Off-resonance saturation enhanced phase contrast of the brain at ultra-short TE

Chunlei Liu[1,2], Wei Li[1], and Peder Larson[3]

[1]*Brain Imaging and Analysis Center, Duke University, Durham, NC, United States,* [2]*Department of Radiology, Duke University, Durham, NC, United States,*
[3]*Radiology and Biomedical Imaging, UCSF School of Medicine, San Francisco, CA, United States*

PURPOSE: Phase and susceptibility contrast of the brain are generally obtained at long echo times (TE ~ 40 ms at 3T) using the gradient-echo sequence (1, 2). The structures of the brain, however, are compartmentalized with a wide range of relaxation times. At such long TE, the short-T2 components are largely attenuated and contribute minimally to phase contrast. The purpose of this study was to determine whether gradient-recalled-echo (GRE) images of the brain exhibit any phase contrast at ultra-short TE (UTE) and whether this contrast can be controlled by off-resonance saturation. Our data demonstrated that proton images of the brain can indeed attain strong phase contrast even at a TE of 64 μs by saturating the short-T2 component.

METHODS: 3D UTE brain images of healthy volunteers were acquired at 7T (GE Healthcare, Waukesha, WI) with anisotropic field of view (FOV) of 16-22 cm, depending on the head size, and with a 1x1x3 mm resolution. Data were sampled with a 3D radial trajectory using an 8-channel-receive head coil. The radial trajectory was designed to allow anisotropic FOVs and resolution (3). The duration of readout was 1 ms. Other parameters of the GRE sequence were: TR = 10 ms, TE = 64 μs, and flip angle = 10°. Images were reconstructed using gridding (3). To assess the effort of suppressing short-T2 component, we used the off-resonance saturation contrast (UTE-OSC) method (4) by applying off-resonance 360-degree adiabatic pulses to partially saturate the broad short-T2 resonance. The saturation frequency was ±1.2 kHz.

After gridding reconstruction, phase images were calculated for each coil separately. Phase wraps were removed with a Laplacian-based algorithm (5). The difference between image phase by each coil and the mean phase was calculated, which contain no anatomical structures. The low-pass filtered phase difference, i.e. coil phase, was subtracted from individual phase images and the resulting phase values are coherent among different coils. The coil-phase-removed phase maps and the magnitude maps from different coils were then reconverted into complex data and averaged. The combined phase was calculated from the averaged complex data and was unwrapped again using the Laplacian-based phase unwrapping. This phase processing procedure avoids signal-cancelation due to incoherent phase, and yields excellent SNR by suppressing noisy phase from coils of low sensitivity.

RESULTS: Fig. 1 shows the UTE contrasts of a representative slice through the cortex with and without off-resonance saturation. Without saturation, both magnitude and phase images exhibited weak tissue contrast. With saturation, magnitude intensity of white matter decreased significantly relative to gray matter and CSF, thus appearing darker as expected. Surprisingly, this saturation induced a strong phase contrast at this ultra-short TE. Specifically, white matter exhibited higher phase shift relative to CSF and gray matter. At the same time, both gray and white matter appeared paramagnetic, which differs from that observed at long TE where white matter appears diamagnetic. This behavior was consistent between negative and positive saturation frequencies. The phase difference between without and with saturation shows that the saturated short-T2 components of the white matter have negative frequency shift.

Fig. 2 compares the frequency between images with and without saturation at the midbrain which demonstrated similar characteristics as the cortex.

