Optimizing contrast-to-noise efficiency for small changes in T1

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Introduction: Contrast-to-noise optimization has been dealt with in great detail over the last 20 years (1-6). However, for small changes in T1 between two tissues or in the same tissue between two identical scans, it becomes possible to derive some rather interesting relationships between flip angle and repeat time by assuming a differential relationship of contrast and change in T1. The motivation for this work is to provide a quick off hand expression for parameters to optimize contrast showing even marginal T1 changes. The two most important imaging parameters considered are the flip angle and repeat time.

Theory: We investigate the angle at which to optimize the contrast-to-noise per sqrt(acquisition time). We begin with the usual steady state incoherent expression for an RF spoiled short TR gradient echo imaging from which we derive the CNR by taking the derivative of $\rho(\theta)$ with respect to T1 which yields (5):

$$CNR(\theta) = \frac{\rho_0 * E_1 * \delta T_1 * TR * \sin\theta * (1-\cos\theta)}{\sigma_0 * T_1^2 * (1-\cos\theta * E_1)^2} \quad \text{-- (1)}$$

In this formula, T1 represents the average of the two T1 values in question. The optimal flip angle is found by differentiating this function and equating it to zero. This process yields the simple expression (5):

$$\cos\theta_{a,optimal} = \frac{2 * E_1 - 1}{2 - E_1} \quad \text{-- (2)}$$

In the limit of TR << T1, this collapses to

$$\theta_{optimal} = \sqrt{3} * \theta_E \quad \text{-- (3)}$$

where θ_E is the Ernst angle. The T1 value used to calculate the Ernst Angle is the initial T1 of the tissue. This is so chosen because the exact T1 change will not generally be known. Finally, the CNR/sqrt(time) is calculated by multiplying Eq.(1) by sqrt(T_{acq}/TR = n_{acq}).

Results: The deviation of Eq.(3) from Eq.(2), for T1 value of 4000 ms and different values of δT1, is shown in Figure 1. The absolute error in maximum CNR, calculated from the original form of the contrast equation ($\rho(\theta,T1) - \rho(\theta,T1-\delta T1)$) and using the simplified form in Eq.(3), is shown in Figure 2. The approximations we taut here are excellent to first order. Although the error in approximated flip angle itself is large at long TRs, not much of actual contrast is lost (less than 5%), even for TRs as long as 0.75T1. The contrast from Eq.(1) multiplied by the sqrt(n_{acq}) factor is shown in Figure 3. As observed by Buxton et al in (5), the best CNR is derived from a short TR experiment and not much of the peak contrast is lost, for a given change in T1, for TRs as long as 0.5T1. So, in those cases where a 2D scan is preferred it is possible to go to long TRs of 4000 ms or less and still remain within 80% of the peak contrast.

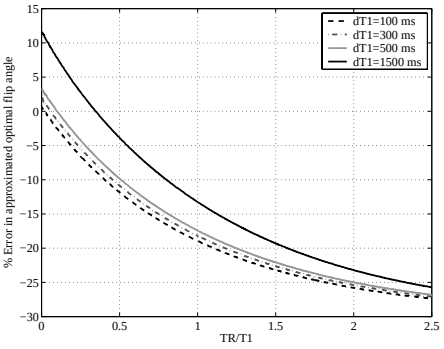

Figure 1. % Error in optimal flip angle Vs TR/T1

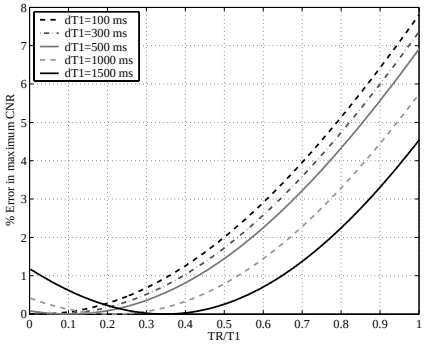

Figure 2. Absolute error in CNR Vs TR/T1

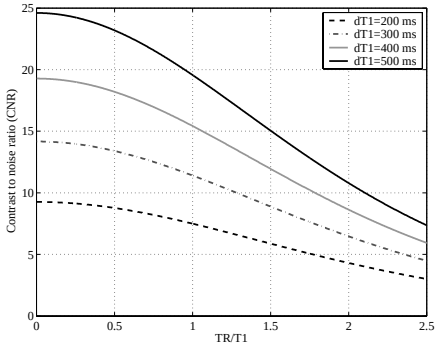

Figure 3. CNR for fixed time acquisition Vs TR/T1

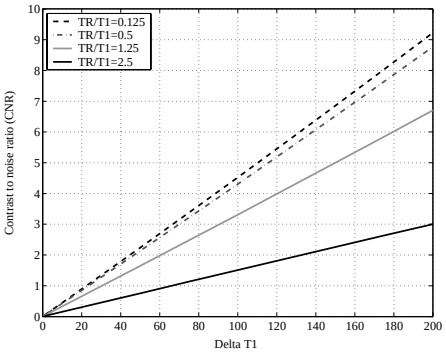

Figure 4. CNR Vs Delta T1

Discussion and Conclusions: The theoretical result presented in this paper has important practical implications. First, if two tissues have close relaxation times then the best flip angle to use is sqrt(3)* θ_E. Second, if a contrast agent is used to visualize changes in the tissue signals pre- and post-contrast, then again this choice of sqrt(3)* θ_E should be made. (These agents could be gadolinium based agents or even oxygen as is sometimes used in imaging the eye (7).) When the CNR is greater than 4, we will be able to detect a single pixel difference great enough to recognize the change in δT1 that led to that contrast. If there are 'p' pixels present in the object one can reduce the CNR needed from 4 to 4/sqrt(p) (6). From Fig.4 we can see that for TRs up to ½T1 (i.e. 2000 ms) a δT1 of 90 ms is enough to "just see" the change.

The contrast concentration for small δT1 is given by - $C=\delta T1/\alpha * T1^2$ where α is the relaxivity and C is the concentration in milli-moles, of the contrast agent. So the minimum amount of contrast agent that needs to be injected to enhance signal from blood even for small blood volume fractions can be found from this expression. Further, from Fig. 4, once the desired change in CNR is chosen, it is possible to determine the necessary dose of contrast agent from the required change in T1. This is important for two research areas. First, making the appropriate choice of dose of contrast agent required for a given problem. Second, determining how much contrast agent (such as oxygen absorption in the vitreous humor) is detectable in a given experiment. In conclusion, for short TR, RF spoiled gradient echo sequences, the optimal flip angle to maximize T1 contrast is $\theta_{optimal} = \sqrt{3} * \theta_E$ and there is not much of an advantage in acquiring the data in 3D over 2D or vice versa.

References: 1. N. J. Pelc, Magn. Res. Med. 29, 695 (1993). 2. E. H. Haselhoff, Magn. Res. Med. 38, 518 (1997). 3. J. Chai et al. Magn. Res. Med 34: 133 (1995). 4) W.A. Edelstein, P.A. Bottomley, H.R. Hart, L.S. Smith. J Comput Assist Tomogr. 1983 Jun;7(3):391-401. 5) Buxton RB, Edelman RR, Rosen BR, Wismer GL, Brady TJ. J Comput Assist Tomogr. 1987 Jan-Feb;11(1):7-16. 6. E. M Haacke et al MRI: Physical Principles And Sequence Design, John Wiley & Sons, 1999. 7) Berkowitz BA. et al. Magn. Reson. Med. 1995;33(4):579-81.