Image Contrast Optimization of the CE-FAST Pulse Sequence on a 0.05T Imager

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In tliis work we present experiments carriecl out on our 0.05T imager in order to optimize tlie image contrast of tlie CE-Fast pulse sequence. We calculatecl the expected contrast for tlie CE-FAST and Spin Echo sequeiices and compare these with values obt'ained from images of a. phantom built for tliis purpose. We conclude that tlie CE-FAST sequence is superior to tlie traditional Spiii Echo technique if one is interesed in producing a single image witli T2 coiitrast for tlie fast survey of a. region.

I. Introduction

Different rapid pulse sequeiices that take advantage of tlie nuclear magnetization steady-state condition[1] have beeii proposed for fast acquisition of MRI images. Some of these sequences have already beeii investigated in detail[2-6] aiid are now being used routinely for clinical purposes such as heart-triggered imaging as well as for other applications lilre functional imaging and localization iinages for *in vivo* spectroscopy.

We have implemented in our home made 0.05T whole body imaging system, a pulse sequeiice that combines two steady-state techniques. Tliis pulse sequence, origiiially proposed by different authors[7-9], permits tlie simultaneous acquisition of two iinages witli clearly *different contrasts*. Tlie signal from tlie first acquisition interval, tlie FID, is tlie same as for tlie standard Fourier Acquired Steady State (FAST) sequeiice, wliicli is also known as Fast Field Echo (FFE). Tlie second part of tlie signal, tlie eclio, wliicli is located immediately before tlie raclio frequency (RF) pulses, is analogous to tlie signal presented by tlie sequence known as coiitrast enhanced FAST (CE-FAST) or T_2 weiglited FFE[2-5]. In tliis work we will focus on tlie technique tliat uses tliis second sigiial (CE-FAST). Images obtained using tliis technique can show liigli T_2 coiitrast when properly optimized. Iii tlie following we will discuss tlie coiitrast optimization of this sequence.

Using steady-state techniques tlie contrast of tlie images is basically controlled by varying the repetition time (TR) and the flip angle (a).Tlie eclio time (TE), wliicli is used conventionally for contrast control, is generally lrept sliort in steady-state techniques to minimize inhomogenity and susceptibility effects that arise due to tlie use of gradient recallecl eclioes. Tlie contrast of tlie images obtained witli steady-state techniques is very sensitive to TR and α[5,6]. In particular, for appropriate TR values tlie CE-FAST sequence presents intrinsically high T_2 contrast. Tliis may he unclerstood in a simplified model regarding tlie acquired eclio as tlie result of two consecutive RF pulses witli an effective echo time of $TE_{\text{eff}} = 2^{*}TR - \text{TE}$, where TE is the iiiterval between tlie echo and tlie nest RF pulse.

II. Fundamental equations

Tlie pulse sequence for CE-FAST is given in Fig. 1 where tlie relevant sequence parameters are *defined*.

In order to analyze tlieoretically tlie contrast of the CE-FAST pulse sequence we have to lrnow tlie analytical expression for tlie signal amplitude, wliicli is proportional to tlie transverse magnetization M_Y. The espression of M_Y in tlie steady-state conditioii in the absence of imaging gradieiits lias been given by Ernst et. al.[1] as

$$M_Y = \frac{M_0(1-E_1)E_2 \sin\alpha(\cos \mathbf{O} - E_2)}{(1 - E_1\cos\alpha)(1 - E_2\cos 0) - (E_1 - \cos\alpha)(E_2 - \cos \mathrm{O})E_2} \quad (1a)$$

witli

$$E_1 = e^{-TR/T_1} \quad (1b)$$

and

$$E_2 = e^{-TR/T_2} , \quad (1c)$$

wliere O is the total precession angle of tlie spins during one repetition cycle. In orcler to avoid artifacts, tlie gradients usually applied for imaging are large enough to produce a rapid spatial variation of O so tliat, within a single voxel, O must be replaced by its mean value[4,10]. This means tliat for calculatioiis Eq. (1a) lias to be integratecl over **O.** Tlie analytical result of tliis integration was given by van der Meulen et. al.[2] as

