Validation of high-resolution water-excitation magnetic resonance imaging for quantitative assessment of thin cartilage layers

H. Graichen*, V. Springer*, T. Flaman*, T. Stammberger†, C. Glaser‡, K-H. Englmeier†, M. Reiser‡ and F. Eckstein*

*Musculoskeletal Research Group, Institute of Anatomy, Ludwig-Maximilians-University Munich, Pettenkoferstr. 11, D 80336 Munich, Germany
†Institute for Medical Informatics, GSF, Neuherberg, Ingolstädter Landstr. 1, D 85764 Oberschleißheim, Germany
‡Institute for Radiologic Diagnostics, Klinikum Großhadern, Marchioninistr. 15, D 81377 Munich, Germany

Summary

Objective: To employ a magnetic resonance (MR) imaging technique for quantitative assessment of thin cartilage layers, and to validate the cartilage volume and thickness measurements.

Methods: We investigated 10 normal elbow joints (age 20 to 69 years) with a 3D gradient echo sequence with selective water excitation (TR 18 ms; TE 9 ms; FA 25°, resolution 1×0.25×0.25 mm², imaging time 19 min). After interpolating the image data to a 0.125×0.125 mm² in-plane resolution, the cartilage plates were segmented, reconstructed in 3D, and the cartilage volume and thickness determined with a 3D Euclidean distance transformation algorithm, independent of the original section plane. The cartilage volume and thickness values were compared with CT arthrography and A-mode ultrasound.

Results: The mean systematic difference between the elbow cartilage volume obtained from MR imaging and CT arthrography was −0.11% (−6.0 mm³) and the mean random difference 5.7% (314 mm³). Except for the fovea capitis radii, the deviations were not statistically significant (range −7.6 to +11.7%). In the humerus, the mean cartilage thickness (average=1.35 mm) was overestimated relative to CT arthrography (+20.7%/+0.23 mm), and slightly underestimated relative to A-mode ultrasound (−6.0%/−0.05 mm). With few exceptions, there were no significant differences between MRI, CT arthrography and ultrasound in the other joint surfaces of the elbow (random deviations between 0.08 and 0.39 mm).

Conclusions: The technique presented can be applied for determining the cartilage volume and 3D thickness in joints with thin cartilage layers with a reasonable degree of accuracy. © 2000 OsteoArthritis Research Society International

Key words: Cartilage, Magnetic resonance imaging, Cartilage thickness, Elbow.

Introduction

Primary and secondary degenerative joint diseases have a considerable economic and social impact, involving costs of currently $65 billion per year in the United States. The technical diagnosis usually relies on conventional radiography, in which the cartilage, however, cannot be visualized directly, and changes in cartilage thickness cannot be measured with high precision. Being a projectional technique, this method is also not capable of assessing the regional distribution of the cartilage throughout the various joint surfaces of synovial joints.

Magnetic resonance (MR) imaging, on the other hand, is a multiplanar technique that is capable of visualizing the cartilage with high contrast in serial, contiguous images, if adequate imaging protocols are employed. Using three-dimensional postprocessing techniques, it has been shown that the volume and the regional thickness distribution of the cartilage can be determined with a high degree of accuracy and reproducibility. With some exceptions, most of the other joints of the human body, however, exhibit a mean cartilage thickness of 1–2 mm or less imposing particular requirements with regard to the spatial resolution necessary for quantitative cartilage measurements. Whereas with radiographic techniques the X-ray dose can be increased for this purpose, MR imaging requires 64 times longer imaging times, if the resolution is to be doubled in all three dimensions and the signal-to-noise ratios in the images are to be kept constant. Most previous studies have employed T1-weighted gradient echo sequences (usually spoiled GRASS or FLASH) with spectral fat-suppression for quantitative cartilage measurements, the technique involving a prepulse that saturates the fat-bound protons in the bone marrow. This procedure increases the dynamic range of the T1-weighted...
images (contrast between cartilage and surrounding tissue) and eliminates chemical shift artifacts at the bone cartilage interface. However, the prepulse prohibits the repetition time to be lowered beyond a critical value, thus setting a lower limit to the imaging time (or the spatial resolution to be obtained with a certain imaging time). In order to successfully measure thin cartilage layers, for instance those of the elbow, a section thickness of 1 mm and an in-plane resolution of less than 0.15 mm should be achieved.

