Advances in Diffusion-Weighted Imaging

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KEYWORDS

• Diffusion-weighted imaging • IVIM • Reproducibility • Apparent diffusion coefficient • MR imaging

KEY POINTS

- Intravoxel incoherent motion is a methodology to evaluate diffusion-weighted imaging (DWI) with the use of multiple *b* values, to separate the contribution of perfusion from tissue diffusion.
- DWI has been applied to the detection and characterization of tumors from multiple organs.
- DWI has been used to predict and evaluate response to treatment for a number of different tumors and treatment modalities.
- Reproducibility of apparent diffusion coefficients (ADC) measurements from DWI is limited by variability in imaging techniques and methods of ADC analysis.

INTRODUCTION

Diffusion-weighted imaging (DWI) has become an increasingly routine component of clinical MR imaging. Its unique soft tissue contrast mechanism exploits differences in the motion of water molecules in vivo at a biologically meaningful scale. The clinical potential of DWI in lesion detection, characterization, and response assessment has been explored in multiple organs and for multiple tumors.[1,2] This review briefly covers basic principles of DWI and introduces some recent advances in the field, specifically for abdominopelvic organs. For additional introductory review articles, several excellent references are available.[3–5]

BASIC PRINCIPLES OF DIFFUSION-WEIGHTED IMAGING

DWI is based on the use of single shot echoplanar imaging sequence with a long time to echo (TE) (60–100 ms), fat suppression, and the addition of motion-probing gradient pulses. When turned on, these gradients are used to decrease the signal intensity (SI) of moving water molecules during image acquisition. The SI of water molecules within each tissue decreases exponentially with the magnitude of their motion and with the strength of the motion-probing gradients (Equation 1).

$$S_b = S_0 \exp(-b \times ADC) \quad (1)$$

In this monoexponential equation, the strength of the motion-probing gradients is summarized in a *b* value that reflects the amplitude, duration, and interval between the gradients. The magnitude of the water diffusion is described by the apparent diffusion coefficient, or ADC, measured in mm^2/s. S_0 and S_b are the baseline SI (before a motion probing-gradient is applied) and the SI at a prescribed *b* value. Thus, various tissues lose their SI at different rates governed by their baseline SI, their ADC, and the choice of *b* value.

Intravoxel Incoherent Motion

DWI performed in body imaging quickly revealed a non-monoexponential behavior of ADC as a function of the *b* value. That is, the choice of *b* value influenced the calculated ADC of tissue (**Fig. 1**).

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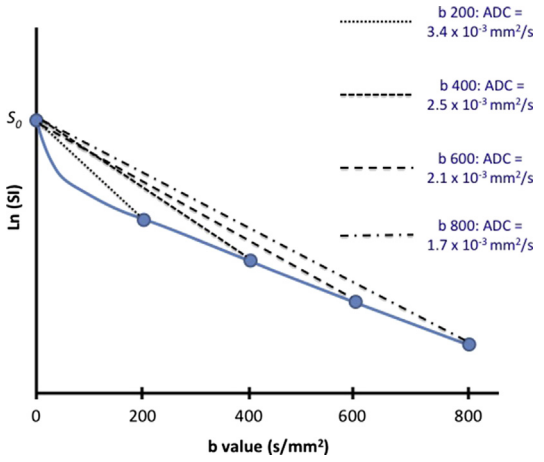

Fig. 1. Dependence of apparent diffusion coefficients (ADC) on *b* value used in single *b* value diffusion-weighted image (DWI). On a logarithmic scale, the signal intensity of soft tissue is usually observed to decrease more rapidly at lower *b* values (<200 s/mm^2) than at higher *b* values (>200 s/mm^2). When DWI is limited to a single *b* value, the calculated ADC can vary from 3.4 $\times$ 10^{-3} mm^2/s (*b* = 200) to 1.7 $\times$ 10^{-3} mm^2/s (*b* = 800).

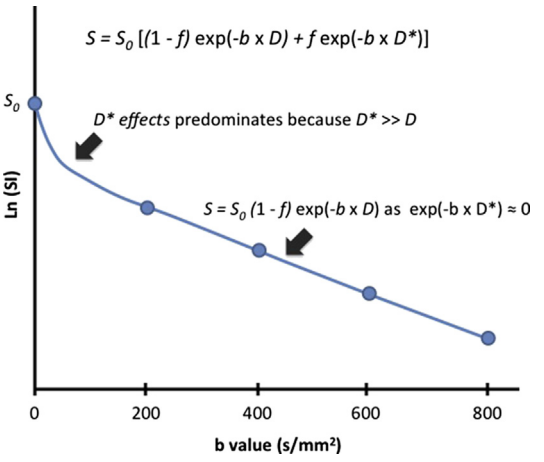

Fig. 2. Intravoxel incoherent motion (IVIM) parameters contribution to tissue signal intensity (SI). The rapid loss in SI of soft tissue, *S*, at lower *b* values is partly explained by the contribution of water signal from the intravascular space, which is defined by the perfusion fraction (*f*) and the pseudodiffusion coefficient *D**. Because *D** is usually several orders of magnitude larger than *D*, its contribution approaches zero as *b* increases above 100 to 200 s/mm^2. Thus, at higher *b* values (>200 s/mm^2), a monoexponential behavior is observed from the extravascular fraction of moving water molecules (1 – *f*), which is governed by the tissue diffusion coefficient *D*.

This observation was explained in part by work from Le Bihan and colleagues,[6,7] recognizing that the motion of water molecules contributing to the signal in DWI arise from different compartments: extracellular space diffusion, intracellular space diffusion, and intravascular space diffusion (or perfusion).[8] Separating the motion of water molecules owing to perfusion in the microcirculation from that owing to diffusion in the extravascular space is summarized by the methodology of intravoxel incoherent motion (IVIM) imaging (Equation 2).

$$S_b = S_0\,[(1 - f)\exp(-b \times D) + f\exp(-b \times D^*)] \quad (2)$$

Where S_0 and S_b represent the SI at baseline and at a specified *b* value, *f* represents the perfusion fraction (or the contribution of water moving in capillaries), *D* represents the tissue diffusion coefficient, and *D** represents the pseudodiffusion coefficient (or diffusion within the microcirculation). Because *D** is greater than *D* by several orders of magnitude, its contribution is negligible at higher *b* values (typically above *b* = 200 s/mm^2). At higher *b* values, the relationship between S_b and *b* again approximates a monoexponential equation dependent on *D* (**Fig. 2**). This limitation led to the 2009 consensus statement on the use of DWI as an imaging biomarker, emphasizing the role of multiple *b* values for measurement of ADC, and the possibility of calculating ADC_{high}, a surrogate for *D*, using only high *b* value DWI.[9]

Treatment Response

Much excitement has been generated from the use of DWI in oncologic imaging because of its potential to monitor treatment response in vivo.[4] The ability of DWI to evaluate oncologic outcomes can generally be separated into a pretreatment prediction of response, and the prediction of the response during or following treatment, such as chemotherapy or radiotherapy. The cellularity and vascularity of tumors are often affected by oncologic treatments, with potential changes affecting all 3 IVIM components, which are quantifiable by analysis of diffusion weighted images.

Diffusion-Weighted Imaging Reproducibility

Several barriers to the widespread adoption of DWI, especially in abdominal imaging, have included technical challenges to ensure a high-quality scan for every patient, and reproducible measurements of ADC. Quantifying the reproducibility of ADC and IVIM parameters is necessary before its use in clinical practice, and has been proposed by a panel of experts in the 2009 consensus statement.[9] The challenges in generating reproducible ADC and IVIM parameters is highlighted in selected studies.