SNR and CNR Comparison of Single-Echo Dixon and Subtraction Contrast-Enhanced MR Angiography

Eric G. Stinson[1], Joshua D. Trzasko[1], Paul T. Weavers[1], and Stephen J. Riederer[1]
[1]*Mayo Clinic, Rochester, Minnesota, United States*

Target Audience: ISMRM members with interest in emerging contrast-enhanced MR angiography techniques.

Purpose: Multi-echo Dixon-based methods have recently gained attention for use in contrast-enhanced MR angiography (CE-MRA) due to their ability to suppress the high signal from fat while avoiding subtraction errors due to motion between pre- and post-contrast images in subtraction CE-MRA. Additionally, multi-echo Dixon CE-MRA provides improved signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) dependent on the number of acquired echoes and the concentration of contrast in the blood[1,2]. However, multi-echo Dixon-based methods require two or more images acquired at different echo times, possibly extending the repetition time and reducing temporal resolution in time-resolved studies. Single-echo Dixon techniques avoid extending the dynamic scan time by obtaining an estimate of the "nuisance" phase (due to B_0 inhomogeneities and the initial phase in the water and fat signals) from either a calibration scan before the dynamic portion of the exam or a "virtual shimming" procedure[3–5]. Water images from single-echo Dixon are expected to avoid subtraction artifacts and exhibit SNR a factor of $\sqrt{2}$ higher than that of subtraction CE-MRA. Single-echo Dixon methods have been used for dynamic fat-suppressed exams in the past, but to our knowledge the technique has not been applied to CE-MRA. Moreover, a rigorous SNR comparison with subtraction CE-MRA has not been performed, nor has the effect of gadolinium-induced (Gd-induced) susceptibility on single-echo Dixon SNR been studied at 3T. The purpose of this study is to theoretically derive and experimentally confirm SNR and CNR in single-echo Dixon CE-MRA compared to subtraction CE-MRA.

Methods: *Theory:* Single-echo Dixon imaging assumes that both the water (W) and the fat (F) signals are real and have known initial phase ϕ_0 as shown in Equation 1. The time-dependent ΔB_0-induced phase $\phi(t)$ and chemical shift-induced phase $\theta(t)$ are also assumed known. To obtain real-valued W and F, a phase constrained reconstruction[6] was used (Equation 2). Theoretical SNR and CNR ratios (Dixon/Subtraction) were derived for a fully sampled image acquired with a single channel (Equations 3 and 4). *Phantom Experiments* were performed with an anthropomorphic fat-water phantom simulating an abdomen (bovine gelatin) with subcutaneous fat (vegetable shortening). Gadolinium-doped (Gd-doped) vials of bovine gelatin were inserted into a void in the center of the phantom to simulate an enhancing abdominal aorta. Fully-sampled axial images were acquired with each vial in place with a birdcage coil at 3.0T (GE, Waukesha, WI) with the following scan parameters: $TE_1/TE_2/TR$=2.3/3.5/6.5msec, α=18°, BW=±62.5kHz, FOV=22×22×9cm, Matrix=224×224×60. Images acquired at TE_1 and TE_2 were used to estimate $\phi(t)$ and ϕ_0 using a two-point Dixon method[7]. The estimated phases were then used to separate fat and water components from the similarly acquired single-echo image (TE/TR=2.8/6.5msec). To determine the effect of Gd-induced susceptibility changes (as described in Hoory et al.[8]) on the SNR and CNR ratios, water images were reconstructed using both the true phase image (with the Gd-doped vial in place) and the pre-contrast phase image (with the undoped vial in place). Subtraction images were formed via complex subtraction of the unenhanced image from each enhanced image. Region-of-interest-based (ROI-based) measurements were performed in ten consecutive slices to determine any SNR or CNR gain. *In vivo experiments* were performed in a volunteer before and after contrast injection. The enhanced image was acquired after the contrast had reached equilibrium. Scan parameters were identical to the phantom experiments except: α=30°, FOV=42.0×42.0×14.4cm, and Matrix=280×280×96. ROI-based measurements were performed in ten consecutive slices in the iliac artery to determine SNR and CNR benefit of Dixon over subtraction CE-MRA.