$$M_Y = \frac{M_0 \sin\alpha}{1+\cos\alpha}\left[\frac{(1+\cos\alpha)E_2^2 - a}{\sqrt{a^2-b^2}} + 1\right] e^{(TR-TE)/T_2} \quad (2a)$$

with

$$a = \frac{1 - E_1E_2^2 + \cos\alpha(E_2^2 - E_1)}{1 - E_1} , \quad (2b)$$

$$b = (1+\cos\alpha)E_2 . \quad (2c)$$

Tlie iinaging gradients as shown in figure 1 shift tlie echo signal from T R to TE (for tliis reasoii tlie factor $e^{(TR-TE)/T2}$ has been included iii Eq.(2a) as in Ref.[2]).

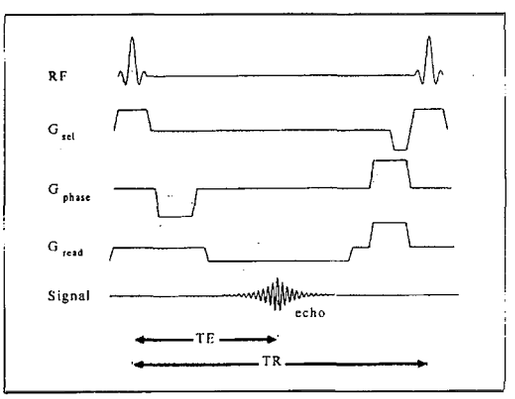

Figure 1. CE-FAST pulse sequence.

We now may calculate tlie contrast between tissues with different relaxation times T_1, T_2 and proton spin deiisities which are proportional to tlie equilihriuin magnetization M_0. For long repetition times tlie sequence gives intrinsically liigli T_2 contrast, though tlie sigiial amplitude and therefore signal to noise ratio decays in an exponeiitial manner. Tlie saine applies to tlie flip angle where tlie coiitrast is in general higher for small angles. A reasonable coinpromise between contrast and signal to noise is needed. The definition of a contrast-to-noise ratio (CNR) is very useful for tliis purpose[11,12].

For two tissues A and B with their respective signal amplitudes S_A, S_B aiid standard deviations σ_A, σ_B we calculate tlie CNR as[13]

$$CNR = \frac{S_A - S_B}{k} , \quad (3a)$$

with

$$k = \sqrt{(\sigma_A^2 + \sigma_B^2)/2} . \quad (3b)$$

III. Contrast calculations

Using Eq. 2, we calculatecl tlie theoretical contrast for tlie CE-FAST sequence for two liypotlietical tissues, A and B, having M_0 equal to unity and relaxation times T_1 aiid T_2 as given bellow. Fig. 2 shows tlie results as contour plots of $S_A - S_B$ versus repetitioii time, TR, and flip angle, α. From tliis one can see that an absolute maximum contrast can be achieved, between two given tissues, by carefully optimizing tlie sequence parameters for typical values of tlie corresponding relaxation times.

