Subchondral Fractures in Osteonecrosis of the Femoral Head: Comparison of Radiography, CT, and MR Imaging

OBJECTIVE. Our objective was to compare the sensitivity of unenhanced radiography, CT, and MR imaging in revealing subchondral fractures.

SUBJECTS AND METHODS. Forty-five subjects with stage I and stage II osteonecrosis of the femoral head were included in the study as part of a multicenter clinical trial to evaluate the effectiveness of recombinant human bone morphogenetic protein as an adjuvant treatment to core decompression. Patients were evaluated with radiography, CT, and MR imaging 6 and 12 months after surgery.

RESULTS. At 6 months, 18 fractures were shown on CT scans, but only 12 were detected on radiographs and six, on MR images. At 12 months, 20 subchondral fractures were detected on CT scans, but only 17 were seen on radiographs and 11, on MR images. Compared with CT, MR imaging has a sensitivity and specificity of 38% and 100%, and unenhanced radiography has a sensitivity and specificity of 71% and 97%, respectively. On T2-weighted MR images, the subchondral fractures were visualized as crescentic high-signal-intensity lines, and in all patients, on the corresponding CT scans, the fracture clearly breached the femoral cortex.

CONCLUSION. CT reveals more subchondral fractures in osteonecrosis of the femoral head than unenhanced radiography or MR imaging. The high-signal-intensity line seen on T2-weighted MR images appears to represent fluid accumulating in the subchondral fracture, which may indicate a breach in the overlying articular cartilage.
research, accurate staging is also important for determining entry criteria into clinical trials and subsequent follow-up [19]. Although MR imaging is the technique of choice for detection of early osteonecrosis, it has been reported to be of limited value in the detection of subchondral fractures. The purpose of our study was to compare the sensitivity of unenhanced radiography, CT, and MR imaging in the detection of subchondral fractures in osteonecrosis of the femoral head.

Subjects and Methods

Forty-five subjects with osteonecrosis of the femoral head were recruited between September 1998 and August 1999 from four orthopedic centers: two in the United States and two in France. They comprised 32 men and 13 women, with ages ranging from 26 to 72 years (mean, 47.8 years). The patients were part of a phase 2 multicenter clinical study to evaluate the effectiveness of recombinant human bone morphogenetic protein (rhBMP-2) (Genetics Institute, Boston, MA), as an adjunct to core decompression. One of the parameters that was recorded as part of this study was the presence or absence of a subchondral fracture. It is generally thought that CT is more sensitive than radiography or MR imaging in the detection of subchondral fractures, so we decided to analyze our results to determine whether this hypothesis was true.

The study population consisted of patients with stage I and II osteonecrosis of the femoral head, either type B involving 15–30% of the femoral head or type C involving more than 30%. Patients were excluded from the study if they had osteonecrosis resulting from trauma, Gaucher’s disease, sickle cell disease, hyperbaric trauma, or HIV infection; if they had coexistent pathology; or if other intervention or treatment was planned; or if they had any of the standard contraindications to MR imaging. Baseline radiographs and MR images were used to stage patients before inclusion in the study. CT was not performed at the time of the baseline study. All patients were scheduled for core decompression and gave written informed consent. The study received appropriate institutional review board approval.

Each patient underwent a surgical core decompression of the affected hip, either alone or with rhBMP-2 on an absorbable collagen sponge (rhBMP/ACS) implanted in the decompression site. Partial weight-bearing was recommended for 6 weeks after surgery to decrease the chance of fracture at the decompression site. Patients were initially evaluated with radiography and MR imaging on enrollment in the study. CT and MR imaging were performed 2 weeks after surgery, and radiography, CT, and MR imaging were performed at 6 and 12 months after surgery.

Radiographic assessment included anteroposterior and frogleg lateral images. CT scans were acquired using a helical scanner (120 kV, 230 mAs, pitch of 1, 512 × 512 matrix, large field of view), with 3-mm axial slices. MR images were obtained on a 1.5-T whole-body MR imaging system using a torso phased array coil (Vision TSE, Siemens Medical Solutions, USA, Erlin, NJ; Signa LX2, General Electric Medical Systems, Milwaukee, WI; Marconi Edge/Picker Edge SE, Picker International Fairfield, OH). In one center, only a 0.5-T MR scanner was available. Coronal T1-weighted spin-echo images (TR/TE, 600/14; excitations, 3; matrix, 512 × 256; field of view, 18 cm; sections, 4 mm) and coronal T2-weighted fast spin-echo images (4000/80; echo-train length, 8; excitations, 3; matrix, 512 × 256; field of view, 18 cm; sections, 4 mm), with and without fat saturation, were obtained.

All images were reviewed by an experienced musculoskeletal radiologist and assessed for subchondral fractures. The assessor was unaware of the patient’s treatment allocation; therefore, the results were pooled irrespective of treatment with rhBMP-2/ACS. On both radiographs and CT scans, a subchondral fracture was defined as a curvilinear or irregular subchondral radiolucent line that may have breached the articular surface. On MR images, a fracture was defined as a curvilinear subchondral low-signal-intensity line on T1-weighted images and a high-signal-intensity line on T2-weighted images.

