Water and Lipid Content Measurements Using Diffuse Optical Spectroscopy and MRI in Emulsion Phantoms

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Abstract: We present a quantitative comparison of lipid and water signals obtained from broadband Diffuse Optical Spectroscopy (DOS) and Magnetic Resonance Imaging (MRI) of emulsion tissue phantoms.

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1. Introduction
Magnetic resonance imaging (MRI) and near-infrared diffuse optical spectroscopy (DOS) are non-invasive techniques that provide complementary structural and functional physiological information. Co-registration of these two methods has the potential to enhance our understanding of the complex biological processes associated with tumor transformation and growth [1,2]. Ultimately, the combination of the two measurement techniques can be applied to monitoring tumor changes in response to therapy, resulting in an improved method to test cancer treatment efficacy.

There are two components of tissue that produce a signal measurable by both modalities: water and lipids. MRI has multiple techniques of chemical shift imaging, which is able to separate water and fat images by utilizing the different resonant frequencies of the protons in the hydrogen of water and fat molecule. DOS also has the ability to measure water and lipids in vivo through its sensitivity to the near-infrared vibrational overtones of the water O-H bond (978 nm) and lipid C-H bonds (930 nm).

In this paper we present results from an investigation of the correlation between MRI and DOS data obtained from water and soybean oil emulsion phantoms. DOS measured water and lipid concentrations are compared with calibrated MRI water and fat images providing a quantitative comparison of measurements by each technique. Our results show excellent agreement between the developing DOS technology and the established technology of MRI for both water and lipid measurements. This work provides validation of the accuracy and sensitivity of DOS measurements in vivo through a quantitative comparison with the medical imaging “gold standard” of MRI.

2. Materials and Methods
The DOS instrument used in this study is a combined frequency-domain and steady-state system that has been described in detail elsewhere [3]. Frequency domain measurements are used to determine the spectral dependence of the reduced scattering coefficient ($\mu_s'$), assumed to follow a power law, and to calibrate a broadband, steady-state reflectance measurement. The absorption coefficient ($\mu_a$) spectrum can then be calculated using diffusion theory. Finally, concentrations of H$_2$O and lipid are determined by a least-squares fit to extinction coefficient spectra. The broadband absorption spectrum (650-1000 nm) provides the spectral information necessary to measure water and lipid concentrations.

An emulsion phantom set was made to simulate tissues composed of different water/lipid ratios. The composition of the phantoms included water, soybean oil and Triton x-100. The water and soybean oil provide the same absorption characteristics as water and lipids in breast tissue. Triton x-100 is an emulsifying agent that was added to each phantom in the amount of 4 percent of the volume of the oil. A
set of twelve 0.5 L phantoms were prepared and measured by DOS with water (lipid) composition ranging from 35 to 94 (65 to 6) percent by volume. A small amount (~10 ml) was removed from nine of these emulsions for MRI measurements. An MRI measurement of the phantoms was performed in a 4 Tesla magnet and chemical shift imaging was used to separate pure water and fat images. Absolute concentrations of water and lipid were then determined by MRI through a calibration using measured values from pure water and soybean oil samples.

3. Results

Figures 1 and 2 show how the DOS and MRI measured water and lipid volume [%] compare with expected values. In general, both figures demonstrate that there is a strong correlation between actual and measured values. For both figures the MRI data is constrained between the pure water and soybean oil measurements, but there is some scatter in the emulsion phantom measurements, which is a result of field in-homogeneities that were difficult to eliminate due to the air-phantom interfaces.

In Figure 1, the line of DOS measurements is tighter than the MRI measurements, except for a single phantom (~80% H2O), which stands out as an anomalous point. The anomalous water value recovered for this phantom is likely due to air bubbles in the phantom that were near the source or detector fibers. Also, a repeat measurement of this phantom on a separate day provided a value of 81% H2O.

In Figure 2 the lipid content is increasingly overestimated by DOS as the soybean oil volume increases. This deviation of the fat from the expected value is most likely due to errors in the estimation of extinction coefficient of soybean oil that is implemented in the chromophore fit. The surfactant (Triton x-100) used to emulsify the phantoms was added as a percentage of the soybean oil in the phantom. Although the Triton x-100 was neglected in the chromophore fit it did share common spectral features with soybean oil. Therefore, as the phantoms increase in percentage of Triton x-100, there is an increase in the recovered lipid content, which is compensating for the small amount of Triton x-100. The correlation coefficients for the DOS and MRI trend-lines are: DOS water $R^2 = 0.96$, DOS lipids $R^2 = 1.00$, MRI water $R^2 = 0.99$ and MRI lipids $R^2 = 1.00$.

Lastly, a direct comparison between DOS measurements and MRI for water and fat, provide excellent correlations ($R^2_{\text{water}} = 0.95$ and $R^2_{\text{lipid}} = 0.99$). This suggesting that optical and MRI signals are derived from identical phantom components. In addition, by comparing DOS results to the MRI “gold standard”, we further validate DOS as a quantitative technique for lipid and water analysis in tissue.
4. Conclusions
To the best of our knowledge this is the first study of a quantitative comparison between MRI and DOS [4]. In practical terms, this work could lead to improvements in both MRI and Diffuse Optical Tomography (DOT) image analysis.

For example, Pogue et al proposed to use a priori information from MR images to constrain the image reconstruction of DOT [5]. Using this approach, the optical inverse problem can be simplified by constraining boundaries on optical images of water and lipid based on water and fat MR images. The resulting image would be higher resolution than DOT could offer independently and the functional information would be absolute and provide higher contrast than MRI.

5. References

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