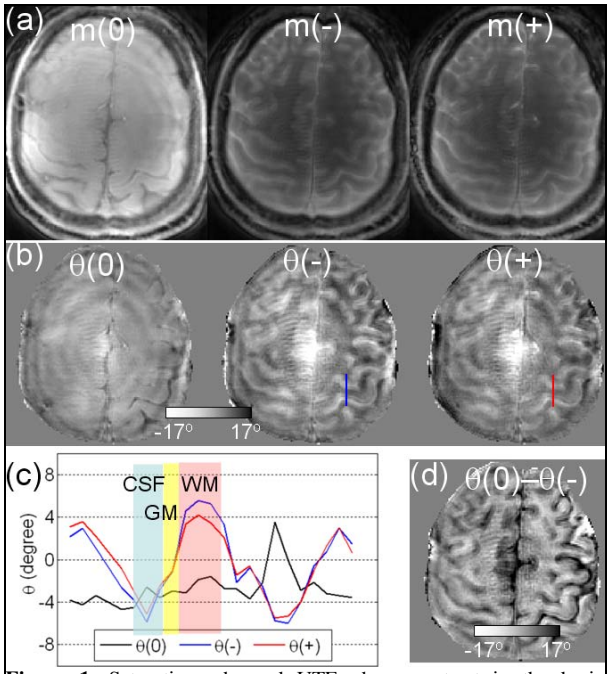

Figure 1. Saturation-enhanced UTE phase contrast in the brain cortex. (a) Magnitude image without saturation (m(0)), with negative frequency off-resonance saturation (m(-)) and with positive frequency saturation (m(+)). (b) Corresponding phase maps showing dramatically enhanced contrast with saturation. (c) A line profile of cortical phase contrast demonstrating positive shift in both gray and white matter with saturation. (d) Phase differences between without and with saturation showing negative difference in white matter.

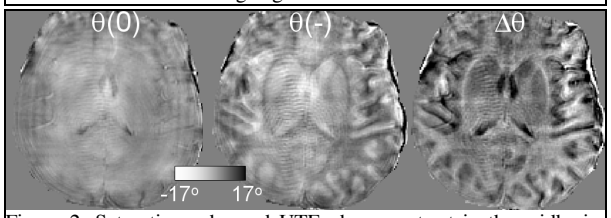

Figure 2. Saturation-enhanced UTE phase contrast in the midbrain. Contrast was weak without saturation and was enhanced with saturation.

DISCUSSIONS AND CONCLUSIONS: We showed that, when the short-T2 component was saturated, brain tissues exhibited strong phase contrast even at a TE as short as 64 μs. Phase angles was measured to be in the range of ±17°. In addition, under off-resonance saturation, white matter appeared paramagnetic at ultra-short TE. While gray matter also exhibited largely paramagnetic shift, in areas close to CSF it may be diamagnetic. This property differs fundamentally from that of long TE. When measured with TEs on the order of tens milliseconds, it has been routinely reported that white matter has a diamagnetic frequency shift while gray matter is paramagnetic. To determine whether the off-resonance saturation pulse affected phase contrast at long TEs, we also measured the phase at 5 ms and 15 ms. Results showed that the off-resonance saturation had minimal effects at these long echo times.

Taken together, our data suggested that the short-T2 component in the white matter has a negative frequency shift relative to surrounding gray matter and CSF. Saturation of this short-T2 component results in a strong positive frequency shift in the white matter. This shift is observable even at ultra-short TE. This short-T2 component is likely composed of bounded protons or restricted water pools such as water between myelin sheaths. The negative frequency shift is consistent with the reported diamagnetic susceptibility of myelin. Although the saturation-enhanced UTE phase contrast varies with saturation frequency, it appears to be insensitive to the sign of the saturation frequency. The exact mechanism for this insensitivity is still under investigation. The observed phase contrast may also include the effects of phase accumulation during the UTE radial readout (8), and future work will include this in data analysis. Further studies are also needed to determine the effect of saturation transfer on the increased phase contrast at UTE.

UTE imaging offers advantages in being able to directly image tissues with T2 values less than a few milliseconds, such as tendons and cortical bone (6). In the brain, short-T2 components are present in white matter (7) - believed to be associated with myelin – as well as in connective tissues and calcifications, and these are known to be altered in neurodegenerative diseases and other neurological pathologies. We believe off-resonance saturation together with UTE offers a new way to generate phase contrast and to probe tissue microstructure. Until now, phase contrast of the brain has been largely generated at long TE. UTE provides the advantage of high efficiency, high SNR and minimal susceptibility-induced distortion. Saturation, on the other hand, offers a means to manipulate phase contrast. This unique capability may provide additional insight into the mechanisms of phase contrast of the brain.

REFERENCES: 1. Haacke, E.M. et al, MRM 52:612-618, 2004. 2. Duyn, J.H. et al, PNAS 104:11796-11801, 2007. 3. Larson et al, IEEE Trans Med Imag 2008; 27(1): 47-57. 4. Du et al. MRM 2009; 62(2): 527-531. 5. Li, W. et al, NeuroImage 2011 ; 55 :1645-1656. 6. Gatehouse et al, Clin Radiol 2003; 58: 1-19. 7. Waldman et al, Neurorad 2003; 45: 887-892. 8. Carl M, et al, MRM 2012 ; 67 : 991-1003.