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Review

Diffusion-weighted imaging and the skeletal system: a literature review

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Diffusion-weighted imaging (DWI) is a magnetic resonance imaging (MRI) sequence that has a well-established role in neuroimaging, and is increasingly being utilised in other clinical contexts, including the assessment of various skeletal disorders. It utilises the variability of Brownian motion of water molecules; the differing patterns of water molecular diffusion in various biological tissues help determine the contrast obtained in DWI. Although early research on the clinical role of DWI focused mainly on the field of neuroimaging, there are now more studies demonstrating the promising role DWI has in the diagnosis and monitoring of various osseous diseases. DWI has been shown to be useful in assessing a patient's skeletal tumour burden, monitoring the post-chemotherapy response of various bony malignancies, detecting hip ischaemia in patients with Legg–Calvé–Perthes disease, as well as determining the quality of repaired articular cartilage. Despite its relative successes, DWI has several limitations, including its limited clinical value in differentiating chondrosarcomas from benign bone lesions, as well as osteoporotic vertebral compression fractures from compression fractures due to malignancy. This literature review aims to provide an overview of the recent developments in the use of DWI in imaging the skeletal system, and to clarify the role of DWI in assessing various osseous diseases.

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Introduction

Diffusion-weighted imaging (DWI) is a magnetic resonance imaging (MRI) sequence that has a well-established role in neuroimaging,[1–3] and is increasingly being utilised in other clinical contexts, including the assessment of various skeletal disorders. Although some studies, including those examining the role of DWI in distinguishing benign from malignant vertebral compression fractures,[4–8] have shown promising results, others have yielded equivocal results on the diagnostic capabilities of DWI in assessing osseous disease.

This literature review aims to provide an overview of the recent developments in the use of DWI in imaging the skeletal system, and to clarify the role of DWI in assessing various osseous diseases. Extra-osseous diseases will not be reviewed in this paper.

Principles of DWI

DWI utilises the variability of Brownian motion of water molecules. Water molecules are in constant motion, with their rate of movement or diffusion dependent on their

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kinetic and thermal energy. In biological tissue, water movement is neither completely free nor random. This is due to the constant physical and chemical interactions of the water molecules with other macromolecules, intracellular organelles, cell membranes, as well as vascular structures.

The differing patterns of water molecular diffusion in various biological tissues help determine the contrast obtained in DWI. Vascular structures and tissues that have lost their cellular integrity, such as necrotic tissues, allow for greater mobility of water molecules and will exhibit lower signals in diffusion-weighted images. Tissues with higher cellularity, intact cell membranes, or excessive fluid distension, have restricted water diffusion and will exhibit high signal. Diffusion-weighted images can therefore provide indirect functional information about the tissues' micro-environment to aid in the differentiation between normal and diseased tissues.

Techniques for DWI

A diffusion-weighted image is obtained by applying two symmetric diffusion-sensitising gradients about a 180° refocusing pulse. Molecules that are static will acquire phase information from the first diffusion-sensitising gradient, but will then be completely refocused by the second diffusion-sensitising gradient. In contrast, water molecules that are in motion will not be completely refocused by the second diffusing-sensitising gradient, thus resulting in a decrease in signal. The degree of water mobility has been found to be proportional to the degree of signal loss, with greater water mobility resulting in greater signal loss.[9]

The strength, duration, and interval between the two diffusion-sensitising gradients, and hence the degree of diffusion weighting, are determined by an operator-selected parameter, the b-value. The b-value is calculated as:

$$b = \gamma^2 G^2 \delta^2 (\Delta - \delta/3)$$

where γ = gyromagnetic ratio, G = gradient amplitude, δ = diffusion-sensitising gradient duration and Δ = time between diffusion-sensitising gradients. A larger b-value is therefore associated with greater gradient amplitude, a longer diffusion-sensitising gradient duration, and a wider interval between the two diffusion-sensitising gradients.

Signal intensity decreases exponentially with increasing b-values. A b-value of 0 preserves the signal-to-noise ratio of T2-weighted imaging; however, the resulting images are strongly affected by diffusion effects. In comparison, increases in the b-value gradually suppress the diffusion effect, better highlighting the differences in diffusion properties of the tissues, but at the expense of signal intensity.

There are five main types of DWI sequences: (1) spin-echo DWI: this is a simple sequence which has a relatively high signal-to-noise ratio (SNR) but a long acquisition time; (2) single-shot echo planar imaging (SS-EPI): this is currently the most commonly used sequence. It offers significantly quicker acquisition times while maintaining relatively high SNR; however, it is vulnerable to susceptibility artefacts, particularly at tissue interfaces; (3) Multi-shot echo planar imaging (MS-EPI): this is an echo planar sequence that divides the echo train into shorter parts. It provides higher spatial resolution and is less susceptible to artefacts or distortions; however, it has a longer acquisition time; (4) single-shot fast spin-echo (SS-FSE): this sequence has similar speed and spatial resolutions to echo planar sequences, and are less sensitive to susceptibility artefacts; (5) steady-state free precision imaging (SS-FPI): this is a type of gradient-echo MRI pulse sequence with fat saturation.

Assessment of DWI images

DWI can be assessed quantitatively or qualitatively. Clinical correlation is essential for proper interpretation of DWI.

Quantitative assessment

Quantitative interpretation of DWI involves the use of apparent diffusion coefficient (ADC) values. The ADC value for a particular region of interest (ROI) can be calculated from the gradient of the line representing the logarithmic decrease in signal between two or more b-values; the accuracy of the calculated ADC improves when greater numbers of b-values are utilised. The ADC is expressed in square millimetres per second. Tissues that have restricted water diffusion will have lower ADCs, while those that allow for greater water mobility will have higher values. It is important to note that ADC values can be affected by factors such as hardware, type of sequence used and vendor software.

Qualitative assessment

DWI can also be assessed qualitatively through visual analysis or ADC maps. Tissues with restricted water diffusion will appear hyperintense on DWI and hypointense on ADC maps, whereas those with increased water diffusion will appear hypointense on DWI and hyperintense on ADC maps. The exception to this involves the "T2 shine-through" phenomenon.[10] This phenomenon occurs in tissues that do not have restricted water diffusion, and have a high T2 relaxation time. These tissues will appear bright on both DWI and ADC maps.

Primary bone malignancies

Osteosarcoma

Diagnosis

Yakushiji *et al.*[11] reported that DWI may be more effective than contrast-enhanced MRI in distinguishing chondroblastic osteosarcomas from chondrosarcomas.[11] They studied five chondroblastic osteosarcomas, 17 lesions of other types

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