The objective of the current study was therefore (1) to employ a gradient echo imaging protocol with selective water excitation and strong T1-weighting (short repetition and echo times) to delineate the articular cartilage of the elbow at high spatial resolution and acceptable imaging times (less than 20 min), (2) to use an interpolation technique to arrive at a nominal in-plane resolution of 0.125 mm for quantitative assessment of thin cartilage layers, and (3) to validate the cartilage volume and thickness measurements in human elbow specimens in comparison with high-resolution CT arthrography and A-mode ultrasound.

**Material and methods**

**MR imaging**

Ten cadaver elbow specimens from nine individuals aged 21 to 69 years (mean age 44.8 years; seven male and two female; four right and six left joints) without signs of musculoskeletal disease were obtained within 48 hours of death, stored at −20°C, and thawed to room temperature before each examination. A 1.5 Tesla MR scanner (Magnetom Vision, Siemens, Erlangen, Germany) was used and a circularly polarized transmit receive extremity coil, in the center of which the elbow specimens were positioned at 30° flexion. Sagittal MR images (Fig. 1) were obtained, employing an experimental, fast 3D gradient echo sequence (FLASH=fast low angle shot) with selective water excitation (TR=18 ms; TE=9 ms; FA=25°). The selective excitation of the non-fat-bound protons was achieved with radio frequency excitation pulses that fit from the chemical shift between fat-bound and no-fat-bound protons, the amplitude ratios being 1-2-1, the phase angles 0, 90, and 180°, respectively, and the time interval between consecutive pulses 1.13 ms. The section thickness was 1 mm and the in-plane resolution (before interpolation) 0.25×0.25 mm² (field of view=128 mm; matrix 512² pixels). The total imaging time (two acquisitions) amounted to 19 min.

**Digital postprocessing**

The MR image data were digitally transferred to a multiprocessing computer with a high performance graphic system (Octane Duo, Silicon Graphics, Moutain View, CA) and linearly interpolated to a nominal in-plane resolution of 0.125×0.125 mm². The humeral, ulnar and radial cartilages were then segmented interactively on a section-by-section basis by one observer, using a B-spline Snake algorithm. This contour detection method is based on a combination of model forces (the initial contour) and image forces (gray value gradients), and has been demonstrated to provide a higher precision of cartilage thickness measurements than manual segmentation. The segmented objects were then interpolated to isotropic voxels (0.125 mm³) and reconstructed three-dimensionally (Fig. 2). The cartilage volume of each plate (humerus, radius and ulna) was then determined from these reconstructions, the dorsal (olecranon) and ventral aspect (coronoid process) of the trochlear notch being considered separately in cases of a divided articular surface of the proximal ulna. The mean and the maximal cartilage thickness were determined from the 3D reconstructions, independent of the original section plane, using a 3D Euclidean distance transformation algorithm. The regional cartilage thickness distribution throughout the joint surfaces was finally visualized by mapping color coded thickness intervals of 0.45 mm on to the 3D reconstructed articular surfaces (Fig. 3).
VALIDATION

After MR imaging, the elbow joints were separated into their proximal (humerus) and distal components (ulna and radius) and the soft tissues removed. All joints were inspected macroscopically to exclude cartilage lesions. Both parts of the joint were then placed in a small container filled with an X-ray contrast agent (Ultravist 300; Schering AG, Berlin, Germany, dilution 1:5) and sagittal images obtained in the extremity mode (120 kV/150 mAs) at a resolution of $1 \times 0.25 \times 0.25 \text{ mm}^3$ with a Somatom Plus 4 (Siemens, Erlangen, Germany) computed tomography (CT) scanner (Fig. 4). These images were interpolated and treated identical to the MR images, in order to obtain cartilage volume and 3D thickness estimates.

Eventually, a regular grid of measuring points was marked throughout the joint surfaces (46 points in the humerus, nine in the fovea capitis radii, 12 in the dorsal aspect, and eight in the ventral aspect of the proximal ulna). The joint components were then placed in Ringer solution and the cartilage thickness measured perpendicular to the joint surface, using an A-mode ultrasound system with a 12.5 MHz transducer (Digital Biometric Ruler, DBR 300, Digital Biometric Systems, Taberna pro Medicum, Lüneburg, Germany). The thickness was calculated by the difference between the ultrasound signal being reflected at the articular surface and that at the bone cartilage interface, the ultrasound velocity being set to 1780 m/s.