Eleven patients had incomplete imaging at the time of analysis. Six patients required total hip arthroplasties and were therefore withdrawn from the study. Four patients had images that were unanalyzable at one of their visits, and three patients did not have all three imaging techniques performed at one visit for an indeterminate reason. In patients with complete imaging sets per visit, the number of subchondral fractures seen on radiography, CT, and MR imaging at this time was tabulated, and we performed a chi-square analysis to see if there was a statistically significant difference among the results (p < 0.01, 2 df). The results of radiography and MR imaging were compared with the number of fractures shown on CT, and from this, the sensitivity, specificity, positive predictive value, and negative predictive value of radiography and MR imaging relative to CT were calculated.

Results

The baseline radiographic and MR imaging analyses of the 45 hips in this study showed that 18 hips were stage IIB, and 27 hips, IIC. The imaging findings on radiography, CT, and MR imaging were compared both at 6 and 12 months after core decompression (Table 1). CT depicted all the subchondral fractures except in one patient in whom the fracture was seen on radiographs and MR images at 6 months, but not on CT scans, even when examined retrospectively. A subchondral fracture was subsequently shown on all three imaging modalities at 12 months in this patient. In five patients, findings on CT were positive only on the 6-month visit, and follow-up imaging at 12 months was available. In four patients, the subchondral fracture was subsequently shown on either radiographs or MR images at 12 months, and in one patient, the fracture remained visible only on CT scans.

A chi-square analysis was performed using data from the patients in whom all three imaging tests were available at one visit (n = 76 sets of imaging of a possible 90). The results showed that there was a statistically significant difference among the abilities of radiography, CT, and MR imaging to detect subchondral fractures (p < 0.01). Imaging sets were incomplete in 14 patients, because of withdrawal of the patient from the study or because images were uninterpretable.

### Table 1

<table>
<thead>
<tr>
<th>Follow-Up Interval</th>
<th>On Radiography</th>
<th>On CT</th>
<th>On MR Imaging</th>
<th>Total Fractures</th>
</tr>
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<tbody>
<tr>
<td>6 months</td>
<td>12</td>
<td>45</td>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td>12 months</td>
<td>17</td>
<td>40</td>
<td>20</td>
<td>43</td>
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</tbody>
</table>

*Total number of imaging sets available for analysis. Numbers are incomplete because some patients have withdrawn from the study, and in some, the data were uninterpretable.*

### Table 2

<table>
<thead>
<tr>
<th>Imaging Modality</th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>Positive Predictive Value</th>
<th>Negative Predictive Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiography</td>
<td>71</td>
<td>97</td>
<td>96</td>
<td>77</td>
</tr>
<tr>
<td>MR imaging</td>
<td>38</td>
<td>100</td>
<td>100</td>
<td>60</td>
</tr>
</tbody>
</table>

*Data were obtained from patients with complete sets of imaging per visit. Numbers are percentages.*
CT is usually the technique of choice for detection of subchondral fractures [19, 20]. Both sets of results on the presence of subchondral fractures at the 6- and 12-month visits were combined to calculate the sensitivity of radiography and MR imaging in detecting subchondral fracture when compared to that of CT. At both these time periods, radiography, CT, and MR imaging were performed as part of the assessment. MR imaging had a sensitivity of 38% and specificity of 100%, and radiography had a sensitivity of 71% and a specificity of 97% when compared with those of CT (Table 2). On radiographs, subchondral fractures were typically seen along the anterolateral portion of the proximal femoral head (Figs. 1 and 2) and were best seen on frogleg lateral images. On CT, the fracture was often seen to breach the cortex of the femoral head in one or more places (Figs. 2 and 3). MR imaging was the least sensitive imaging technique for the detection of subchondral fractures. The fracture was visualized as a well-defined crescentic high-signal-intensity line on T2-weighted images (Fig. 4), and in all patients, the fracture on corresponding CT images clearly extended through the cortex of the bone. In patients in whom the findings of CT were positive, but radiography and MR imaging failed to show the fracture (Fig. 5), the fracture was seen to extend through the cortex of the bone on CT in 63% of patients.

To meet entry criteria, no patient in the study could have a detectable subchondral fracture before surgery, which would indicate stage III
disease. However, in view of the findings of low sensitivities of MR imaging and radiography for showing subchondral fractures, CT and MR images obtained 2 weeks after surgery were reviewed to see whether a subchondral fracture was present at this stage. Five patients had subchondral fractures present 2 weeks after core decompression, all seen on CT, and three fractures were also seen on MR imaging. These findings suggest that the fractures may have been present before surgery and that our initial staging with radiography and MR imaging may have been inadequate. However, even in retrospect, these fractures could not be seen on the screening images, and these fractures may have been incurred during surgery or in the immediate postoperative period.

