MRI of Mineralized Bone: Seeing Beyond the Signal Void

Lecture by Pr F. Lecouvet

Text by Chatgpt revised by Pr B Vande Berg

Introduction

Magnetic resonance imaging (MRI) is traditionally considered an excellent technique for evaluating bone marrow but a relatively poor technique for assessing mineralized bone. This apparent limitation is fundamentally related to MR physics. Cortical bone and heavily mineralized trabeculae contain very few mobile protons, and their transverse relaxation is extremely rapid. Consequently, conventional MR sequences provide little or no measurable signal from mineralized bone, which appears as a signal void.

For decades, this has established a simple division of labor in musculoskeletal imaging: radiographs and computed tomography (CT) evaluate mineralization, cortical morphology and trabecular architecture, whereas MRI evaluates bone marrow and surrounding soft tissues. This distinction remains clinically useful but is becoming increasingly incomplete. MRI can provide considerable information about mineralized bone indirectly, and newer techniques using ultrashort or zero echo times are beginning to allow more direct visualization of cortical and trabecular structures.

Why is mineralized bone dark on conventional MRI?

Approximately two-thirds of the dry weight of bone consists of inorganic mineral, predominantly hydroxyapatite, while the remaining organic matrix is largely composed of type I collagen. Water exists in several compartments, including free pore water and water bound to the collagen matrix and mineral surfaces.

Conventional clinical MRI predominantly detects signals from relatively mobile hydrogen protons. In mineralized bone, however, much of the water is tightly bound, resulting in extremely short transverse relaxation times. By the time conventional spin-echo or gradient-echo sequences acquire the MR signal, most of the signal from cortical bone has already disappeared. The cortex therefore appears as a low-signal or black structure on essentially all conventional pulse sequences. This explains why MRI cannot simply replace radiographs or CT for characterization of mineralization.

Trabecular bone: MRI sees the spaces as much as the trabeculae

Individual mineralized trabeculae generate little MR signal and appear dark, whereas the intervening marrow provides high or intermediate signal depending on its fat and water

content. The resulting appearance of trabecular bone therefore represents an interaction between the signal-producing marrow and the signal-poor trabecular network.

This becomes particularly important in regions with dense trabeculation, such as the vertebral bodies, proximal femur, calcaneus and epiphyses.

Nevertheless, conventional MRI remains less suited than high-resolution CT for directly analyzing fine trabecular architecture.

MRI versus CT: different representations of bone

One conceptual error is to regard CT and MRI as simply two different ways of producing anatomical images. They measure fundamentally different tissue properties. CT attenuation is strongly influenced by tissue density and atomic composition and is therefore particularly sensitive to calcium-containing structures. MRI signal reflects proton density, molecular environment and relaxation behavior. The resulting images represent different aspects of bone biology.

A densely mineralized structure is conspicuous on CT precisely because of its mineral content. On conventional MRI, the same structure is conspicuous primarily because it lacks

New MRI techniques: making cortical bone visible

The traditional concept that MRI cannot directly image cortical bone is being challenged by technical developments. Conventional sequences use echo times measured in milliseconds. By contrast, ultrashort echo-time (UTE) and zero echo-time (ZTE) techniques acquire signal extremely rapidly and can therefore detect proton populations with very short T2 or T2* relaxation times.These techniques can produce images in which cortical bone is directly visualized rather than merely appearing as a signal void.

UTE and ZTE imaging have several potential applications, including assessment of cortical morphology, fractures, bone microstructure and quantitative evaluation of bone composition. Appropriate image processing can also produce CT-like images that are intuitively familiar to radiologists.

Another emerging approach is synthetic CT derived from MRI, increasingly using machine-learning techniques. MR datasets can be transformed into images that approximate CT-like representations of bone. Such techniques are particularly attractive when both bone and soft tissues need to be evaluated while avoiding ionizing radiation.

However, CT-like appearance should not automatically be considered equivalent to CT. Very small cortical lesions, subtle mineralization and fine trabecular abnormalities may remain

challenging, and performance depends on anatomical region, acquisition technique and reconstruction methodology.

Mineralized bone as a living structure

Perhaps the most important contribution of MRI is to remind radiologists that mineralized bone is not simply an inert structural framework. Radiographs and CT predominantly demonstrate the structural consequences of bone disease. MRI frequently demonstrates the biological response occurring around those structural changes. Bone marrow edema surrounding a fracture, hyperemia associated with infection, marrow replacement adjacent to cortical destruction, reactive changes around an osteoid osteoma, or edema surrounding a subchondral insufficiency fracture may be considerably more conspicuous than the underlying mineralized abnormality.

The low-signal cortex therefore represents only one component of the MRI examination. What happens immediately adjacent to that cortex may provide the most clinically relevant information.

Conclusion

Conventional MRI does not visualize mineralized bone in the same manner as radiography or CT. MRI provides unique information about the interface between mineralized bone, marrow and soft tissues and is exceptionally sensitive to the biological consequences of bone injury and disease. The radiologist should therefore interpret mineralized bone on MRI through three complementary elements: the morphology of the low-signal mineralized structure, the condition of the surrounding marrow, and the associated soft-tissue response.

Emerging UTE, ZTE and synthetic CT techniques are progressively narrowing the historical gap between MRI and CT. In the future, MRI may increasingly provide both the extraordinary tissue characterization for which it is already valued and a more direct representation of mineralized bone.