Reliability of an efficient MRI-based method for estimation of knee cartilage volume using surface registration

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Summary

Objective: To aid in detection of osteoarthritis (OA) progression in serial magnetic resonance (MR) scans, we assessed feasibility and accuracy of rapid 3D image registration of the tibial plateau in normal and arthritic subjects, and inter-scan reliability of semi-automated cartilage volume measurement from these images.

Design: Two T1 fat-suppressed knee MR scans were obtained 2 weeks apart in healthy adults (n = 9, age 23–48 years). Four scans of each of three patients with established OA were obtained over 2 years. At baseline, the tibial surface was digitized by semi-automated edge detection and medial tibial plateau cartilage volume was calculated from high-intensity voxels within a manually drawn region of interest (ROI). In subsequent scans, the digitized tibial surface was registered to the baseline location by photogrammetric 3D coordinate transformation, and cartilage volume was automatically recalculated by reuse of the ROI. We measured registration accuracy by root mean square (RMS) distance between registered tibial surfaces.

Results: In normals, RMS distance between tibial surfaces in baseline and subsequent scans was 1/3 voxel length (0.121 mm), and medial tibial plateau cartilage volumes varied by 1.4 ± 3.2%. Despite change in cartilage volumes by up to 20% over 2 years in arthritic patients, surface registration accuracy was unaffected (0.122 mm). User-supervised processing time was 15 min at baseline and 7 min in subsequent scans.

Conclusion: Tibial surfaces on magnetic resonance imaging (MRI) can be rapidly and accurately co-registered, even in arthritic knees, allowing direct visualization of changes over time. Compared to most current methods, cartilage volume measurement in registered images is faster and has equivalent inter-scan reliability in initially normal subjects.

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Key words: Cartilage volume, Image registration, MRI, Osteoarthritis, Inter-scan reliability, Knee.

Introduction

To understand the natural history of osteoarthritis (OA) and to assess the efficacy of new treatments aimed at altering its progression, direct quantification of cartilage thickness and volume via magnetic resonance imaging (MRI) is preferable to indirect radiographic measures such as joint space narrowing. Although MRI-measured knee cartilage volumes have been used as outcome measures in recent trials assessing whether meniscal tears or focal cartilage defects affect OA progression, large-scale clinical application remains limited by tedious and labor-intensive techniques of volume measurement. We seek to develop a simplified approach which would reliably measure cartilage volume on MRI with a minimum of technologist training and radiologist time. The more complex the shape of a bone, the more difficult and time consuming it is to manually measure the overlying cartilage. However, a complex bone surface can also be valuable as a unique "fingerprint" feature with which we register successive scans to the same 3D coordinate system. If surface registration is sufficiently accurate and reliable, this can be used to overcome some of the logistical problems encountered in cartilage measurement and thereby improve its accuracy and feasibility in larger populations.

To clearly show cartilage distinct from neighboring bone, meniscus, ligament and joint fluid, most groups use T1-weighted fat-saturation gradient-echo MRI sequences with a scan time of 15–45 min. Volume measurement can take much longer than this. Tracing of the 3D boundary of a given region of cartilage ("segmentation") remains too complicated for automatic processing and requires supervised, semi-automated routines. Either the cartilage surface is drawn as a set of smooth B-spline curves joining user-defined control points, or a seed voxel is selected and the adjacent voxels forming the cartilage volume are selected by interactively defining the range of intensities to be included. These routines can require 45 min to several hours of supervision by a skilled operator with up to 3 months of intensive training. Improvements in speed are being made: a recent study used cardiac MRI
post-processing software to reduce measurement time to about 15 min per knee without significant reduction in accuracy. However, even this represents half an hour of radiologist or technologist time for every pair of knees scanned. Since the medial compartment often shows the most severe arthritic changes in the knee, and since tibial cartilage volumes measured by MRI correlate strongly ($r = 0.81$) with those in the femur, it may be reasonable to limit volume measurement to the medial tibial plateau.

