lopez et al. Images were reviewed and measurements were made with a dedicated workstation. The reference axis for measuring tibial translation was constructed parallel to the reference tunnel in the sagittal plane (Figure 4). Tibial position was measured as the distance between the most caudal point of the medial and lateral femoral condyles and the caudal aspect of the medial and lateral tibial condyles, respectively. The magnitude of translation that occurred after CrCL transection was defined by subtracting the distance between the femoral and tibial condyles measured before transection from the distance measured after transection, in their respective compartments.

The MRI images were evaluated by 3 observers unaware of group assignments (GT, AP, and SK), to assess interobserver variability. Each observer reviewed all images in a single session. No randomization of the subjects was performed.

Statistical analysis—The overall intraclass correlation coefficient was calculated with pooled data to define the agreement of all measurements among the observers. A 2-way repeated-measures ANOVA was used to compare the medial and lateral femorotibial subluxation in the CrCL-deficient stifles via MRI-TCT and MRI-CDT. The measurement variable was femorotibial subluxation, and the nominal variables were compartments (medial vs lateral) and MRI technique (MRI-TCT vs MRI-CDT). The values used for statistical analysis of quantifying subluxation were the mean of the 3 observers’ measurements. A P value of 0.05 was considered significant.

Results—Specimens—Eight male dogs and 2 female dogs with a mean ± SD body weight of 27 ± 5 kg were used. Seven right pelvic limbs and 3 left pelvic limbs were used for the study.

MRI measurement of femorotibial subluxation—The proton density sequence was used to obtain the MRI measurements because it allowed the best combination of spatial and contrast resolution for evaluation of the stifle joint within a clinically convenient period. No significant difference in femorotibial subluxation was found between MRI-TCT and MRI-CDT in the medial and lateral compartments (Figure 5). When MRI-TCT was performed in the CrCL-deficient stifle joint, the mean ± SD medial and lateral femorotibial subluxations were 9.6 ± 3.7 mm and 10 ± 4.1 mm, respectively. When MRI-CDT was performed in the CrCL-deficient stifle joint, the mean ± SD medial and lateral femorotibial subluxations were 9.6 ± 3.7 mm and 10 ± 4.1 mm, respectively.
was performed, the mean ± SD medial and lateral tibial translations were 8.3 ± 3.3 mm and 9.5 ± 3.5 mm, respectively. Femorotibial subluxation measured with MRI-CDT was significantly greater in the lateral compartment than in the medial compartment. The overall intraclass correlation coefficient variation was 0.998, indicating strong agreement between observers (Table 1).

### Discussion

On the basis of the results, the hypothesis that both stress methods performed with the custom jig would cause femorotibial subluxation in a CrCL-deficient stifle joint that was measurable via MRI was accepted. Obtaining accurate measurements of femorotibial subluxation by use of MRI was not the primary goal of the study. Rather, the goal was to determine whether a stress MRI technique developed for dogs would induce femorotibial subluxation and therefore simulate weight bearing. In humans, stress MRI has been used to identify conditions in which symptoms occur only in certain positions or only when the affected joint or body part is stress loaded or bearing weight.33,34 Therefore, stress MRI in dogs could potentially help in evaluation of intra-articular structures that may deform or change in position under a load that simulates weight bearing.

In a CrCL-deficient stifle joint, femorotibial subluxation was greater in the lateral than in the medial compartment. The greater magnitude of translation of the lateral compared to the medial femoral condyle following CrCL transection has been reported in ex vivo and in vitro studies of CrCL-deficient stifle joints.30,35 Following CrCL transection, the collateral ligaments become the primary restraint against cranial tibial translation. Internal tibial rotation occurs because the lateral collateral ligament is not as taut as the medial collateral ligament when the stifle joint is in extension, and thus the lateral aspect of the tibia translates further cranially than the medial aspect.37 It is likely that the magnitude of tibial rotation would be reduced in a dog with chronic rupture of CrCL because of the periarticular fibrosis. Both stress MRI techniques resulted in a degree of femorotibial subluxation comparable to values observed during weight bearing in vivo, suggesting that both techniques may be tested for clinical applications.

All specimens had femorotibial subluxation following CrCL transection that was visualized by use of the stress MRI images. In MRI-TCT, different weights were tested in pilot specimens to elicit tibial subluxation. In humans, weights ranging from 4.5 to 15 kg are used to apply stress to the knee joint.22,23,34,38 Following pilot testing, we selected a force equal to 20% of the dog’s body weight, which approximately corresponded to a single pelvic limb load during standing.31 However, the load may need to be increased for future clinical applications of this technique. One of the major limitations of evaluating stress MRI in cadaveric joints or in unconscious patients is that the stress applied to the joint is only an estimation of the in vivo conditions. The cadaveric methodology did not simulate any compensatory muscular tone that can limit cranial tibial subluxation. Additionally, the lack of periarticular fibrosis in a cadaveric stifle joint may not reflect the typical CrCL-deficient stifle joint that is encountered in clinical cases. In dogs with chronic CrCL insufficiency and moderate periarticular fibrosis, greater force may be necessary to induce femorotibial subluxation. Another limitation of the study was that a small arthrotomy was performed to transect the CrCL. Although a sham arthrotomy was performed before beginning the imaging protocol to have the same stifle joint conditions in each scan, the disruption of the joint capsule may have increased the amount of femorotibial subluxation, and the presence of intra-articular gas after the arthrotomy procedure may have introduced imaging artifacts, which were especially evident on the gradient echo sequences.

In addition to clinical applications, stress MRI of the stifle joint may allow investigation of the articular contact patterns in normal and CrCL-deficient stifle joints. Previous contact mechanics studies in dogs following stabilization techniques for CrCL-deficient stifle joints30,39 and following meniscal surgical procedures had several limitations.40,41 The technique used in such cadaveric studies requires intra-articular sensors, use of which is not routinely feasible in clinical cases. Another limitation arising from the sensors is that contact mechanics can be investigated only between the meniscus and tibia and in a limited area. In contrast, MRI-based contact mechanics studies take into account the cartilage and meniscus and attempt to simulate the complex geometry of the joint.42 In vivo evaluation of meniscofemoral and meniscotibial contact mechanics may be possible with stress MRI, which may provide valuable information on in vivo biomechanics of CrCL-deficient stifle joints. However, it should be noted that the exact technique that was described in this study could not be used in clinical patients because it required bone tunnels in the tibia. In humans, MRI tracking systems allow for automatic continuous adjustments of scan plane positions.43 Other methods described in humans include use of anatomic landmarks such as collateral ligaments, tibial condyles, or the caudal aspect of the tibial plateau.44 Because the validation study reported here required precise repeatability, a method that would allow exact alignment of the scans was used. Further
work is required to validate anatomical landmarks in the canine stifle joint for clinical application of stress MRI.

Results of the study reported here indicated that stress MRI caused a significant cranial femorotibial subluxation in CrCL-deficient stifle joints, compared with intact stifle joints. Although conventional static MRI is often helpful in the diagnosis of stifle joint abnormalities, this novel technique may increase the accuracy of diagnosing meniscal tears. The standard technique for stifle joint MRI rarely reveals signs of instability. An appealing aspect of stress MRI is the potential ability to objectively measure meniscal motion and femorotibial contact mechanics in a joint under a known direct stress. To our future studies, this testing apparatus is the first reported to allow stress MRI of the canine stifle joint in vitro. 

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