Effect of Chondral Defect Size, Shape, and Location on MRI Diagnostic Performance in the Porcine Knee

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abstract

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The purpose of this study was to determine the sensitivity and positive predictive value of magnetic resonance imaging (MRI) in the identification of full-thickness articular cartilage defects in the porcine knee. Seventy-two full-thickness chondral defects (small or large; circular, oval, or triangular) were created in 12 porcine knees. The authors used 3.0-T MRI with 3-dimensional gradient echo water-selective/fluid (WATSF) sequences acquired in axial, coronal, and sagittal planes. Sensitivity and positive predictive value parameters were calculated for 2 readers. Magnetic resonance imaging was highly sensitive for detection of full-thickness defects in the knee (85%). The highest sensitivity was observed at the medial femoral condyle (93%), while the lowest was observed at the medial patella (71%). The sensitivities for detecting different shapes were unique to each shape, with oval lesions identified with greatest sensitivity (93%). Small lesions (86%) were detected at a similar sensitivity as large lesions (83%). The positive predictive values for accurate true-positive reads were low for all lesion shapes (18%-57%) and moderate for small (69%) and large (59%) sizes, with significant differences observed between the 2 readers. Magnetic resonance imaging has a high sensitivity in the detection of full-thickness articular cartilage defects in the porcine knee. Variability in defect shape and intra-articular location affects MRI sensitivity, while size does not. Magnetic resonance imaging was not effective in describing lesion shape or size. Further, there was subjectivity in reading defect shape and size between 2 radiologists.
Full-thickness articular cartilage defects are found in 16% of knee arthroscopies. Patients with these lesions have significant pain and loss of function. Quality of life is reduced similar to that of patients scheduled to undergo prosthetic knee arthroplasty or osteotomy. Further, symptoms are significantly worse than those of patients with anterior cruciate ligament insufficiency. These defects lack the ability to innately heal on their own and may be precursors to osteoarthritis.

In symptomatic patients, cartilage surgery techniques may be indicated to delay or prevent the onset of knee joint osteoarthritis. Therefore, early detection of full-thickness defects with noninvasive imaging modalities, such as magnetic resonance imaging (MRI), is highly valuable.

Magnetic resonance imaging is a highly sensitive, specific, and accurate diagnostic tool in identifying chondral defects in the knee. Nevertheless, arthroscopy is the gold standard for their diagnosis. The latter’s invasiveness frequently precludes its use simply for diagnostic purposes. Therefore, the degree of diagnostic reliability of MRI is critical for accurately characterizing chondral lesions and their amenability to surgical intervention. Advancements in MRI sequences, stronger magnetic fields, and quantitative techniques have improved its utility. However, little evidence exists that analyzes the diagnostic capability of MRI with regard to defect size (area and depth), shape, and anatomic location within the knee.

The purpose of this ex vacuo study was to determine the sensitivity and positive predictive value of MRI in the identification of full-thickness articular cartilage defects in the porcine knee (a validated cartilage defect animal model). A secondary purpose was to investigate the potential effects of size, shape, and intra-articular location of defects on MRI sensitivity. The authors’ hypothesis was that 3-T MRI is highly sensitive for detecting chondral defects; however, it may be less sensitive for characterizing defect topography (size, shape, and intra-articular location).