Since most clinical applications involve tracking changes in cartilage volume over time, greater efficiency can be obtained through registration of a series of scans at different times to the same coordinate system as the original data set. If registration is sufficiently accurate, cartilage volume need not be tediously remeasured in each scan, but can be automatically recalculated (except in case of dramatic interval change). This procedure also allows direct visual assessment of changes in cartilage over time. Two sets of randomly distributed points such as from two different MR images can be efficiently matched by an algorithm based on photogrammetry and remote sensing. The algorithm simultaneously estimates rigid 3D similarity transformation parameters relating two surfaces and establishes correspondences between surface elements, using points for one surface and triangular patches for the other, via the Modified Iterated Hough Transform and the Iterative Closest Point algorithm. Unlike elastic registration, this technique does not require deforming the surfaces, minimizing sources of error by preserving irregularities in surface shape that may be clinically significant (e.g., cartilage defects). Surfaces such as the intercondylar eminence of the tibia, like fingerprints, are uniquely shaped and relatively unlikely to change in shape between scans. Accurate registration using these surfaces may be possible without the need for time-consuming manual digitization of all bone–cartilage interfaces in the knee as done by others.

Knee cartilage volume can be rapidly measured in serial scans in a two-step process: (1) image registration, where each subsequent scan is transformed to the same 3D location as the baseline scan via matching of bone surfaces, followed by (2) cartilage measurement, where the region containing cartilage (e.g., in the medial tibial plateau) is interactively defined in the baseline scan, with automated recalculation of the volume of cartilage in this region in each subsequent scan (Fig. 1). We performed a preliminary evaluation of the feasibility of this technique. We hypothesized (1) that surface registration using a uniquely shaped “fingerprint” portion of the central tibia would be faster than and equivalent in accuracy to digitization of the entire tibial plateau, (2) that the accuracy of surface registration would not be impaired in patients with advanced OA despite local changes in bone surfaces (e.g., osteophyte growth) between scans, and (3) that speed, inter-scan and inter-observer reliability of cartilage volume measurement using image registration would be at least comparable to reports by others in normal subjects.

Methods

PATIENT GROUP

Institutional ethics approval was obtained. After giving written informed consent, nine healthy subjects (five male), aged 23–48 years (mean ± standard deviation (SD) 37 ± 8 years), with no symptoms or signs of knee...
OA, had scans of one knee (five left, four right) performed twice on different days within an interval of up to 2 weeks. In addition, data from scans of three patients (aged 59, 65 and 71 years at first scan) with established knee OA, collected as part of a clinical trial of experimental OA therapy, were obtained for analysis. These patients had four scans of the same knee performed in 6-month intervals over a 2-year period. Investigators were blinded as to whether OA patients were in the treatment or control group in that study.

**IMAGING**

Sagittal T1-weighted 3D spoiled gradient-echo fat-saturated MRI (repetition time TR = 42 ms, echo time TE = 10 ms, flip angle = 20°) was performed in a 1.5 T scanner (Symphony, Siemens AG, Munich). Voxel size was 0.31 × 0.31 × 1.0 mm (0.096 mm³), with a 512 × 512 voxel field of view and ~100–140 sagittal slices. Knees were imaged in extension, with careful attention to obtain true sagittal orientation. Scan time in normals was 25–35 min.

**IMAGE REGISTRATION TO COMMON 3D COORDINATES**

In each scan, points on the proximal tibial surface were digitized, at first manually, using commercial software [SliceOmatic, TomoVision, Canada; Fig. 2(a)]. The operator selected the fewest possible points (e.g., one point per 3–10 voxels) to produce a visually appropriate tracing of the surface contour, with more points in regions of complex curvature than in relatively flat areas. Fortunately, high contrast between the tibia and overlying cartilage allowed faster semi-automatic definition of this surface using the edge-detection method of Canny 26 in Matlab (The Mathworks Inc., Natick, MA, v. 6), for each sagittal slice through the medial tibial plateau in the baseline scan following image registration, which in practice was primarily translational (3D rotations were generally under 5°). We found no visible difference in the resulting image whether we calculated intensity of each voxel in the transformed coordinate system from a weighted average of the 3 × 3 neighborhood of voxels that mapped to that location or simply adopted the intensity of the closest-mapping voxel (a quicker calculation). Either method was mathematically suitable for our nonuniform voxels (0.3 × 0.3 × 1.0 mm). An average normal distance (root mean square, RMS) between the registered surfaces was derived to assess the quality of fit of these surfaces.