$$S(t) = \left(W + Fe^{i\theta(t)}\right)e^{i(\phi(t)+\phi_0)} \quad (1)$$

$$\begin{bmatrix} W \\ F \end{bmatrix} = [Re\{A^*A\}]^{-1}Re\{A^*S\}, \quad A = e^{i(\phi(t)+\phi_0)}[1\ e^{i\theta(t)}] \quad (2)$$

$$\frac{SNR_{Dixon}}{SNR_{sub}} = \frac{|f_{\mathrm{CE}}|}{|f_{\mathrm{CE}} - f_{blood}|}\sqrt{2}\sqrt{1-\cos^2(\theta)} \quad (3)$$

$$\frac{CNR_{Dixon}}{CNR_{sub}} = \frac{|f_{\mathrm{CE}} - f_{bg}|}{|f_{\mathrm{CE}} - f_{blood}|}\sqrt{2}\sqrt{1-\cos^2(\theta)} \quad (4)$$

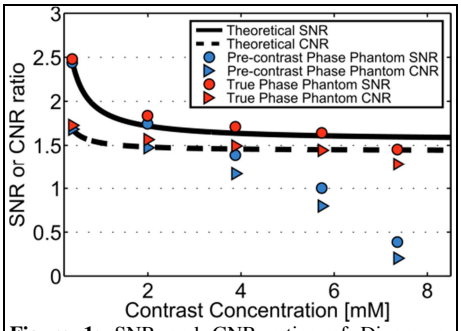

Figure 1: SNR and CNR ratios of Dixon vs. Subtraction CE-MRA within the phantom. Results are shown using pre-contrast phase and true phase in the Dixon reconstruction.

Results: SNR and CNR ratios from the phantom experiment are shown in Figure 1 demonstrating a contrast concentration-dependent improvement in both SNR and CNR compared to subtraction CE-MRA. In theory, for a properly chosen echo time, SNR and CNR are improved by a factor of at least $\sqrt{2}$ with greater improvement at lower contrast concentrations. When the pre-contrast phase image is used (blue), the SNR and CNR ratios are reduced at higher contrast concentrations. When the true phase is used (red) the ratios track very closely with theory and show the predicted factor of $\sqrt{2}$ or greater improvement. In vivo SNR and CNR results are shown in Figure 2. The SNR and CNR improvement using either pre-contrast or post-contrast phase estimate are very close. Again, SNR and CNR improvements of a factor of $\sqrt{2}$ or greater are observed.

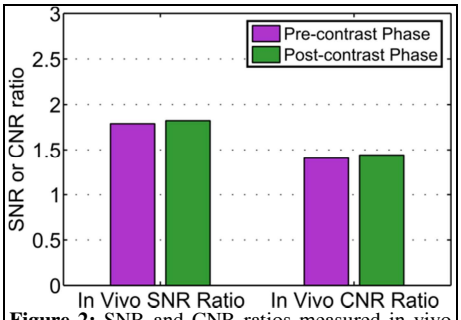

Figure 2: SNR and CNR ratios measured in vivo using the phase measured before (purple) and after (green) contrast injection.

Discussion: The theoretical improvement in SNR and CNR shows a contrast concentration-dependent improvement similar to previous results for multi-echo Dixon vs. subtraction CE-MRA[2]. In short, as the contrast concentration approaches zero, the denominators of Equations 3 and 4 do so as well and the SNR and CNR ratios tend toward infinity. The discrepancy between the SNR and CNR measurements in the physical phantom using the true phase and the pre-contrast phase indicates that there are Gd-induced susceptibility effects at higher contrast concentrations as indicated in Hoory et al.[8]. The artifacts of these susceptibility effects manifest in the single-echo water images as signal loss within the Gd-doped vials. The in vivo results, however, do not show a large difference in SNR or CNR between images reconstructed with phase estimated from pre-contrast images or post-contrast images. This may indicate that with the in vivo contrast concentrations present in this study – in which contrast had reached equilibrium – the effects of the Gd-induced susceptibility are minimal. From this study, it is unclear if the contrast concentrations present in a first-pass angiographic study would reduce SNR and CNR due to Gd-induced susceptibility artifacts.

Conclusion: A careful theoretical and experimental analysis of the SNR and CNR improvement of single-echo Dixon vs. subtraction CE-MRA has been performed. Phantom and in vivo experiments confirm the predicted SNR and CNR improvement of a factor of $\sqrt{2}$ or greater. At high contrast concentrations (>3-4mmol) Gd-induced susceptibility artifacts can reduce the SNR and CNR of Dixon CE-MRA. The single-echo Dixon technique may allow time-resolved CE-MRA which has both higher SNR and CNR and improved resistance to motion than current subtraction-based methods.

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