**Discussion**

Osteonecrosis of the femoral head is characterized by variable areas of dead trabecular bone and bone marrow, extending to and including the subchondral plate. However, the mechanical properties of this dead bone have been reported to be similar to those of viable bone [15], and it is the repair response in this area of dead bone that is thought to lead to subchondral fracture and subsequent femoral head collapse [21]. Repair begins at the junction of the necrotic and viable bone, with the advancing front of vascular repair tissue extending into the necrotic segment of bone as repair is attempted. Because of the rounded shape of the femoral head, the reparative interface reaches the lateral aspect of the necrotic subchondral plate first, leading to ex-
tensive bony resorption. The repetitive microtrauma of continued weight-bearing can lead to small fractures, which propagate through the dead bone of the subchondral plate and bone immediately subjacent to the subchondral plate, resulting in the crescent sign (Figs. 1 and 2), which is characteristic of collapse associated with osteonecrosis [21–23].

Osteonecrosis should be diagnosed at an early stage at which surgical procedures such as core decompression and rotational osteotomy may prevent disease progression. Early intervention may reduce the risk of subsequent collapse, with development of secondary arthritis. MR imaging has been shown to be the most sensitive method of detecting early osteonecrosis of the femoral head, with a reported sensitivity of 88–100% [24–30]. Identifying radiologic features indicating disease progression, such as subchondral fractures at an early stage, may alter ongoing management of patients. When this study began, CT was used as the gold standard for subchondral fracture detection. Although we have shown in our study that CT is the most sensitive imaging technique for detection of subchondral fractures (Table 2), one fracture seen on unenhanced radiography and MR imaging was not visualized on CT. This fact suggests that we may be missing some early subchondral fractures on imaging. CT is excellent for depicting the cortical surface of bones, an area devoid of signal on MR imaging. CT also depicts detail of the underlying bone trabeculae, and, with appropriate window settings, the soft tissues surrounding a joint. CT is widely used in trauma to detect fractures, usually depicted as radiolucent lines breaching the cortex, with associated trabecular disruption. CT can be used to show osteonecrosis, having a higher sensitivity than radiography, but CT is more useful in the investigation and staging of more established osteonecrosis, revealing subchondral fractures, articular collapse, or secondary degenerative changes [19, 20, 30, 31].

On MR imaging, fractures typically appear as low-signal-intensity lines on T1-weighted images, with marked surrounding bone marrow edema on T2-weighted images. These appearances, for example, are seen in subchondral insufficiency fractures of the femoral head [32]. However, in osteonecrosis of the femoral head, the bone marrow is largely necrotic, and usually little bone marrow edema is associated with subchondral fractures. The necrotic bone marrow, cellular debris, granulation tissue, and bone sclerosis can all result in low signal intensity on T1- and T2-weighted MR images, potentially obscuring subchondral fractures. In our study, subchondral fractures were depicted as high-signal-intensity lines on T2-weighted MR images (Figs. 2B and 4B), a finding that has also been reported in other studies [27, 30, 33, 34]. This high signal appears to represent fluid accu-
mulating in the subchondral fracture, and the fractures that were seen initially on CT but not on MR imaging may be explained by the absence of fluid in the fracture defect. The fluid seen on MR imaging could extravasate from the distal bone marrow into the fracture. However, given that in all these patients, the fracture clearly extended through the cortex of the bone, we believe it more likely that the fluid may result from extension of joint fluid through the fracture in the subchondral bone. In this case, there must also be damage to the overlying articular cartilage. This finding may hold therapeutic importance because it may be indicative of early compromise of the articular surface and may be a predictor of more rapid progression to secondary osteoarthritis.

Our study has shown that although MR imaging is suitable for the early diagnosis of femoral head osteonecrosis, CT is required for subsequent staging and follow-up. These findings may partly explain differences in success of treatment between various studies. If CT is not used for accurate differentiation between stage II and stage III disease, findings may be classed as stage II disease, and patients may be wrongly allocated to treatment groups, adding unwanted bias of results. Our study has several limitations. When the study was originally designed, MR imaging and radiography were believed to be adequate to stage the disease, and CT was not included as part of the initial evaluation. We may, therefore, have missed some subchondral fractures in the preoperative imaging and, therefore, understaged the disease. CT findings missed one subchondral fracture in our study; therefore, it cannot be called a true gold standard. However, there is currently no perfectly accepted gold standard for assessing the presence or absence of a subchondral fracture. Even histology has false-positive results because a subchondral fracture-like appearance can be artificially induced during cutting of the specimen [25].

In conclusion, MR imaging is sensitive in the diagnosis of early osteonecrosis but has only limited sensitivity for detection of subchondral fractures. CT appears to be the imaging technique of choice for diagnosing subchondral fractures and, therefore, is important for accurate staging and subsequent treatment. On MR imaging, the subchondral fracture can be seen as a crescentic high-signal-intensity line on T2-weighted images, suggesting that this represents fluid in the fracture site, probably resulting from extension of joint fluid through a breach in the cortex and overlying articular cartilage, and this finding would therefore have both therapeutic and prognostic implications.

References