**CARTILAGE SELECTION AND VOLUME CALCULATION**

Using a custom supervised algorithm written in Matlab (The Mathworks Inc., Natick, MA, v. 6), for each sagittal slice through the medial tibial plateau in the baseline scan of each patient [Fig. 3(a)], a region of interest (ROI) was drawn to enclose the visible cartilage [Fig. 3(c)]. The ROI was drawn loosely as a simple box around the cartilage (except at the junction of tibial and femoral cartilage), since adjacent bone and soft tissues were automatically rejected by subsequent image thresholding. The same ROIs were reused in subsequent scans, as they were in the same coordinate system as the baseline scan following image registration. Image data were smoothed by a 3-pixel median filter to reduce noise, and high-intensity cartilage pixels were emphasized by use of nonlinear windowing (gamma = 1.7, selected by visual optimization across a broad range of data). This pre-processing enhanced contrast between cartilage and adjacent structures without visually altering cartilage contours [Fig. 3(a and b)]. In our data, image intensity was visually nearly equivalent between first and second scans of normal patients, which were obtained within a 2-week interval. To adjust for wider variation in image intensity in scans of OA patients, which were obtained

![Fig. 2. Image registration.](image-url)
over a 2-year period, histogram equalization was applied to match overall intensity of each scan to that of the corresponding baseline scan.

Following pre-processing, an optimal threshold was then automatically calculated using Otsu’s method to minimize intraclass variation among bright and dark voxels within each ROI. This automated threshold was not necessarily optimal to distinguish cartilage from other tissues when calculated from a full data slice due to multiple tissue intensities present (e.g., muscle, ligament, and subcutaneous fat). However, when applied to the limited ROI containing primarily cartilage and bone, Otsu’s method automatically produced a visually appropriate selection of cartilage voxels without the need for manual correction in the tested data sets. For each sagittal slice, cartilage volume was calculated from the sum of the high-intensity cartilage voxels captured within the ROI [Fig. 3(d)] in the baseline scan and in the same region in each registered subsequent scan. The procedures for image registration and cartilage volume calculation are outlined in a flow chart (Fig. 1).

**DATA ANALYSIS**

Descriptive statistics were calculated in terms of mean and SD. For each pair of scans of each subject (two scans in each of nine normals and four scans in each of three OA patients), the quality of the surface registration was assessed using the RMS distance between the matched portions of the registered tibial surfaces. For three pairs of scans (two normals, one OA), we assessed the change in RMS distance between surfaces when registration was performed after digitizing only the small central intercondylar eminence compared to more laborious digitization of the entire tibial plateau. In the same three pairs of scans we also tested the effect on RMS inter-surface distance and resulting cartilage volumes from use of rapid semi-automated Canny edge detection in comparison to slower manual digitization of the tibial surface.

Cartilage volumes obtained for each scan of each patient were compared by computing the mean and SD of differences in volume as well as the associated coefficient of variation (CV = SD/mean).
To assess intra- and inter-observer reliability of cartilage segmentation with minimal user training, following a 1-h training session given by an experienced observer (a radiology resident) to a novice observer (an orthopedic surgery resident), the two observers each segmented the cartilage in the first scan of each normal patient twice. Observers proceeded patient-wise through the data twice (patient N1, N2, ..., N9, then N1, N2, ..., N9) rather than immediately repeating segmentation of the same scan (N1, N1, then N2, N2, ...). Coefficients of variation of the resulting cartilage volume measurements were computed.

**Results**

**REGISTRATION**

Three-dimensional registration of subsequent scans to the initial scan was visually successful in both normal and OA patients [Fig. 2(c)]. The RMS distance between tibial plateau surfaces following registration was $0.121 \pm 0.003$ mm (mean $\pm$ SD) in the nine normal patients, with a CV of 2.6% (Table I). In the three OA patients, despite the presence of large osteophytes at the medial and lateral margins of the tibia (particularly in patients OA2 and OA3), there was little visible change in the tibial interspinous area during the 2-year period, and the quality of fit of the interspinous surfaces after registration remained nearly identical to that in normal subjects ($0.122 \pm 0.004$ mm, CV $= 3.2\%$, Table II).

In patients N2, N5 and OA2, registration of just the interspinous region rather than the entire tibial plateau resulted in a 3.5% ($0.005$ mm) increase in mean RMS inter-surface distance (from 0.122 to 0.127 mm).

In the same patients, use of the semi-automated Canny edge-detection algorithm rather than manual surface point selection (Table III) reduced user-supervised processing time from approximately 20 to 7 min per tibia. RMS inter-surface distances were similar between the two methods (average difference $= 0.06$ mm), and this small change led to similarly small changes in the resulting measured cartilage volumes ($10$–$70$ mm$^3$ for overall volumes of 1298–2068 mm$^3$, Table III).

