Optimal Enhancement of Brain Structures by Combining Different MR Contrasts: Demonstration of Venous Vessel Enhancement in Multi-Echo Gradient-Echo MRI

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TARGET AUDIENCE: Researchers with interest in venous vessel visualization, susceptibility weighted imaging, and novel MR image contrasts.

PURPOSE: Multi-echo gradient-recall echo (GRE) sequences provide quantitative information about the effective transverse relaxation rate, $R_2^*$ (magnitude of the signal) and magnetic field perturbations caused by the tissue susceptibility distribution (phase of the signal). They also reveal information of the magnitude signal immediately after the rf-pulse, $S_0$, which depends on tissues’ spin density and $T_1$, as well as on the flip angle. The complex GRE information is, for instance, employed in susceptibility weighted imaging (SWI), a heuristic approach for combining magnitude and phase of the GRE signal into a composite image to enhance the contrast of cerebral veins and brain lesions. While SWI is today established in hospitals throughout the world a considerable drawback of SWI is that the visualization of veins depends on the orientation of the vessels with respect to the main magnetic field. This is reflected in sometimes ambiguous representations of veins, in particular in sagittal and coronal views, and impedes accurate segmentation of cerebral veins and quantification of their radii. Automatic generation of 3D models of the venous vasculature based on SWI is also hampered because the inter-hemispheric fissure is hypointensively displayed, just like veins. In this contribution, we present a supervised approach for creating image contrast that enhances specific structures of interest. We apply linear discriminant analysis (LDA) to optimally combine multiple image contrasts generated from complex-valued multi-echo GRE information (magnetic susceptibility, $R_2^*$, and $S_0$) to yield a novel contrast with increased venous vessel contrast.

THEORY: LDA is a technique for feature extraction and dimension reduction. LDA projects data onto a lower-dimensional vector space such that the ratio of the between-class distance to the within-class distance is maximized, thus achieving maximum discrimination. Volumes of interest (VOIs) were identified in 4 subjects and the means and standard deviations of magnetic susceptibility, $R_2^*$, and $S_0$ were assigned as features. VOIs were divided into two classes: vein (cortical veins, sinuses) and remaining tissue (arteries, cerebral spinal fluid (CSF), white matter (WM), cortical gray matter (GM), deep GM structures, interhemispheric fissure). LDA was applied to these data (training step) and the resulting base vectors were then applied to other GRE data (evaluation step) to generate composite images.

METHODS: Dual-echo GRE data sets (TOP-SWI-sequence, $\Delta T_E/T_E/TR/TA=3.5\mathrm{~ms}/25.4\mathrm{~ms}/15^\circ/13.31\mathrm{~min}/\mathrm{sec}$, voxel size $=0.45\mathrm{~mm} \times 0.45\mathrm{~mm} \times 1.12\mathrm{~mm}$) were acquired from six healthy volunteers on a 3T MR scanner. Four data sets were employed to find the optimal base vectors using LDA (training step) which were then evaluated on the remaining two data sets (evaluation step). Maps of $R_2^*$ (in ms$^{-1}$) and $S_0$ were computed using mono-exponential fitting of the magnitude signal decay. Aliasng in phase images was resolved by 3D phase unwrapping and background phase contributions were eliminated with the SHARP method. Homogeneity enabled incremental dipole inversion of the background-corrected phase images yielded quantitative susceptibility maps. To reduce inter-subject variability, the magnetic susceptibility was normalized with respect to frontal white matter ($\Delta \chi$), and the range of $S_0$ values was adjusted to be between 0 and 1. For comparison, SW images were created from magnitude and phase images according to the SWI standard processing scheme (i.e., 4-fold multiplication of the linearly weighted high-pass filtered phase images with the magnitude images). Venous vessel visibility was assessed by computing the contrast-to-noise ratio (CNR) of 5 veins for the different contrasts according to $\text{CNR} = \sqrt{\langle S \rangle - \langle S \rangle^2}$, where $S$ and $\langle S \rangle$ denote the mean and standard deviation of a VOI and the subscripts v and t indicate whether the VOI represents a vein or tissue.

RESULTS: Mean $R_2^*$ values were plotted against mean magnetic susceptibility differences (Fig. 1). Although the majority of veins were characterized by high susceptibilities, certain deep GM structures (globus pallidus, substantia nigra, and red nucleus; black points in Fig. 1) yielded similar susceptibility and $R_2^*$ values, resulting in a slight overlap between the two classes. LDA yielded maximum separation if $\Delta \chi$ and $R_2^*$ were merged according to $0.325 \text{ppm} - \Delta \chi + 0.907 s \cdot R_2^* - 0.27 - S_0 - 0.013$. The LDA-combined images are presented in Fig. 2e and f. In these images the apparent intensity of CSF increased (blue arrow in Fig. 2e) and of highly myelinated regions decreased (red arrow in Fig. 2f) compared to the magnetic susceptibility map. Furthermore, the inter-hemispheric fissure was displayed isointense on LDA-combined images (black arrows in Fig. 2e and f). The sinus veins were accurately displayed in the composite image, whereas hypointensities around veins were observed in SW images (red arrows in Fig. 3). The average CNR was highest for the LDA-combined image based on $\Delta \chi$, $R_2^*$, and $S_0$ (CNR=6.46). The CNR of the remaining contrasts were: 4.70 for magnetic susceptibility, 4.46 for $R_2^*$, and 4.31 for the magnitude, 5.12 for SWI, and 6.01 for the LDA-combined data based on $\Delta \chi$ and $R_2^*$.

DISCUSSION: Base vectors derived from training data allowed the combination of multiple contrasts into composite images that yielded increased venous contrast compared to the magnetic susceptibility and $R_2^*$ maps alone. The base vectors can also be transferred to data collected with different acquisition parameters because magnetic susceptibility is nearly independent of acquisition parameters and the dependence of acquisition parameters on $R_2^*$ can be considered. The venous contrast, in particular in deep GM regions, may be further improved by incorporating additional features obtained after post-processing of GRE data (e.g., application of vessel enhancing filtering to magnetic susceptibility images) or additional MRI scans as well as employing non-linear discriminant analysis.

CONCLUSION: Discriminant analysis provides base vectors for optimized combination of multiple contrasts. The technique can be easily adjusted to emphasize other tissue properties in composite images by changing the definition of classes in the training step to yield, e.g., improved delineation of pathologies such as cortical lesions.