Simultaneous MR Elastography and Fat+Water Imaging

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Target Audience: Clinicians and scientists interested in quantitative MRI applications.

Purpose: Non-alcoholic fatty liver disease (NAFLD) is a condition that is increasing in prevalence in western countries (now affecting nearly 33% of the North American population) and can lead to liver fibrosis and end-stage liver disease. NAFLD-related liver failure is expected to be the most common reason for liver transplantation in the United States within the next few years [1]. In the past, the only option for clinicians to obtain quantitative information about the extent of steatosis and fibrosis was to perform a liver biopsy. MRI-based techniques are increasingly being used as safer, more comfortable, and less expensive alternatives to biopsy in this assessment. Dixon techniques with advanced processing [2] have been shown to provide accurate quantitative estimates of proton-density fat fraction throughout the entire liver in very short acquisition times [3]. Similarly, MR elastography (MRE) [4] has been shown to provide reliable quantitative assessment of liver fibrosis throughout the entire liver in scan times as short as one minute. These two techniques can be performed sequentially [5,6] to provide a comprehensive assessment of liver health with short total exam time. However, the independent nature of these two data sets offers the possibility of acquiring this information simultaneously in a single acquisition. Potential advantages of simultaneous acquisition include the opportunity to increase signal-to-noise ratio (SNR) within the same combined acquisition time, decrease scan time without SNR loss, and eliminating motion misregistration between the data sets. The purpose of this research was to implement and test a modified MRE protocol that enables simultaneous stiffness and fat+water estimation from a single data set. After describing the MRE sequence modification and image reconstruction pipeline, we present experimental results that demonstrate this new capability.

Methods: In a standard MRE exam, motion-encoding gradient (MEG) directions, polarities, and offsets are varied such that mechanically-induced tissue is motion encoded in the phase of the acquired image series. Similarly, in a standard fat+water exam, echo times (TE) are varied to reveal chemical shift effects. Motion-induced phase and chemical shift are fundamentally orthogonal effects, which suggests that they can be simultaneously encoded into a single data set. To achieve this goal, we utilize a modified MRE sequence wherein a different TE is used for each MEG direction. Letting t, i, and $\pm$ denote phase-offset, TE/MEG direction, and MEG polarity indices, respectively, the (image-domain) signal generated by this modified MRE sequence can be modeled as:

$$\boldsymbol{g}_{\pm}[t,i] = \left(\boldsymbol{f}_{water} + \boldsymbol{\rho}[i]\boldsymbol{f}_{fat}\right)\mathrm{e}^{\mathrm{j}(\boldsymbol{\omega}\mathrm{TE}[i]\pm\boldsymbol{\phi}[t,i]+\boldsymbol{B_C}[i])} + \boldsymbol{z}_{\pm}[t,i] \qquad (1)$$

where $\boldsymbol{f}_{water}$ and $\boldsymbol{f}_{fat}$ are (complex-valued) water and fat signals, $\boldsymbol{\rho}$ is the chemical shift phasor, $\boldsymbol{\phi}$ is the motion-induced phase, $\boldsymbol{\omega}$ is the B_0 field map, and $\boldsymbol{z}$ is zero-mean proper complex Gaussian noise. Additionally, $\boldsymbol{B_C}$ denotes (*a priori* known) concomitant field-induced phase [7,8] that results from applying the MEGs; for mono-directional MRE sequences considered here, this phase is independent of MEG offset or polarity. Given $\boldsymbol{g}$, the first step of image reconstruction isolates $\boldsymbol{\phi}$ via simple phase differencing: $\boldsymbol{\phi}[t,i]=\frac{1}{2}\mathrm{PU}\left(\angle\boldsymbol{g}_{+}[t,i]\overline{\boldsymbol{g}_{-}[t,i]}\right)$, where PU denotes phase-unwrapping (here via graph cuts [9]). Next, both $\boldsymbol{\phi}$ and $\boldsymbol{B_C}$ are demodulated out of $\boldsymbol{g}$, and the signal is reduced:

$$\boldsymbol{h}[i] = \frac{\mathrm{e}^{-\mathrm{j}\boldsymbol{B_C}[i]}}{2T}\sum_{t=0}^{T-1}\left(\boldsymbol{g}_{+}[t,i]\mathrm{e}^{-\mathrm{j}\boldsymbol{\phi}[t,i]} + \boldsymbol{g}_{-}[t,i]\mathrm{e}^{+\mathrm{j}\boldsymbol{\phi}[t,i]}\right) \approx \left(\boldsymbol{f}_{water} + \boldsymbol{\rho}[i]\boldsymbol{f}_{fat}\right)\mathrm{e}^{\mathrm{j}\boldsymbol{\omega}\boldsymbol{\tau}[i]} + \boldsymbol{z}[i] \qquad (2)$$