**CARTILAGE VOLUMES**

Cartilage volumes were visually similar between scans of normal subjects obtained within a 2-week interval (Fig. 4), with inter-scan variation of $1.4 \pm 3.2\%$ (i.e., CV $= 3.2\%$; Table I). In OA patients scanned over 2 years, cartilage was substantially narrowed and measured cartilage volumes showed more variation (Fig. 5). Cartilage volumes for patient OA1 fluctuated by approximately $\pm 5\%$, while volumes for patient OA2 were approximately 20% less than at initial scan after 2 years, and those in patient OA3 stabilized after an initial apparent rise in volume of nearly 20%. This apparent initial increase in cartilage volume in patient OA3 between the first and subsequent scans may have been partly due to low cartilage signal intensity along the bone–cartilage interface in the first scan. Capture of femoral cartilage above the very thin layer of tibial cartilage within the original selected region in subsequent scans was also possible. Both of these problems were also present to lesser degrees in patient OA2.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age (years)</th>
<th>Scan #</th>
<th>Date</th>
<th>Reg. error vs. 1st scan* (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OA1</td>
<td>65</td>
<td>1</td>
<td>Jul-2002</td>
<td>0.127</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Mar-2003</td>
<td>0.125</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Aug-2003</td>
<td>0.117</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>Jul-2004</td>
<td>0.125</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
<td>0.123</td>
</tr>
</tbody>
</table>

| OA2     | 71          | 1      | Jul-2002 | 0.125                         |
|         |             | 2      | Mar-2003 | 0.125                         |
|         |             | 3      | Aug-2003 | 0.125                         |
|         |             | 4      | Jul-2004 | 0.117                         |
| Mean    |             |        |          | 0.123                         |

| OA3     | 59          | 1      | Jul-2002 | 0.123                         |
|         |             | 2      | Mar-2003 | 0.123                         |
|         |             | 3      | Aug-2003 | 0.119                         |
|         |             | 4      | Jul-2004 | 0.119                         |
| Mean    |             |        |          | 0.120                         |

Overall mean 0.122
CV 3.2%

*Mean normal distance between matched tibial surfaces in scan # 1 and the given scan.

### Table I

**Accuracy of tibial surface registration and variation of medial tibial plateau cartilage volumes in normal subjects scanned twice in 2 weeks**

<table>
<thead>
<tr>
<th>Patient</th>
<th>Sex</th>
<th>Age (years)</th>
<th>Knee</th>
<th>Registration error (mm)*</th>
<th>Volumes (mm$^3$)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>Male</td>
<td>48</td>
<td>Left</td>
<td>0.120</td>
<td>3297</td>
<td>3479</td>
</tr>
<tr>
<td>N2</td>
<td>Female</td>
<td>42</td>
<td>Right</td>
<td>0.120</td>
<td>1920</td>
<td>1967</td>
</tr>
<tr>
<td>N3</td>
<td>Male</td>
<td>41</td>
<td>Left</td>
<td>0.120</td>
<td>2187</td>
<td>2117</td>
</tr>
<tr>
<td>N4</td>
<td>Male</td>
<td>41</td>
<td>Right</td>
<td>0.122</td>
<td>2038</td>
<td>2062</td>
</tr>
<tr>
<td>N5</td>
<td>Male</td>
<td>39</td>
<td>Right</td>
<td>0.125</td>
<td>2068</td>
<td>2085</td>
</tr>
<tr>
<td>N6</td>
<td>Male</td>
<td>34</td>
<td>Right</td>
<td>0.120</td>
<td>2453</td>
<td>2393</td>
</tr>
<tr>
<td>N7</td>
<td>Female</td>
<td>33</td>
<td>Right</td>
<td>0.117</td>
<td>1736</td>
<td>1836</td>
</tr>
<tr>
<td>N8</td>
<td>Female</td>
<td>28</td>
<td>Right</td>
<td>0.124</td>
<td>1124</td>
<td>1166</td>
</tr>
<tr>
<td>N9</td>
<td>Female</td>
<td>23</td>
<td>Left</td>
<td>0.117</td>
<td>1896</td>
<td>1881</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
<td>0.121</td>
<td>Mean</td>
<td>2095</td>
</tr>
</tbody>
</table>

CV 2.6%
SD 3.2

*Registration error = mean normal distance between matched tibial surfaces in scan 1 and scan 2.
When we assessed repeatability of same-scan cartilage volume selections, i.e., when the same observer selected cartilage volumes in the first scan of each normal patient \((n = 9)\) twice, the measured volumes varied within a similar range as the inter-scan error (CV for observer \#1 = 2.0\%, observer \#2 = 6.7\%). The inter-observer variability, i.e., the difference between the initial estimates of cartilage volume made by each observer, was higher (mean difference = 10.7\%, CV = 11.9\%).