To compare the MRI with the CT arthrography and ultrasound data, we calculated the absolute and percentage systematic deviation (pairwise differences without eliminating the $+/-$ signs) and the absolute and percentage
random deviation (pairwise differences with elimination of the +/− signs). A potential systematic deviation was evaluated for statistical significance, using the Wilcoxon signed-rank test.

Results

The total volume of the elbow joint cartilages was 5266 (±1039) mm³ when determined with MR imaging and 5272 (±709) mm³ with CT arthrography (Table I). The mean systematic difference was −0.11% (−6.0 mm³), no statistical significance, the mean random difference 5.7% (314 mm³), and the correlation coefficient 0.93 (Fig. 5). The cartilage volume of the humerus amounted to 2960 (±456 mm³) with MR imaging, that of the radial head to 1016 (±513 mm³), and that of the ulna to 803 (±70 mm³) in the dorsal and to 609 (±121 mm³) in the ventral aspect). The systematic deviation from CT arthrography ranged from −7.6 to +11.7%, with a statistically significant difference (P<0.05) in the fovea capitis radii, but not in the other joint surfaces. The mean random error was between 6.7 and 12.6% (Table I).

The mean cartilage thickness in the elbow joint surfaces (as computed from the MR image data) ranged from 0.99 mm in the ventral ulna to 1.35 mm in the humerus (Table II, Fig. 6). The thickness was significantly overestimated relative to CT arthrography in the humerus (+20.7%; +0.23 mm), but there was no significant systematic deviation in the other joint surfaces (Table II, Fig. 6). The random deviation ranged from 6.7% (0.08 mm—dorsal ulna) to 21.7% (0.24 mm—humerus) (Table II). Relative to A-mode ultrasound, the mean cartilage thickness was slightly underestimated with MR imaging in the humerus (−5.9%; −0.05 mm), significantly underestimated in the dorsal and ventral aspect of the ulna (−23.7% = −0.29 mm, and −14.0% = −0.18 mm), respectively, but somewhat overestimated (+14.9%; +0.13 mm) in the fovea capitis radii (Table III, Fig. 6). The random deviation ranged from 6.2% (0.06 mm—humerus) to 23.7% (0.29 mm—dorsal ulna) (Table III).

The maximal cartilage thickness (MR imaging) ranged from 2.3 mm in the ventral ulna to 2.9 mm in the dorsal ulna (Table IV). In comparison with CT arthrography, the thickness was significantly overestimated in the humerus (+14.7%; +0.35 mm), in the radial head (+11.8%; +0.26 mm), in the dorsal ulna (+11.8%; +0.30 mm), and slightly overestimated in the ventral aspect of the ulna (+4.7%; +0.09 mm) (Table IV). The random deviation ranged from 11.8% (0.26 mm—radius) to 14.7% (0.35 mm—humerus) (Table IV).

Discussion

The objective of this study was to employ and validate an MR imaging protocol for quantitative assessment of thin cartilage layers with high spatial resolution and clinically acceptable imaging times. We find an acceptable agreement between the cartilage volume and thickness data obtained with a gradient echo sequence with selective water excitation (involving 3D Euclidean distance transformation), and those determined with CT arthrography and A-mode ultrasound. The humeral cartilage thickness was significantly overestimated relative to CT arthrography, but slightly underestimated relative to A-mode ultrasound. Apart from the ulna (MR imaging vs. A-mode ultrasound), there were no significant systematic deviations of the mean cartilage thickness in the elbow joint surfaces, and, apart from the fovea capitis radii, no significant systematic errors for analyses of the cartilage volume.

In order to be able to image thin cartilage layers with a high spatial resolution at acceptable imaging times, we have employed a gradient echo sequence (FLASH) with selective water excitation. Due to the low repetition time (TR=18 ms) and echo time (TE=9 ms), a high T1-weighting could be achieved. In this way, the cartilage could be visualized with homogeneous signal intensity (no signal loss in deeper cartilage layers with higher T2 times), with high contrast, with high spatial resolution (1 × 0.25 × 0.25 mm³), and with an imaging time of less than 20 min for the entire elbow joint. Due to fat-suppression
Because the resolution of $1 \times 0.25 \times 0.25 \text{mm}^3$ is still insufficient for adequate characterization of cartilage layers with a mean thickness of 1 mm, we have employed linear interpolation to arrive at a nominal resolution of $1 \times 0.125 \times 0.125 \text{mm}^3$. Although this is not identical to directly acquiring images at this resolution, it does allow one to exploit the sub-pixel resolution inherent in digital images, without extending the acquisition time. It should, however, be mentioned that this technique is still insensitive to focal defects beneath the threshold of the acquisition resolution, and it may therefore bias the measurements toward uniform cartilage thinning versus heterogeneous, focal loss, when monitoring disease progression in osteoarthritis. Further limitations of the study include that the joints were frozen prior to imaging, that the precision (reproducibility) of the technique has not yet been demonstrated in an in-vivo setting, that the elbow is not a common site of degenerative cartilage changes, and that the method’s sensitivity to change could not be assessed in this cadaver study.

