INTRODUCTION: Tissue often contains a spectrum of $T_2$ values. Measurement of the full $T_2$ spectrum could potentially provide information on tissue composition and pathology that goes beyond what is available from methods used in current clinical practice. For example, the $T_2$ spectrum of white matter (Figure 1) provides detailed information on the processes of demyelination and inflammation in diseases such as multiple sclerosis. Despite its promise, $T_2$ spectrum analysis is rarely used clinically. This is because the current method used to measure $T_2$ spectra, multi-exponential fitting, requires very long scan times (~20-30 minutes) [1]. An alternate method for obtaining information from $T_2$ spectra is linear combination filtering (LCF) [2,3]. The advantage LCF is that it can be performed in clinically reasonable scan times. The disadvantage is that it only provides information on a single, extended region of the $T_2$ spectrum. In this project, we develop a novel technique that uses LCF to provide an estimate of the full $T_2$ spectrum in a clinically reasonable scan time.

THEORY: LCF begins with a multi-echo acquisition. In each pixel, this produces a signal at $n$ echo times: $S(TE_1), \ldots, S(TE_n)$. The signals are then linearly combined in a weighted sum with arbitrary weighting coefficients ($a_i : i=1, \ldots, n$) to produce a composite signal:

$$S_{\text{composite}}(T_2) = \sum_{i=1}^n a_i \cdot S(T_2, TE_i)$$

(1)

With an appropriate choice of $a_i$'s, the signal from one part of the $T_2$ spectrum can be highlighted, while the signal from the rest of the spectrum is suppressed. The curve that defines the relative weighting of $T_2$ components is the “filter response function” (Fig. 1). Previous studies have designed filter response functions to isolate a single component of the spectrum (e.g. myelin, Fig. 1). In the present study, we develop a method using LCF to estimate the full $T_2$ spectrum. To accomplish this task, we employ two modifications (Fig. 2): First, a narrower-band filter response function is used. The purpose is to isolate signal from within a $T_2$ peak, as opposed to the whole peak as in conventional LCF. Second, a series of response functions centered at consecutive $T_2$ values, rather than just a single function centered about one specific $T_2$ value, is used. It can be shown that this provides an estimate of the $T_2$ spectrum ($\hat{m}$) that is a convolution between the true $T_2$ spectrum ($m$), and the filter response function:

$$\hat{m}(T_2) = m \ast f$$

(2)

Thus, the effect of the filter response function is to generate a distorted estimate of the true $T_2$ spectrum. However, the distortion is fully controlled by the user-designed filter response function. This provides significant opportunity for optimization.

METHODS AND RESULTS: Phantom and in vivo experiments were performed to validate the new technique. All data was acquired using a multi-echo spin echo pulse sequence (16 echoes, TE=8ms, matrix=128x128). Scan time was five minutes. The first experiment estimated the $T_2$ spectrum of a Gd phantom. Figure 3a indicates that the measured shape of the estimated $T_2$ spectrum corresponds very closely to theoretical predictions (Eq. 2). Note that due to the distortion inherent in the technique, the estimated $T_2$ spectrum is broadened relative to the true single, monoexponential $T_2$ value. A second experiment applied the technique in vivo to white matter. Figure 3b illustrates that the estimated $T_2$ spectrum contains two peaks in accordance with the known white matter $T_2$ spectrum (see Fig. 1). Unlike the expected true shape of the $T_2$ spectrum, however, the peaks overlap due to distortion in the estimate.

DISCUSSION AND CONCLUSIONS: A novel application of LCF for providing estimates of full $T_2$ spectra in a clinically reasonable scan time was shown. Although estimates had distortion relative to the true $T_2$ spectrum, the presence of peaks could still be detected. This may be sufficient for clinical purposes, where the presence of absence of peaks can provide information on pathology. In the future, it may be possible to reduce distortion through optimization of the filter response function. Alternately, since Eq. 2 indicates that distortion is caused by convolution, another possibility for reducing (or perhaps even eliminating) distortion is deconvolution.


A Novel Method for Characterizing $T_2$ Spectra

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Figure 1: White matter $T_2$ spectrum (red) with axonal and myelin peaks indicated. Examples of wide (blue) and narrow (green) filter responses are shown.

Figure 2: a) $T_2$ spectrum and three narrow filter responses at different $T_2$ values. b) The dot product of each filter response and $T_2$ spectrum provides an estimate of the $T_2$ spectrum at each $T_2$ value

Figure 3: a) $T_2$ spectrum estimate of a Gd phantom. For comparison, the $T_2$ value derived from monoexponential fitting is indicated. b) $T_2$ spectrum estimate of white matter. The small peak may be myelin.