**Discussion**

Registration of the tibial surface in subsequent scans to a baseline scan was highly successful both visually and quantitatively (error \(\sim 0.13\) mm, or about one-third of the width of one voxel). Limiting digitization to the central portion of the tibia and use of a semi-automated edge-detection technique reduced supervised processing time by 2/3 and on only minimally increased error of surface fit (by 0.01 mm on average). Even in patients with established OA including only minimally increased error of surface fit (by 0.01 mm on average). Even in patients with established OA including only minimally increased error of surface fit (by 0.01 mm on average).

The method of MRI cartilage volume measurement based on tibial surface registration presented here was much faster than the 45–90 min\(^1\)\(^7\)\(^9\) or several hours\(^8\) per scan that others have reported, and was similar in speed to the 15 min per knee achieved by one method using nonregistered data\(^6\). In practice, on the baseline scan a trained user spent about 8 min loosely identifying the ROI containing cartilage on the medial tibial plateau (a simpler task than closely tracing the cartilage surface as some other methods have required). On each subsequent scan, the user took about 7 min to supervise definition of the tibial surface at the intercondylar eminence. Cartilage volume calculation then proceeded automatically without the need to redraw the ROI, although the user could manually correct visually inappropriate cartilage volume selection in a given slice. Quoted times were for custom algorithms running on standard 1.0–1.8 GHz IBM-compatible personal computers. In a clinical setting, processing time would certainly be faster on a MRI workstation, and since detection of the high-contrast tibial surface is a relatively simple task, this could either be fully automated or left to a technician with minimal training.

Although the interplay between registration quality and the resulting estimate of cartilage volume is complex and will require further study, we found that small changes in image registration due to different edge-detection technique (0.1 mm change in RMS distance) led to similarly small changes in measured cartilage volumes in normals (10–30 mm\(^3\) or <2\% of original volume). The effect of slight misregistration was greater when the cartilage plate was thin: a 0.05 mm (3\%) change in RMS inter-surface distance in an OA patient led to a 70 mm\(^3\) (5\%) change in measured tibial cartilage volume. Partial volume effects related to voxel size and to recalculation of voxel locations, particularly in the mediolateral direction where our nonuniform voxels were 1 mm thick compared to 0.3 mm in-plane, likely explain at least part of the increased error in OA patients, whose thin cartilage plates have a relatively high proportion of edge voxels. It is likely that partial voluming effects would be somewhat greater in the curved femoral condyles than in the essentially flat tibial plateaux studied here. We plan to investigate this in future.

Variation in cartilage volumes in this study, both between two scans of each normal patient on different days (inter-scan CV = 3.2\%) and between repeat analyses of the same scan (intra-scan CV = 2.0\% for an experienced observer and 6.7\% for a novice), was similar to that of other more laborious techniques. Published coefficients of variation in MRI-based knee cartilage volume measurement

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**Table III**

<table>
<thead>
<tr>
<th>Patient</th>
<th>RMS distance between tibial surfaces (mm)</th>
<th>Initial cartilage volume (\text{mm}^3)</th>
<th>Change in tibial cartilage volumes between scans (\text{mm}^3,%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2 (scans 1–2)</td>
<td>0.120 0.110</td>
<td>1920</td>
<td>22.2 (–1.1)</td>
</tr>
<tr>
<td>N5 (scans 1–2)</td>
<td>0.125 0.111</td>
<td>2068</td>
<td>17.8 (–0.9)</td>
</tr>
<tr>
<td>OA2 (scans 2–4)</td>
<td>0.129 0.125</td>
<td>1928</td>
<td>−53.7 (–4.1)</td>
</tr>
</tbody>
</table>

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Fig. 4. Change in cartilage volume between two scans of a normal subject (N5). (a) Summed cartilage regions, white = present in both scans, gray = present in only one scan. (b) Difference in cartilage regions, white = cartilage present in first scan but absent in second. The two cartilage regions are almost identical.
were on the order of 3%, ranging from 1.6 to 9% (higher for difficult regions such as curved ends of femoral cartilage)\textsuperscript{18,13,16,17,21}. MRI-based cartilage volumes have been reported to vary from true cartilage volumes measured by water displacement in surgical specimens by up to 9.1\%\textsuperscript{6}. For comparison with these ranges of error, although one small early study found no change in cartilage volume over 3 years\textsuperscript{11,}, more recent studies using quantitative small early study found no change in cartilage volume for comparison with these ranges of error, although one.