Both CT arthrography and A-mode ultrasound are established techniques for measuring cartilage thickness\textsuperscript{9,25–28,38} and are therefore suitable for validating MR-based cartilage thickness measurements. These techniques delineate the thickness of the uncalcified cartilage, the physical basis of CT arthrography being the different X-ray attenuations by the subchondral bone (including the calcified cartilage layer), the uncalcified cartilage, and the contrast agent at the articular surface. For A-mode ultrasound it has been verified in direct comparison with optical techniques that the method determines the difference between the signal reflected at the articular surface and at the tidemark (border between the calcified and uncalcified cartilage).\textsuperscript{26,27} When comparing the MR with the CT and ultrasound data, it should be kept in mind that with MRI and CT arthrography the mean cartilage thickness was computed at 6400 points per square centimeter of the articular

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### Table I

<table>
<thead>
<tr>
<th></th>
<th>MRI</th>
<th>CTA</th>
<th>Systematic deviation</th>
<th>Random deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elbow (total)</td>
<td>5266</td>
<td>5272</td>
<td>−0.1 (% –6.0)</td>
<td>5.7 (314)</td>
</tr>
<tr>
<td>Humerus</td>
<td>2960</td>
<td>3015</td>
<td>−1.9 (% –56)</td>
<td>6.7 (211)</td>
</tr>
<tr>
<td>Radius</td>
<td>1016</td>
<td>911</td>
<td>+11.7 (% +106*)</td>
<td>11.8 (107)</td>
</tr>
<tr>
<td>Ulna dorsal</td>
<td>803</td>
<td>855</td>
<td>−7.6 (% –52)</td>
<td>12.6 (106)</td>
</tr>
<tr>
<td>Ulna ventral</td>
<td>609</td>
<td>614</td>
<td>−0.7 (% –5.0)</td>
<td>12.2 (74)</td>
</tr>
</tbody>
</table>

*Systematic deviations were not statistically significant at 5% level.

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### Table II

<table>
<thead>
<tr>
<th></th>
<th>MRI</th>
<th>CTA</th>
<th>Systematic deviation</th>
<th>Random deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humerus</td>
<td>1.35</td>
<td>1.12</td>
<td>+20.7* (+0.23*)</td>
<td>21.7 (0.24)</td>
</tr>
<tr>
<td>Radius</td>
<td>1.20</td>
<td>1.20</td>
<td>+2.1 (+0.01)</td>
<td>10.4 (0.12)</td>
</tr>
<tr>
<td>Ulna dorsal</td>
<td>1.23</td>
<td>1.21</td>
<td>+1.3 (+0.02)</td>
<td>6.7 (0.08)</td>
</tr>
<tr>
<td>Ulna ventral</td>
<td>0.99</td>
<td>0.95</td>
<td>+4.4 (+0.05)</td>
<td>10.9 (0.10)</td>
</tr>
</tbody>
</table>

\*Deviation significant at 5% level.
surface, whereas with A-mode ultrasound only few points could be measured throughout the joint surfaces, owing to the size of the transducer. It is of particular relevance that the ultrasound measurements could not be made at the very margin of the surface, but rather throughout the central aspects of the joint surface, and this provides an explanation why the ultrasound values were in general somewhat higher than the MR measurements (the latter also involving the thinner aspects in the periphery of the joint surface). An exception to this was the radial head, where the maximal cartilage thickness is not to be found in the center, but in the periphery of the fovea capitatis radii (Fig. 3). Nevertheless, the MR and ultrasound values were found to be in the same range. The MR measurements were generally in good agreement with CT arthrography, except at the humerus, in which the values were somewhat lower for the CT based method. It should also be noted that the measurements were not made under precisely the same conditions, the articular surface being in contact with synovial fluid in the MRI measurements, with a contrast agent in the CT imaging, and with Ringer solution in the A-mode ultrasound analysis. These conditions may also account for small differences in the cartilage thickness measurements with the three methods.

