Optimization of pulse echo time for maximum enhancement in susceptibility-weighted imaging

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Introduction: To enhance susceptibility contrast in gradient echo (GRE) images, signal phase $\varphi(t)$ can be combined with magnitude $M(t)$ to generate a susceptibility weighted image (SWI) $I(t) = M_0 \cdot e^{-t/T2^*} \cdot (1 - \varphi(t)/\pi)^4$, where M_0 represents initial magnitude and t is echo time (TE) [1]. Here we derive a method for choosing the optimal TE to maximize the enhancement of susceptibility contrast by the applied phase mask.

Theory: To generate the phase mask for SWI, phase is pre-processed to remove phase wraps and low frequency components to preserve local phase variations generated by differences in tissue susceptibility. A normalized phase mask is typically designed to be $\varphi_m(t) = (\pi - \varphi(t))/\pi$ for regions with phase characteristics to be enhanced, and equal to 1 elsewhere [1]. We model the phase mask as being linearly dependent on echo time. Considering the boundary conditions $\varphi_m(0) = 1$, and $\varphi_m(T_\pi) = 0$, the SWI signal can be rewritten as: $I(t) = M_0 \cdot e^{-t/T2^*} \cdot (1 - t/T_\pi)^4$, where T_π signifies the time point that phase accumulates to π radians. T_π can be empirically derived by fitting the phase mask over multiple TEs. Like magnetic susceptibility χ, T_π varies among different types of tissues. To maximize the enhancement, $E(t) = M(t) - I(t)$, the optimal echo time TE_{opt} must satisfy

$$\frac{dE(t)}{dt} = M_0 \cdot e^{-t/T2^*} \cdot \left[\frac{1}{T2^*} \cdot \left(1 - \frac{t}{T_\pi}\right)^4 + \frac{4}{T_\pi} \cdot \left(1 - \frac{t}{T_\pi}\right)^3 - \frac{1}{T2^*}\right] = 0 \qquad \text{(Eq.1)}.$$

Fig.1 depicts the contour map of the analytical solution for TE_{opt}, which is a function of $T2^*$ and T_π.

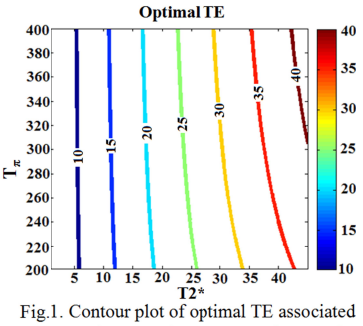

Fig.1. Contour plot of optimal TE associated with maximum enhancement of SWI for varying T2* and T_π.

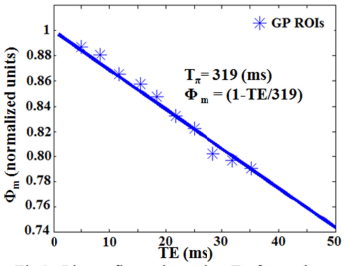

Fig.3. Linear fit to determine T_π from phase accumulation in selected tissue.

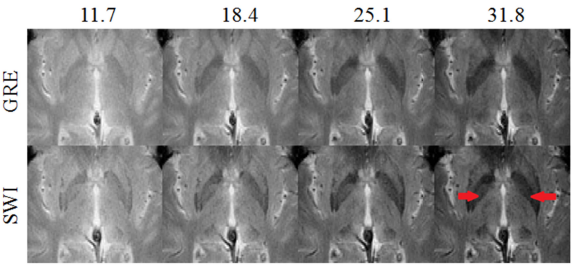

Fig.2. Magnitude *(top row)* and SWI *(bottom row)* images at different echo times, indicating by the numbers at top. Red arrows point size of 3x3 ROIs for GP. Maximal SWI enhancement occurs at TE 25.1(ms).

Materials and Methods: Simulations of signal change were performed in a time range (0 ms to 45 ms), corresponding to the practical range of clinically used TE values. Reference experimental data were acquired on a healthy volunteer under an IRB-approved protocol on a 3T Siemens MRI system. 3D multi-echo GRE data with 10 echoes evenly spaced from 5 ms to 35.15 ms were obtained. Other image parameters were: flip angle 20 degree, TR 110ms, 28 slices, matrix 256×256, resolution 1×1×2.5 mm^3. After data acquisition, all 10 echo data were SWI-processed using a Homodyne-Gaussian filtering method. Within manually defined ROIs in the globus pallidus (GP), $T2^*$ values were computed by nonlinear fitting. T_π value was empirically determined using the method mentioned above. Although the GP was selected to illustrate our approach, other structures, such as thalamus or vessels, are also possible.

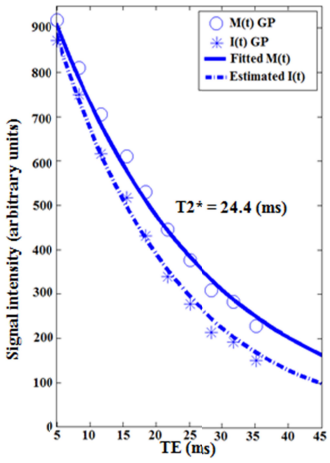

Fig.4. Measured signal from ROIs in GP for magnitudes and susceptibility weighted data.

Results: Fig. 2 shows original magnitudes and SWI results for the 10-echo GRE data. From the linear fitting of phase masks, the T_π for GP was 319 ms (*Fig.3*). To determine the optimal TE for enhancement, $M(t)$ *(blue line - Fig 4)* was fitted to the measured magnitude data *(blue circles-Fig.4)*) to obtain $T2^*$ of the GP. Using obtained values of $T2^*$ and T_π, the calculated $I(t)$ is derived *(blue dashed line - Fig.4)*. The measured SWI data *(blue asterisks - Fig.4)* is well estimated by the $I(t)$ curve *(blue dashed line)*. Fig.5 illustrates the enhancement $E(t)$ for the GP as a function of TE. Using Eq. 1, and the estimated $T2^*$ and T_π gives a TE_{opt} of 24.0 ms indicated by the blue arrow in Fig.5. This corresponds to the peak of the measured enhancement curve.

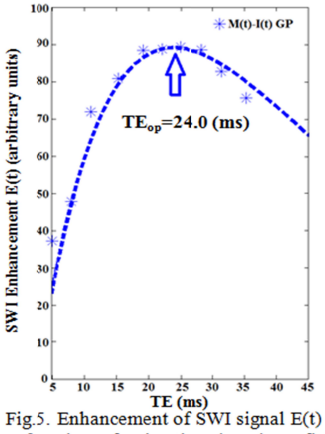

Fig.5. Enhancement of SWI signal E(t) as a function of echo time based on fitted M(t) and derived I(t) in Fig.3. Blue arrow indicates expected maximum of E(t).

Conclusion: A novel approach for choosing TE to optimize SWI enhancement for selected tissues is introduced in this study. Use of this approach requires derivation of $T2^*$ and T_∂ for the tissue of interest. Both are easily characterizable using multi-echo datasets. Note that Fig.1 suggests that the optimal TE is very close to the $T2^*$ of the tissue, and that T_∂ has relatively smaller influence than $T2^*$ over the range evaluated. T_∂ is related to tissue susceptibility, ÷, but the precise relationship has not been established and the physiologic range of T_∂ is yet to be determined.

Reference: [1] Haacke *et al*., AJNR 2009;30: 3019-30 .