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The limiting factor in reliability of cartilage volume measurement in our study was not 3D image registration, which was highly robust, but the user-dependent process of selecting the cartilage-containing region. Subjective differences in interpretation of knee cartilage margins will remain even after user training. Koo et al. found that in measurement of knee cartilage volumes by four observers who had each trained on between 3 and 30 data sets, inter-observer error (CV = 6.6–8.3\%) was substantially higher than intra-observer error (CV = 1–3\%)\textsuperscript{18}. When we trained a novice observer with a minimal 1-h practice session, far less than the 3 months of intensive training given by others\textsuperscript{19}, we noted somewhat higher inter-observer error in measured cartilage volume compared to an experienced user (CV = 11.9\%). Although user training is required to reliably distinguish tibial cartilage from intimately associated structures such as insertions of cruciate ligaments and menisci, this result suggests that the training time to reduce error to acceptable levels is likely not long, perhaps on the order of 1 or 2 days.

Changes in cartilage volume over the 2-year study period in three subjects with OA were dramatic, with a 20% decrease in one patient and a 20% increase in another. Some variation was likely due to technical challenges in measuring the volume of a thin and irregular cartilage plate. However, these patients were enrolled in a trial of experimental therapy, and since the authors were blinded as to whether the patient was receiving treatment, observed changes may have been due to actual variation in cartilage volume resulting from either OA or its treatment. The most significant finding in the OA patients was that despite established joint degeneration and widely varying cartilage volume, image registration using tibial surfaces remained consistently accurate and essentially unchanged from that in normals over 2 years. It may be that even if parts of the bone surfaces change over time, as when an osteophyte grows at a tibial spine, the overall surface contours retain a sufficiently consistent “fingerprint” shape to enable accurate image registration within the time-frame of a few years. Change in overall bone morphology is more likely in situations of severe cartilage loss and these techniques are more likely to be applied in clinical trials that exclude subjects with end-stage disease.

We plan further refinement of our technique, including further increases in speed via improved edge-detection methods and automated adaptation of a single ROI from slice to slice (following\textsuperscript{30}). A cadaveric validation study is underway to determine registration accuracy by comparing results obtained by our technique to a gold standard established using fiducial markers. We are also comparing MRI cartilage volume measurements by our technique to actual measured cartilage volume in animals. We intend to move to larger clinical trials, including study of the minimum level of user training and maximal extent of joint degeneration that can be present while still maintaining acceptable reliability of surface registration and cartilage volume estimation.

**Conclusion**

We evaluated a streamlined approach to MRI-based knee cartilage volume measurement in serial scans via 3D image registration and reuse of a ROI drawn around cartilage on the baseline scan. Reliability was similar to other more laborious techniques. We found that (1) accuracy of surface registration was only minimally reduced by digitization of a small, uniquely shaped portion of the bone surface rather than the entire bone, (2) the quality of surface registration using the tibial plateau was not degraded even over 2 years in patients with advanced OA, and (3) cartilage volume measurement using this image registration approach was faster than, and had similar inter- and intra-observer variability to, several available techniques. Although others have described registration of serial knee cartilage scans\textsuperscript{19} or developed rapid cartilage segmentation techniques\textsuperscript{20}, no rapid technique using image registration (with its added benefit of easy visualization of changes over time) to aid in cartilage volume measurement has yet been described.

The ability to rapidly and accurately register multiple scans of the knee to one another based on highly consistent bone surface contours opens new possibilities, including
estimation of cartilage volume within a reproducible core of weight-bearing cartilage centrally within the joint, or fusion of multiple scans using different protocols within the same patient visit. This small pilot study showed that rapid cartilage volume estimation in serial follow-up scans based on image registration was highly reliable in initially normal subjects. Since many patients in clinical trials of treatment or prevention of OA have initially normal or mildly arthritic knees, cartilage volume measurement by methods such as those described here may be broadly applicable, offering substantial reductions in the time and effort required to accurately monitor the natural history and response to treatment of this frustratingly common and debilitating condition.

References