When comparing our analysis with those of Hodler et al., Robson et al., Peterfy et al., and Mc Gibbon et al., certain methodological differences should be kept in mind. Hodler et al. and Robson et al. compared the apparent cartilage thickness in single supposedly identical sectional images, but not throughout entire joint surfaces. Hodler et al. found substantial deviations in comparison with anatomical sections applying resolutions between $3 \times 0.46 \times 0.46$ mm$^3$ (hip) and $1 \times 0.9 \times 0.9$ mm$^3$ (shoulder) for cartilage layers with a mean thickness of 1 to 1.5 mm. Robson et al. used a subtraction technique of two different MR-sequences in the distal interphalangeal joint (mean cartilage thickness around 1 mm), but did not attempt to validate their measurements. Peterfy et al. imaged the metacarpophalangeal joints of three cadavers at a resolution of $0.7 \times 0.31 \times 0.31$ mm$^3$ and found very similar cartilage volumes in comparison with surgically retrieved tissue. However, these authors did not determine the 3D cartilage thickness or the regional distribution of cartilage thickness throughout the joint surfaces. Finally, Mc Gibbon et al. provided cartilage thickness maps throughout the left and right acetabulum of one individual.

Table III

<table>
<thead>
<tr>
<th>Joint</th>
<th>MRI</th>
<th>US</th>
<th>Systematic deviation</th>
<th>Random deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humerus</td>
<td>1.35</td>
<td>1.44</td>
<td>-5.9% (-0.05)</td>
<td>6.2% (0.06)</td>
</tr>
<tr>
<td>Radius</td>
<td>1.20</td>
<td>1.08</td>
<td>+14.9% (+0.13)</td>
<td>19.4% (0.19)</td>
</tr>
<tr>
<td>Ulna dorsal</td>
<td>1.23</td>
<td>1.62</td>
<td>-23.7% (<em>-0.29</em>)</td>
<td>23.7% (0.29)</td>
</tr>
<tr>
<td>Ulna ventral</td>
<td>0.99</td>
<td>1.18</td>
<td>-14.0% (<em>-0.18</em>)</td>
<td>17.8% (0.22)</td>
</tr>
</tbody>
</table>

*Deviation significant at 5% level.

Table IV

<table>
<thead>
<tr>
<th>Joint</th>
<th>MRI</th>
<th>CTA</th>
<th>Systematic deviation</th>
<th>Random deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humerus</td>
<td>2.77</td>
<td>2.42</td>
<td>+14.7% (+0.35*)</td>
<td>14.7% (0.35)</td>
</tr>
<tr>
<td>Radius</td>
<td>2.53</td>
<td>2.28</td>
<td>+11.8% (+0.26*)</td>
<td>11.8% (0.26)</td>
</tr>
<tr>
<td>Ulna dorsal</td>
<td>2.90</td>
<td>2.59</td>
<td>+11.8% (+0.30*)</td>
<td>12.2% (0.31)</td>
</tr>
<tr>
<td>Ulna ventral</td>
<td>2.30</td>
<td>2.21</td>
<td>+4.7% (+0.09)</td>
<td>13.7% (0.28)</td>
</tr>
</tbody>
</table>

*Deviation significant at 5% level.
(resolution 0.8 x 0.31 x 0.31), but imaging was performed in excised specimens in saline solution (without the femoral head being in contact with the acetabular cartilage). They found standard errors of around 0.35 mm in comparison with an optical technique, with no significant over- or underestimation. In comparison with these studies, the accuracy errors observed in our investigation are relatively small and apply for the characterization of entire joint surface, including the cartilage edges which are often difficult to identify. The random deviations of the mean surface, including the cartilage edges which are often small and apply for the characterization of entire joint accuracy errors observed in our investigation are relatively small.

Quantitative cartilage thickness measurements can be a potentially valuable tool clinically, for instance to monitor the magnitude and rate of tissue loss in osteoarthritic joint degeneration, or to evaluate the success of various therapeutic approaches aimed to reverse, stop, or slow down the degenerative process. However, the technique is also interesting in the context of basic research questions, for instance to assess the interindividual variability, gender differences, functional adaptation, and deformational behavior of articular cartilage. Finally, quantitative measurements of cartilage thickness throughout joint surfaces make it possible to design computer models of diarthrodial joints (e.g., in living individual, in order to be able to study the load transmission, and to plan and optimize surgical procedures (e.g. a correction osteotomy) that aim to improve the pressure distribution within the cartilage surfaces.

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References