**Materials and Methods**

Twelve porcine hind limbs were acquired from a local butcher. A medial parapatellar arthrotomy was performed to obtain intra-articular access. All knees were inspected for abnormality. Included knees in this study were free of any visual pathology to the knee and cartilage surface. Full-thickness articular cartilage defects were created on the articular surfaces in all 12 knees (6 regions of interest: medial and lateral patella, medial and lateral femoral condyles). Three lateral patellar facets served to define “lateral patella” region of interest, while 3 medial and 1 odd facet served to define “medial patella” region of interest. Seventy-two total defects were created. Not all regions of interest had a defect created within each knee, and some regions of interest had more than 1 defect created within the same region of the same knee. Defect depth was controlled by the identification and removal of the calcified cartilage zone. The subchondral bone was not penetrated while creating the defect. No osteochondral defects were created or observed in the knees investigated. Remaining cartilage was removed with a curette to ensure vertical perpendicular defect rims. Lesions were either circles, ovals, or triangles. Circular lesion surface area was considered either small (0.13 cm², 4 mm diameter) or large (0.28 cm², 6 mm diameter). Oval lesion surface area was either small (0.29 cm²) or large (0.64 cm²). These sizes were selected based on the available sizes of mechanical coring biopsy punches that were used to create the circumference of the defect. To create oval defects, 2 circular defects were first established and tangentially connected with an incision made with a #11 scalpel blade to create the defect edges parallel to the long axis (Figure 1). The oval defect was thus characterized by a major axis that was equal in length to 2 times the minor axis. The triangular defects had equilateral sides either small (4 mm, 0.08 cm²) or large (8 mm, 0.32 cm²) in length.
Overall, 26 circles, 22 ovals, and 24 triangles were created (Figure 2). Overall, 37 small and 35 large defects were created. Outside of the defects created, no other intra-articular or reconstructive procedure was performed on the knee, and no implants were placed. After the defect was created and prepared, the knee joint was closed in layers and ultrasound transmission gel (Chester Labs Liquid Sonic Gel; Medline Industries, Inc, Mundelein, Illinois) injected into the joint to minimize air artifact. The knees were then imaged immediately at room temperature with no warming pad around the ex vacuo knee specimen.

Porcine knees were imaged in a 3.0-T MR system (Philips, Andover, Maryland) using an 8-channel SENSE knee coil. Image sequences included 3-dimensional gradient echo water-selective/fluid (WATSf) (Figures 3-4). This sequence has been shown to be an accurate method for sizing and grading cartilage defects. Three-dimensional WATSf sequences were acquired in sagittal, coronal, and axial directions with the following parameters: TR/TE=20/5 ms (TR=repetition time; TE=echo time); flip angle=35°; pixel spacing=0.29×0.29 mm; slice thickness=1 mm; NSA=2. Field of view was 150 mm for all axial, coronal, and sagittal WATSf sequences. The smaller slice size in the porcine knee would translate to that of the slice thickness of the human knee.

All MR images were independently reviewed by 2 experienced (4 and 2 years’ experience) (G.J., S.C.) readers blinded to the lesion results. The cartilage lesions were manually delineated in sagittal WATSf images by loading to the Medical Image Processing, Analysis and Visualization (National Institutes of Health, Bethesda, Maryland) software package. First, both readers decided on the presence or absence of a defect. Interobserver reliability was calculated via Pearson product moment correlation coefficient. Sensitivity was defined as the ability of MRI to detect a surgically created defect (total number of defects observed via MRI [numerator]/total number of defects created [denominator]). Next, the readers decided on lesion shape (circle, oval, or triangle) and size (small or large). Positive predictive value was calculated based on true-positive decisions made by the readers (total number of true-positive readings [numerator]/total number of false- and true-positives [denominator]). Interobserver reliability was calculated via Pearson product moment correlation coefficient. All statistical analyses were performed using PASW Statistics Student version 18.0 (IBM, Armonk, New York).

RESULTS

Overall, a total of 72 lesions were created within the 12 knees (13 medial trochlea, 12 lateral trochlea, 12 medial patella, 11 lateral patella, 13 medial femoral condyle, and 11 lateral femoral condyle). Overall, the sensitivity of MRI to detect a full-thickness chondral defect was 85% (Figure 5). The highest sensitivity was observed at the medial femoral condyle (93%), while the lowest sensitivity was observed at the medial patella (71%). The sensitivities for detecting different shapes were unique to each shape (Figure 6A), with oval lesions identified with greatest sensitivity (93%). Small lesions were detected at a similar sensitivity as large lesions (Figure 6B). The positive predictive values for each reader for accurate true-positive reads were low for all lesion shapes and moderate for small and large sizes. Small positive correlation was observed between readers for the identification of the presence or absence of a defect on all regions of interest (Pearson r=0.283; P=.038), for the identification of defect shape (Pearson r=0.200; P=.147),