Finally, the water, fat, and B_0 signals are estimated from the composite signal in (2) by solving:

$$\left[\hat{\boldsymbol{f}}_{water}, \hat{\boldsymbol{f}}_{fat}, \hat{\boldsymbol{\omega}}\right] = \arg\min\left\{\lambda P(\boldsymbol{\omega})) + \sum_{i}\left|\left(\boldsymbol{f}_{water} + \boldsymbol{\rho}[i]\boldsymbol{f}_{fat}\right)\mathrm{e}^{\mathrm{j}\boldsymbol{\omega}\boldsymbol{\tau}[i]} - \boldsymbol{h}[i]\right|^2\right\} \qquad (3)$$

where $P()$ is a quadratic finite difference penalty. As in [10], we solve this problem with graph cuts. To test our framework, motion was induced (Resoundant, amplitude=25%, freq=60 Hz, dir=A/P) in a phantom constructed of bovine gelatin and vegetable shortening (Fig. 1), and imaged at 1.5 T (General Electric, HDxt, v16.0) using a 2D GRE MRE sequence (matrix=256^2, FOV=24cm, Δz=5mm, TR=100ms, TE={28.000,29.588,31.176}ms, BW=15.63kHz, phase offsets=4, MEG dir={R/L,A/P,S/I}). A total of 24 images were collected during the scan. Following wave field estimation, a stiffness map of the phantom was generated from the MRE signal (2) via local frequency estimation [11].

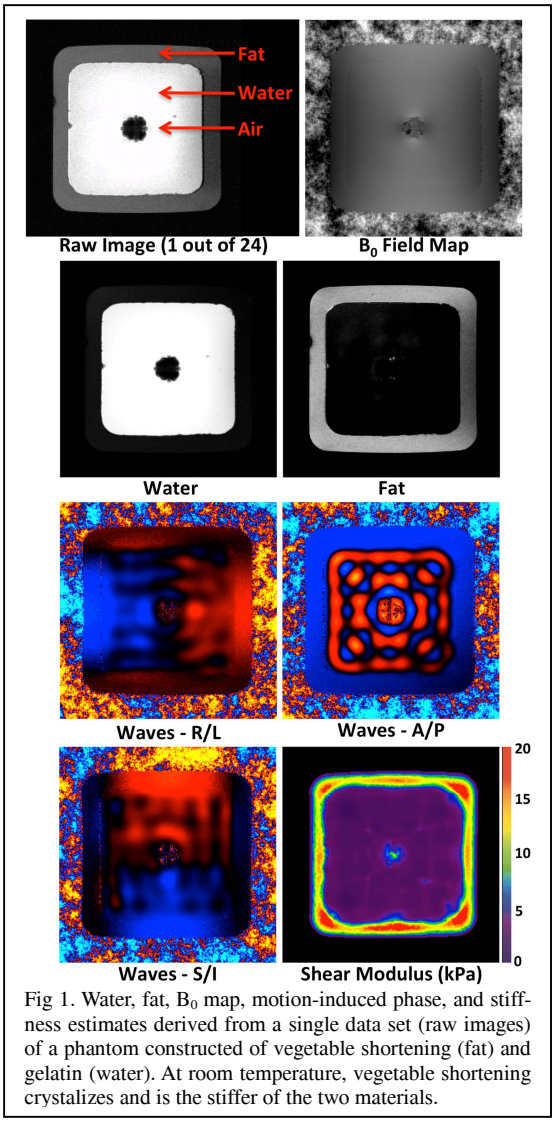

Fig 1. Water, fat, B_0 map, motion-induced phase, and stiffness estimates derived from a single data set (raw images) of a phantom constructed of vegetable shortening (fat) and gelatin (water). At room temperature, vegetable shortening crystalizes and is the stiffer of the two materials.

Results: Fig. 1 shows the different MRE and fat+water image quantities estimated by the proposed strategy from the acquired data set. Note the clean separation of the fat and water phantom components, as well as the strong apparent wave field in the A/P phase image (in which driving motion is through-plane). Also, as expected, the stiffness map indicates that the vegetable shortening (18.3±4.1kPa) – which is crystalized at room temperature – is substantially more stiff then the gelatin (3.1±0.5kPa).

Discussion: In this work, we proposed a simple (multi-echo) modification to a standard multi-directional MRE acquisition sequence and demonstrated how this enables water, fat, stiffness, and B_0 field map information to all be simultaneously estimated from this single data set. Unlike existing MRE protocols [1,2] – particularly for the liver – a separate fat+water scan is not required with our proposed approach, which may offer benefits in terms of scan efficiency, SNR, and artifact reduction. Future directions for this work will include *in vivo* testing and method generalization to incorporate acceleration strategies like parallel imaging. Additionally, it may be possible to also vary TE within MEG directions, such that >3 TEs are obtained in the same overall scan time. This would enable R_2^* to be simultaneously estimated and used for iron quantification and improving fat fraction accuracy, as well as account for possible signal variations between data acquired with different echo times.

Conclusion: The proposed multi-echo MRE protocol and reconstruction strategy enables simultaneous stiffness and fat+water signal estimation from a single data set.

References: [1] Charlton, Clin Gastro Hepat 2004;2:1048-58 [2] Reeder, MRM 2004;51:35-45 [3] Reeder, JMRI 2012;36:1011-1014 [4] Muthupillai, Science 1995:269;1854-57 [5] Low, ISMRM 2010:4639 [6] Chen, Radiology 2011;259:749-6 [7] Bernstein, MRM 1998;39:300-8 [8] Johnson, MRM 2010;63;1564-74 [9] Bioucas-Dias, IEEE TIP 2007;16:698-709 [10] Hernando, MRM 2010;63:79-90 [11] Manduca, MIA 2001;5:237-54