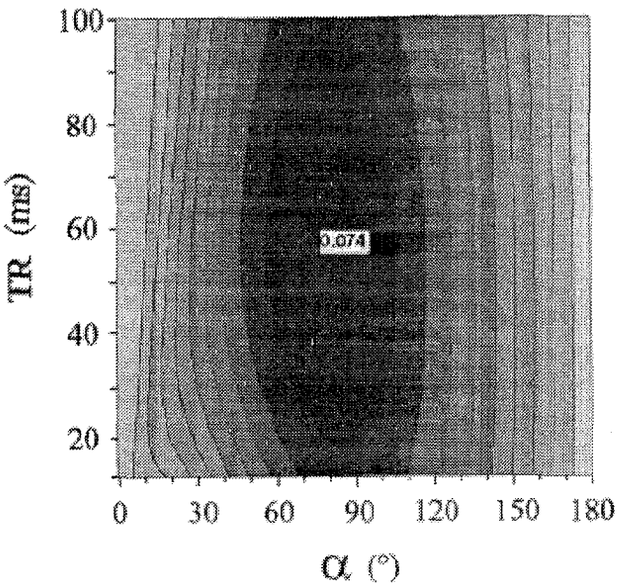

Figure 2. Contour map of tlie contrast between tissues A and B for the CE-FAST sequence. Tlie maximum is at TR = 56ms, a = 79° with a value of 0.074.

In order to prove that tlie above procedure allows to correctly optimize the sequence we performed a series of experiments using a phantom huilt for tliis purpose. The phantom consists of two coiicentrical tubes: the outer one contains $CuSO_4$ solution with a small amount of $MnCl_2$, the concentrations being 0.5mM and 0.05mM respectively, and tlie inner tube is filled witli a 0.5mM $MnCl_2$. These solutions, A and B, had tlie same relaxation times respectively as those assumed above foi tlie two hypothetical tissues A ancl B, given in Table 1. In the experiments we variecl the flip angle from 24° to 136° for four different repetition times. The results are shown in Fig. 3 as the difference between tlie mean values over regions of interest of the same area for solutions A and B of tlie non normalized images. Tlie error bars represent tlie quantity k in Eq. 3b obtained froni the standard cleviations of the intensities over the same regions. The continuous lines in Fig. 3 are plots of tlie expected contrast as calculated from Eq. 2, where tlie value of M_0 was obtained froin a series of images using the spin echo sequence with long TR and varyiiig TE. This was done by extrapolating tlie fitted image intensities to TE = 0. In this way the gain of the instrument is taken care of and the figure allows to check the accuracy of Eq. 2.

In all tlie above experiments the flip angles were measurecl using a direct method based on a stimulated echo experiment as described in a previous paper[14].

Table 1: Relaxation times of tissues A and B.

T_{1A} (ms)	T_{2A} (ms)	T_{1B} (ms)	T_{2B} (ms)
273 ± 14	162 ± 1	237 ± 9	86 ± 1

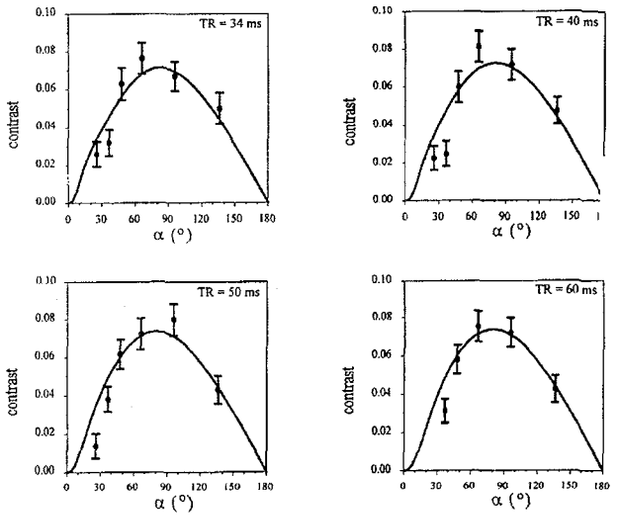

Figure 3. Comparison hetween experimental and calculated contrast for tlie CE-FASS sequence using different repetition times. The asterisks show tlie measured difference between tlie mean values over regions of interest of the same area for solutions A ancl B of tlie non normalized images. Tlie error bars represent tlie quantity k in Eq. 3b obtained from the stanclard deviations of tlie intensities over the same regions. Tlie continuous lines are plots of the expected contrast as calculatecl from Eq. 2.