Figure 3: Coronal 3-dimensional water-selective/fluid (WATSf) image showing 2 circular lesions in the femoral trochlea (arrows) (A). The smaller lateral trochlea lesion was visible on the axial 3-dimensional WATSf image (arrow) (B).

Figure 4: Sagittal 3-dimensional water-selective/fluid image showing a circular lesion in the lateral femoral condyle (arrow) (A). The lateral femoral condyle (arrow) lesion was filled with ultrasound gel that gave higher signal intensity at an echo time of 120 ms (B).

Figure 5: Sensitivities and positive predictive values (PPV) for all lesions based on intra-articular location.

Figure 6: Sensitivities and positive predictive values (PPV) for shape (A) and size (B).
and for the identification of defect size (Pearson r = 0.152; P = .274).

**Discussion**

The purpose of this study was to determine the sensitivity and positive predictive value of MRI in the identification of full-thickness articular cartilage defects in the porcine knee. A secondary purpose was to investigate whether the size, shape, or intra-articular location would affect MRI sensitivity. The authors’ hypothesis that MRI is a highly sensitive modality in identifying the presence of a defect was confirmed. Further, their hypothesis that variability in shape and intra-articular location would significantly affect MRI sensitivity was confirmed. However, there was no apparent difference in MRI sensitivity based on defect size.

This study has demonstrated that 3.0-T MRI is a highly sensitive (85% overall; up to 93% on medial femoral condyle) imaging modality in detection of full-thickness chondral defects in the porcine knee. In addition, it has shown a high positive predictive value (94% overall) for true-positive identification of the presence of a defect. Given the high prevalence of chondral defects in knees undergoing arthroscopy (up to 63% for all lesions), early detection and characterization is of paramount importance in either delaying or preventing lesion progression to osteoarthritis. Further clinical relevance is illustrated in that following cartilage surgery in the knee (microfracture, osteochondral autograft, and autologous chondrocyte implantation), MRI findings correlate with clinical outcome, while the specific parameters that correlate best differ based on the specific procedure performed. This topic needs to be investigated further. Additionally, despite the use of a 3.0-T magnet in this study, other recent research has demonstrated that 3.0-T strength may not yet completely supplant the use of arthroscopy in the diagnosis of full-thickness chondral lesions. A level I evidence diagnostic in vivo study of 40 patients reported that the sensitivity, specificity, positive predictive value, and negative predictive value for identification of full-thickness defects using 3.0-T MRI were 74%, 95%, 74%, and 95%, respectively.

This study has exhibited site-specific differences in MRI sensitivity (the medial patellofemoral joint [both patella and trochlea] had the lowest sensitivities of all 6 analyzed regions of interest, while the lateral patellofemoral joint and the femoral condyles had higher MRI sensitivities). A combination of the complex intra-articular anatomy of the femoral condyles and patellofemoral joint and the plane of the MR images likely play a large role in the difference in MRI sensitivity. While the trochlea is often recognized as the “hidden half of the patellofemoral joint,” it is still thicker in depth (as is the patella) than both femoral condyles and one would assume a higher MRI sensitivity for the former vs the latter. This study used only full-thickness defects. The differences in radii of curvature for the patellofemoral joint and femoral condyles (integral in axial and sagittal plane series) must therefore play a larger role in MRI sensitivity. This difference may be over- or under-represented with partial-thickness lesions (not used in this study, but necessary in future research). Despite the complexities of the patellofemoral joint, MRI has been shown to be a highly sensitive, specific, and accurate imaging modality for the patella and trochlea using an arthroscopic gold standard. Given the constraints imposed by standard axial, sagittal, and coronal planes of MRI, perhaps oblique planar series may better represent the true differences in intra-articular location sensitivity. Further, although 3.0-T MRI was used in this study, newer advanced cartilage-sensitive quantitative MRI techniques may help clarify the true differences based on intra-articular location better.

