

MRI of Bone Marrow

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MRI is the imaging modality of choice for the investigation of bone marrow disorders. Accurate interpretation of MR examinations of bone marrow requires an understanding of the anatomy, physiology, distribution, and conversion patterns of bone marrow. Technical factors of the MR examination are also important. Common pathophysiologic pathways allow a useful classification of bone marrow disorders.

BONE MARROW ANATOMY AND PHYSIOLOGY

The bone marrow is the 5th largest organ of the human body. Its chief function is hematopoietic, providing the optimal supply of circulating platelets, white and red blood cells to meet the body's requirements for coagulation, immunity, and oxygenation.

The histology of normal bone marrow consists of a number of components including: (1) an osseous component; (2) a cellular component; (3) a supporting system. The osseous component consists of cancellous bone composed of primary and secondary trabeculae. The cellular component includes hematopoietic, fat, and reticulum cells. The bone marrow supporting system consists of vascular, neural, and lymphatic elements.

Hematopoietically active bone marrow is referred to as hematopoietic marrow or red marrow. Red marrow contains approximately 40% water, 40% fat, and 20% protein. Hematopoietically inactive marrow is referred to as yellow marrow or fatty marrow. It contains approximately 15% water, 80% fat, and 5% protein. These differences in chemical composition account for the appearance of red and yellow marrow on various MRI pulse sequences. There is also a structural difference between red and yellow marrow. In particular, the vascular network of red marrow can be characterized as being rich, while that of yellow marrow is more sparse.

At birth, red marrow is present throughout the entire skeleton. Epiphyses and apophyses are cartilaginous at birth, however, they later contain yellow marrow throughout life. Epiphyseal red marrow can be a normal variant in adults, however, in the humeral head and femoral head. Normal physiological conversion of red-to-yellow marrow occurs in a predictable and orderly fashion with completion by the age of 25 years when the adult pattern is reached. Conversion occurs first in the

hands and feet. There is then a "distal-to-proximal" trend of conversion within the bones of the extremities. Conversion also occurs at different rates within the same bone. Within long bones, marrow converts first in the diaphysis, then in the distal metaphysis, and finally in the proximal metaphysis.

By age 25 years, the adult distribution of bone marrow is attained which is characterized by red marrow persisting in the axial skeleton, proximal humeri, and proximal femora. With advancing age there is further replacement of red marrow by yellow marrow, with older individuals commonly having a spine and pelvis dominated by yellow marrow. Residual islands of hematopoietic marrow can persist in the long bones. The most common sites are the proximal and distal femora, and proximal humeri. This pattern should not be mistaken for pathology. Another common normal variation in distribution of marrow is the presence of focal fatty marrow within the spine. The distal appendicular skeleton usually has a uniform distribution of yellow marrow in adults.

MR TECHNIQUE

Pulse sequence selection determines the MR appearance of normal bone marrow as well as the sensitivity and specificity for evaluating bone marrow disorders. A highly effective combination of pulse sequences for the evaluation of bone marrow pathology includes: (1) T1 weighted spin-echo; and either (2) fat-saturation T2 weighted fast spin-echo; or (3) STIR / Fast STIR.

There is superb differentiation between red and yellow bone marrow on T1 weighted spin-echo images. On T1 weighted images the yellow marrow is hyperintense in signal intensity as contrasted with the relatively decreased signal intensity of red marrow. These differences in signal intensity are a direct reflection of the differences in fat/water content within red and yellow marrow. Specifically, increased fat content within yellow marrow contributes to significant shortening of the T1 relaxation time compared with red marrow. Both benign and malignant disorders of bone marrow have long T1 values which result in marrow signal intensity that is significantly decreased. The signal intensity of these lesions on T1 weighted spin-echo images is usually less than that of intervertebral discs in the spine and less than that of muscle in the extremities.

The clinical advantages of STIR are due to the following characteristics: (1) additive T1 and T2 contrast; (2) marked fat suppression; (3) a two-fold increase in the magnetization range of spin-echo sequences. As a result, STIR images demonstrate extraordinarily high contrast, conspicuousness, and sensitivity for the depiction of most types of bone marrow pathology. The obvious drawbacks of this pulse sequence, however, include relatively long imaging times, and a low signal-to-noise ratio.

Conventional intermediate weighted and T2 weighted spin-echo sequences demonstrate relatively low contrast between red marrow and yellow marrow. In addition there is decreased sensitivity and conspicuousness for the depiction of most types of bone marrow pathology. These problems are corrected by utilizing the very long TR and TE times of heavily T2 weighted fast spin-echo images used in conjunction with fat-saturation. The sensitivity of this sequence for detecting bone marrow pathology is similar to that of STIR imaging. Several practical advantages compared with STIR include: (1) significantly decreased imaging time; (2) improved signal-to-noise ratio. The major disadvantage of T2 weighted fast spin-echo with fat saturation is its dependence on excellent magnetic field homogeneity for adequate fat suppression. Optimal results with fat saturation usually require high-field strength systems, whereas STIR images can be obtained on low-or high field strength systems.

The fast inversion recovery techniques significantly reduce the imaging time required for STIR-like images. The role of these techniques in the evaluation of bone marrow pathology is currently evolving. Recent studies suggest an emerging role for this pulse sequence for performing whole-body bone marrow MRI for the evaluation of patients with suspected skeletal metastasis or multiple myeloma.

Opposed-phase GRE sequences with a long repetition time have recently been shown to be sensitive for demonstrating red bone marrow pathology. This type of sequence results in low signal intensity of intact red bone marrow and high signal intensity positive contrast imaging of pathology.