IV. Comparison between CE-FAST and Spin Echo

Tlie above calculations give the optimum TR for maximum contrast, $S_A - S_B$, In order to optimize the contrast to noise ratio that can be obtained in a given time it is necessary to take into account the fact that reclucing TR allows to increase the number of averages and tlierefore to reduce the noise. To account for this me have to divide the calculatecl value of $S_A - S_B$ by the square root of TR. We have clone this for both, the CE-FAST and tlie Spin Echo sequences, and the results are plottecl in Fig. 4 bellow. The figure shows that for the shortest TR that could be realized on our system, 34 ms, it is possible to expect better contrast with a CE-FAST sequence than with optimized spin echo. This is

particularly significant if one is interested in producing a single image with T_2 contrast for the fast survey of a region.

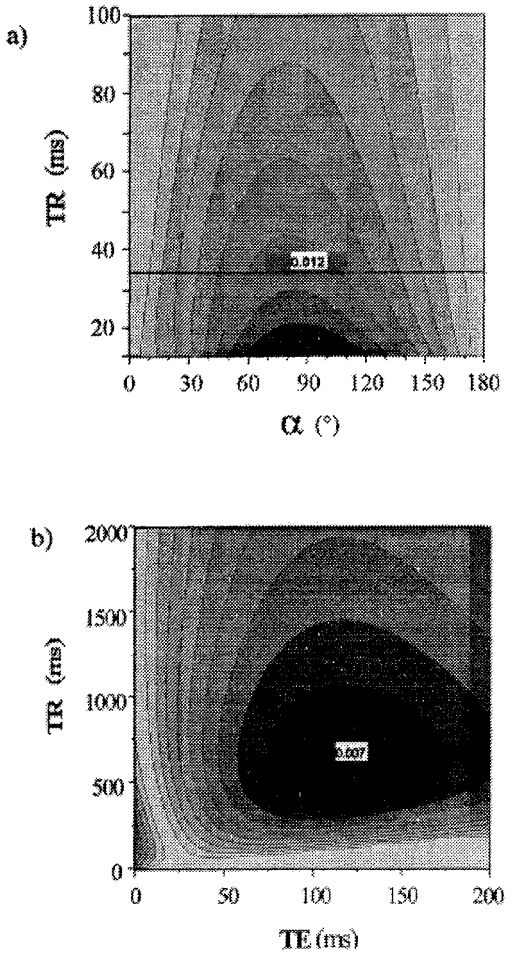

Figure 4. Contour plots of tlie expected contrast per unit time: **a)** for the CE-FAST sequence tlie inaximum occurs for TR=34ms, $\alpha = 82°$ and equals 0.012; b) for the Spin Echo sequence, the maximum is at TR=617ms, TE = 116ms witli a value of 0.007.

In order to see how tlie two sequences compare experimentally in our 0.05 Tesla scanner we have imaged our previously descrihed phaiitom with hotli metliods. The resulting image are given in Fig. 5, sliowing the imaging pararneters used, tlie resulting total acquisition times and the Contrast to Noise ratio, C/N, measured in the images using tlie definition given in Eq. **3.** One optimized CE-FAST and two differeiit Spin Echo images, all acquired with the same total imaging time T_{tot}=2':45", show tlie superior result obtained with the first when short acquisition of a single slice is desired. We have so included, as a reference, the image obtained with our standard T2 Spin Echo multislice protocol, which uses 4 averages and takes 17':00" minutes giving practically the same C/N ratio, as the CE-FAST image.

We want to point out that the above discussion was based on the assumption that in a given acquisition time only one image is being acquired, which is one restriction of the CE-FAST sequence. However with the spin echo technique it is possible to acquire multiple images of slices in different positions of the sample using interleaced acquisition. When using CE-FAST for multiple slices the experiment normally has to be executed separately for each image, which increases the total acquisition time significantly. Nevertheless our results are valid for the case that only one image is needed and maximum CNR is of concern as for example in a first scan for localization of a subsequent complete MRI or MRS experiment.