This study has demonstrated that MRI has a high sensitivity for detecting large and small defects similarly well. It must be recognized, however, that preoperative MRI often significantly underestimates articular cartilage defect size compared with findings at arthroscopic knee surgery. The difference in positive predictive values (based on both lesion size and shape) between both radiologist readers illustrates the subjectivity in reading full-thickness defects. Further, even during knee arthroscopy, there is significant variability between orthopedic surgeons in measurement of full-thickness defects. Large defect sizes tend to be underestimated, while small defect sizes tend to be overestimated. Although femoral condyle defects are reliably and accurately sized between different surgeons, significant differences exist in accuracy for estimation of trochlear defect sizes.

This study has demonstrated that MRI has a high sensitivity for detection of circular and oval defects, but less so for triangular defects. The intra-articular geometry likely accounts for why the latter irregular-shaped lesions are less readily detected. This is clinically relevant in that the shape, location, and defect orientation all play a significant role in the biomechanics of both circular and oval defects in the knee. Therefore, the effect that these parameters have on surgical technique selection is uniquely dependent on the defect-specific geometry. Osteochondral autograft/mosaicplasty and osteochondral allograft techniques require a circular defect recipient site for graft transplantation. Thus, if osteochondral grafting techniques are chosen, oval and triangular defects are as large as the widest diameter, not the smallest, thus potentially greatly influencing selection of surgical technique and also size of graft taken. Oblique planar imaging may better illustrate these defect shapes. In comparing circular and oval defects, the differences in coronal and sagittal plane radii of curvature are well defined and would account for differences.
in normal cartilage-defect resolution, in which MRI volume-averaging would less likely resolve. This was evident in this study in the low positive predictive values for accurately assessing the lesion shape.

Limitations of this ex vacuo animal model imaging study include its use of a porcine model. Although this animal model has been used extensively in the cartilage imaging literature, its intra-articular anatomical geometry is different from that of the human knee. The MRI slice thickness in this porcine knee investigation was 1 mm. Porcine knees are smaller than human knees, which commonly use a 2- to 4-mm slice thickness. Therefore, the authors feel this is an acceptable scaled slice thickness. Despite suture closure of the arthotomy and injection of gel into the joint, air artifact was inevitably introduced, confounding reading of the MR images. Furthermore, 3-dimensional gradient echo WATSF has the potential limitation of susceptibility artifacts from metallic debris confounding the images. Although this was not seen in the images from creation of the cartilage defects, it is a potential limitation of the study and this MR technique in postoperative evaluation. Given the ex vacuo nature of the study, lesions created and visualized in this situation are different from those seen in vivo. Although the readers were aware that defects were intentionally created in the knees (bias), placement of defect location was unknown, thus minimizing potential bias. Further, the experience of the readers was dissimilar (4 vs 2 years’ experience), possibly accounting for the difference in Pearson correlation coefficients, sensitivity, and positive predictive values for each reader. Additionally, although defects were not created in all condyles, no specific control group of knees without a defect was used. This may allow for a comparison to assess any differences in false-positive readings. Additionally, only a limited number of defect sizes was used in this study. Further assessment of larger defect sizes is indicated in future research. Thus, extrapolation of the results of this study to other defect sizes is limited.

**CONCLUSION**

Magnetic resonance imaging has a high sensitivity in the detection of full-thickness articular cartilage defects in the porcine knee. Variability in defect shape and intra-articular location affects MRI sensitivity, while size does not. Magnetic resonance imaging was not effective in describing lesion shape or size. Further, there was subjectivity in reading defect shape and size of the lesions.

**REFERENCES**


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