The Use of Tomosynthesis in the Global Study of Knee Subchondral Insufficiency Fractures

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Rationale and Objectives: Subchondral insufficiency fractures (SIF), previously termed spontaneous osteonecrosis of the knee, are marked by a sudden onset of severe pain. Other than the size of the lesion, prediction for progression to joint replacement is difficult. The objective was to determine if quantitative analysis of bone texture using digital tomosynthesis imaging would be useful in predicting more rapid progression to joint replacement.

Materials and Methods: Tomosynthesis studies of 30 knees with documented SIF were quantified by fractal, mean intercept length (MIL), and line fraction deviation analyses. Fractal dimension, lacunarity, MIL, and line fraction deviation variables measured from these analyses were then correlated to short interval progression to joint replacement surgery.

Results: Higher odds for joint replacement were related to higher values of the standard deviation of slope lacunarity and to morphometric measures (eg, MIL).

Conclusions: Using digital tomosynthesis images for bone texture assessment may help distinguish condylar bone response in SIF, potentially acting as a clinically relevant predictive tool. In the future, contrasting SIF to the more gradual long-term process of osteoarthritis, there may be a better understanding of the different mechanisms for the two conditions.

Key Words: Tomosynthesis; fractal; bone; knee; insufficiency fracture.

INTRODUCTION

Subchondral Insufficiency Fractures (SIF)

The term *spontaneous osteonecrosis of the knee* was first described as a finding in osteoarthritis (1). The condition usually presents with a sudden onset of severe, acute, unilateral knee pain, mostly in women more than 50 years old. It has been renamed as there is usually no history of trauma and the majority of patients have no risk factors for osteonecrosis (2,3). Many patients have a very painful course that can be followed by resolution of symptoms over months. Progressive collapse can occur and may lead to early surgical interventions, including joint replacement (2). Insufficiency fractures have been linked with osteoarthritis (4). In broader use, the term *insufficiency fracture* has been defined as a fracture that occurs due to the inability of the bone to support normal loads (5). The term implies that an insufficiency fracture would occur only in individuals with poor bone quality or mass. However, review of a larger series of patients with SIF reveals a systemic bone mass that is above normal for age (6). This is in contrast to patients with early osteoarthritis who appear to have decreased bone perfusion and osteocyte activity in the femoral condyle (7). Histology of SIF has shown that in six of eight cases, there was no osteonecrosis, and the only areas of osteonecrosis in the remaining two were in regions of bone collapse (8). Four stages have been described comparing plain radiographs to histology (4). The radiographic stage ranged from no abnormality to a lucent area surrounded by sclerotic bone with osteoarthritic changes. Histology ranged from areas of granulation with fracture healing and no osteonecrosis, to cases of focal necrosis or complete separation. These patterns are very different from the patterns seen in secondary osteonecrosis.

Clinical Imaging in SIF

When radiographs are obtained within weeks of the onset of severe pain, they may appear normal with little or no evi-

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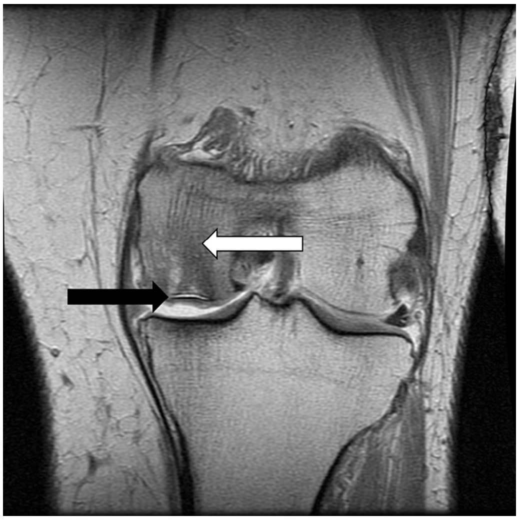

Figure 1. Coronal magnetic resonance image slice of a more advanced lesion in the medial femoral condyle. The *black arrow* denotes an area of subchondral collapse and fracture within the lesion. The *white arrow* marks an area of more proximal bone changes.

dence of osteoarthritic changes (9). The biologic activity within and outside of these lesions has been documented with fluorine-18 positron emission tomography (10). The overall size of the lesion correlates to what is seen on magnetic resonance imaging (MRI). The T1 or proton density-weighted image typically has a curvilinear area of decreased signal that parallels the articular margin of the subchondral bone of the proximal tibial plateaus and femoral condyles (6). All lesions have direct connection to the articular subchondral bone. In one review, the average surface area was 431 mm^2 (standard deviation [SD]: 218 mm^2 [11]) (range: 210–1025 mm^2) and the volume was 4.8 cm^3 (SD: 3.1 cm^3), placing the diameter between 0.5 and 2 cm (10). There are a variety of MRI bone marrow lesions seen in osteoarthritis (12). However, none of these have the clear line of demarcation that is seen in SIF (Fig 1). Albeit the size of the lesion is predictive for progression to total knee replacement (13), smaller lesions can progress to rapid articular cartilage changes. Given that bone changes are not apparent in conventional radiology, we have not had an imaging tool that can better predict clinical outcome or help define the biologic process.

Tomosynthesis to Evaluate SIF

An imaging tool, such as digital tomosynthesis (DTS), could help define the SIF process. Conventional DTS produces a multi-slice image of an object (14). In DTS, the x-ray source and detector are moved together during exposure, rapidly producing sharply focused planes (Fig 2). The DTS system produces two-dimensional slice images with a high in-plane resolution of 150–300 μm, with about one fifth of the exposure of a computed tomography examination (15). DTS has been used in fracture healing and in the detection of occult fractures (16,17).

Figure 2. Standing views were obtained with the knee moved forward to press on the table pad. A table tilt of 70° with a waist restraint was used for safety reasons. A sequence of digital radiographs is obtained as the detector translates down and the x-ray tube moves up with the central beam directed at the joint surface at an angle that varies from −20° to +20° (indicated by *arrows*). Coronal slice images are formed from projection images via filtered back-projection reconstruction.

Cancellous bone texture can be captured by DTS and quantified by fractal analysis (eg, fractal dimension [FD] [18]), lacunarity (19), and morphometric measures (eg, mean intercept length [MIL] [20] and line fraction deviation [LFD]) (21). Fractal and LFD methods can use gray-level images and binarized images. MIL requires the binarization of images, and therefore it is a segmentation-dependent method. A fractal is a natural phenomenon or a mathematical set that exhibits a repeating pattern that displays at every scale or nearly the same pattern at different levels. An FD is a quantity that provides a mathematical means to compare how detail in a fractal pattern changes with scale. Bone texture is not expected to be a true fractal, but the concept is useful in understanding the complexity of trabecular organization. In fractal analysis, a region of interest (ROI) is identified in each image. A grid is placed on the ROI, dividing the ROI into subregions, which provides a size scale for the analysis. The analysis is repeated by varying the grid (each with a different subregion size) within the same ROI. By doing so, a metric is determined for each grid for a given ROI. This metric is plotted against a size scale determined from the subregion size, from which a slope variable is calculated for that ROI. Patterns that have larger gaps generally have higher lacunarity. When lacunarities are averaged over the range of size scales, a mean lacunarity (λ) can be calculated for each ROI. Similarly, changes of lacunarity with change in size scale can create a slope lacunarity (S_λ). LFD is more sensitive to anisotropy (21). MIL methods are based on recognition of feature boundaries. In this case, one is asking “how many times does a test line change from bone