V. Conclusion

From our measurements on a doped water phantom we proved that CNR calculations hased on the relaxation times of two tissues are in agreement with experimentally determined CNR values. It is tlierefore possible to find the maximum CNR of two tissues by calculation solely knowing their relaxation times and proton spin densities which, in many cases, are readily available in literature. When tissue parameters are not available the CNR can easily be optimized clioosing tlie lowest possible repetition time and maximizing the CNR with respect to the flip angle α.

We conclude tliat the CE-FAST sequence, with adequate experimental settings and even at a low field of 0.05T, is a possible alternative to the standard spin eclio technique when highly contrasted single scans are needed, such as for example in a first scan for localization of a subsequent complete MRI or MRS experiment.

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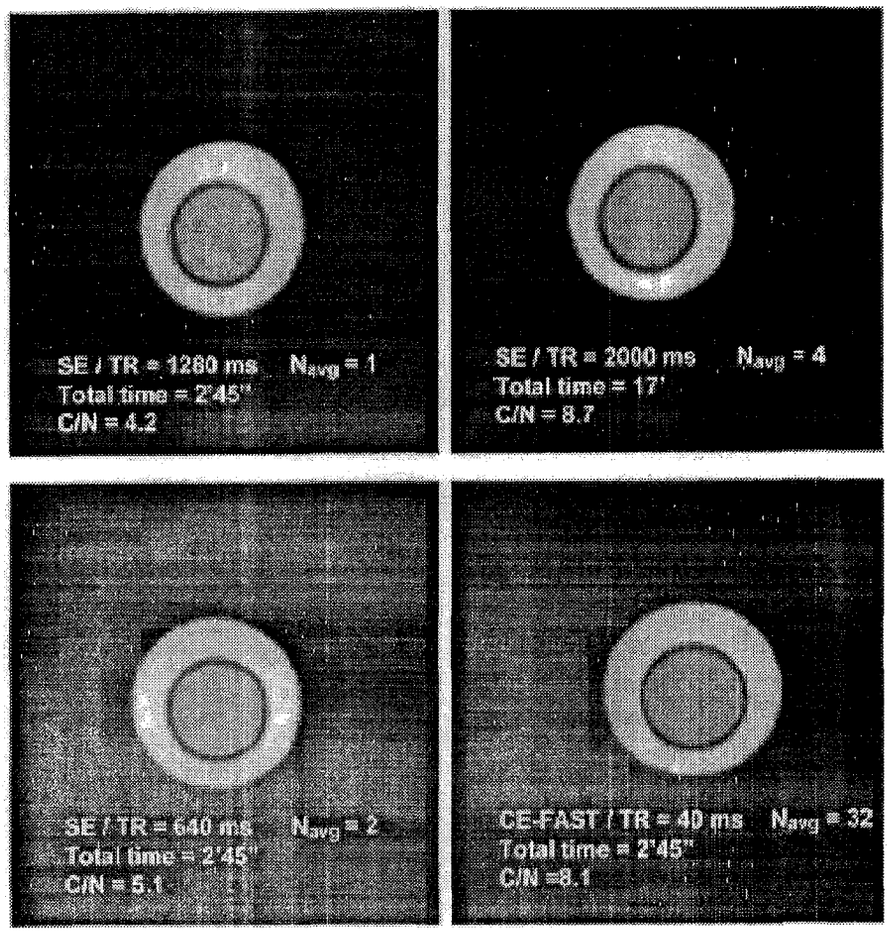

Figure 5. Comparison between CE-FAST aiid Spin Echo techniques. The two bottom images show that CE-FAST is superior for quick single slice acquisition. The two images on the right show that CE-FAST can achieve tlie same C/N ratio a.s the standard T2 weighted Spin Eclio, in a much shorter time. The two images on the left show tlie improvement in C/N, for equal acquisition times, obtained by choosing a compatible TR close to tlie optimiim value according to Fig. 4.

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