CLASSIFICATION OF BONE MARROW DISORDERS

MRI is ideally suited for evaluation of both diffuse and focal bone marrow disease. The

bone marrow can be affected by a wide variety of pathologic processes, such as myeloproliferative diseases, osteomyelitis, and hemochromatosis, but metastatic disease and multiple myeloma are the most common causes of bone marrow disease. Vogler et. al., have nicely grouped the bone marrow disease conditions according to common pathophysiological patterns.

Reconversion

The first group includes diseases where there is an increased need for hematopoietic marrow. Failure of conversion from red marrow to yellow marrow occurs when the disorder develops in childhood. Reconversion occurs when the adult bone marrow is stressed. Reconversion occurs in the reverse order of normal conversion, progressing from proximal-to-distal. This is seen in entities such as anemia of chronic illness, thalassemia, and sickle cell disease.

Marrow Infiltration

Marrow infiltration can be either focal or diffuse and is most commonly due to neoplastic disease. There is replacement of the normal fatty marrow cells by neoplasia or other pathologic tissue. Examples of neoplastic disease include metastatic disease, lymphoma/leukemia, and multiple myeloma. Examples of non-neoplastic disorders include eosinophilic granuloma, Gaucher's disease, and the mucopolysaccharidoses.

Myeloid Depletion

These disorders are characterized by replacement of hematopoietic elements by fat cells. These processes include aplastic anemia, radiation therapy, and chemotherapy. Following bone marrow transplantation, a marrow "band" pattern is seen reflecting repopulation of the bone marrow in the peripheral sinusoids of the vertebral body. This finding consists of central fatty marrow with a peripheral hematopoietic marrow band of intermediate signal intensity on T1 weighted images.

Marrow Edema

Bone marrow edema is usually focal. There is a nonspecific increase in water content within the bone marrow which manifests decreased signal intensity on T1 weighed spin-echo images, and markedly increased signal intensity on STIR images and T2 weighted fast spin-echo images with fat saturation. T2* weighted images are frequently less sensitive in detecting bone marrow edema due to obscuration of the high signal from the edema by magnetic

susceptibility "blooming" of trabeculae. The finding of bone marrow edema is non-specific, and can be seen as a result of trauma, infection, ischemia, reaction to adjacent neoplasia, or it may be idiopathic. For example, the bone marrow edema seen on MR images of the hip may be secondary to transient or migratory osteoporosis, early osteonecrosis, or the bone marrow edema syndrome.

Marrow Ischemia

This category of bone marrow disease encompasses both avascular necrosis of subchondral bone and medullary bone infarcts. Bone marrow ischemia favours fatty marrow over hematopoietic marrow. This is most likely due to the limited vascular supply of yellow marrow relative to red marrow.

POTENTIAL PROBLEMS

There are a number of potential problems encountered in the interpretation of bone marrow MR imaging. The most common include recognition of normal variants. These include: (1) residual islands of hematopoietic marrow, especially in the proximal femora and humeri; (2) residual red marrow within the proximal humeral epiphysis and femoral capital epiphysis; (3) focal fatty marrow, especially within the spine.

Other problems are purely technical in nature. For example, there is a significant decrease in sensitivity for bone marrow pathology when intermediate weighted sequences are utilized in place of true T1 weighted spin-echo images. Similar problems arise if fast spin-echo imaging is utilized without adequate fat saturation. Similarly, it is important to obtain pre-contrast T1 weighted spin-echo images as post-gadolinium images alone, without the use of fat saturation, can cause yellow marrow to appear homogeneously high signal, completely obscuring lesions which are easily seen on pre-gadolinium images.

Problems can also arise differentiating benign from malignant processes. Degenerative discogenic changes within the spine on MRI are relatively common. These findings include a spectrum of marrow signal alteration adjacent to a degenerated disc including marrow edema, increased fatty marrow, or end plate sclerosis. Well described marrow signal alteration also takes place following radiation therapy, chemotherapy, and bone marrow transplantation. Heavy smokers, marathoners, and menstruating-age females are noted to have increased residual red marrow within the distal femora about the knees. Benign processes such as these

should not be confused for more significant pathology.

One of the most common clinical problems is the distinction of benign osteoporotic compression fracture of the spine from pathologic compression fracture due to malignant processes. A vertebral body wedge compression fracture that demonstrates complete preservation of normal bone marrow signal intensity is consistent with a chronic benign compression fracture. Acute or subacute benign vertebral body compression fractures demonstrate marrow signal alteration in a regular pattern with smooth margins. Frequently this is in a band-like pattern paralleling the involved vertebral body end plate. An underlying fracture line is frequently visible. The posterior height of the vertebral body is also frequently preserved. The marrow signal returns to normal in one-to-three months. Malignant vertebral body compression fractures demonstrate complete replacement of normal marrow signal intensity in 88% of cases. If incomplete, it is generally in an irregular distribution. Focal metastasis elsewhere, posterior element involvement, cortical disruption, and a ballooned morphology of the vertebral body favour a neoplastic etiology. Neither the presence nor the absence of enhancement following intravenous gadolinium appears specific enough to preclude serial MRI or biopsy. The presence of a paraspinal mass can also be present with either a benign or malignant etiology.

It should be noted that vertebral compression fractures in patients with multiple myeloma can appear benign at MR imaging, and their distribution is similar to that observed in osteoporotic fractures. The possibility of multiple myeloma, therefore, should not be excluded in patients with benign-appearing vertebral compression fractures at MR imaging.

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