

Contrast Enhancement by the Butterfly Effect and Chaos Control in High-Field MRI

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Introduction

The ability to generate adaptable soft tissue contrast is one of MRI's greatest strengths. Two readily observed effects in solutions with abundant protons, radiation damping and the distant dipolar field (DDF), combine to generate chaotic spin dynamics in routine MR experiments at high fields [1]. Radiation damping is a macroscopic feedback interaction between the magnetization and the RF coil that becomes stronger at higher fields and with more sensitive probes [2]. The DDF arises from long-range dipolar interactions that persist in liquids even after spatial and temporal averaging [3].

Here we develop the resulting chaotic spin dynamics into a flexible, general contrast enhancement mechanism suited to a wide range of MR contrast sources. The extreme sensitivity of the chaotic spin dynamics to initial conditions, known as the "butterfly effect," renders the magnetization evolution exceedingly sensitive to the slightest variations in MR parameters, such as spin density, relaxation times, chemical shifts, and proton chemical exchange rates. Furthermore, we show that the butterfly effect can be further heightened by manipulating the chaotic spin dynamics through tailored radiofrequency (RF) control schemes [4]. Possible applications include highlighting small spatial variations in chemical shift and proton chemical exchange rates in tissue to expedite the detection of nascent tumors. We have used the butterfly effect and control of spin chaos to create images of phantoms and a carrot leaf stalk that reflect enhanced contrast arising from versatile endogenous sources.

Methods

Experiments demonstrating contrast enhancement by the butterfly effect and chaos control were first performed on a phantom to validate techniques and then extended to a biological sample. The magnetization in each sample was manipulated using the sequence shown in Fig. 1. The initial θ pulse tips the magnetization to regions of varying stability under radiation damping, while the gradient enhances the DDF effect. The modulated magnetization then evolves under the joint feedback fields during the τ evolution period before being imaged by a FLASH sequence. A phantom was prepared from water in a 5 mm tube with an inserted 1 mm capillary tube containing 5% ethanol solution by volume. Contrast enhancement was also tested on a carrot leaf stalk immersed in water.

Results

Figure 1(a-d) shows phantom images taken after a $\theta = 120^\circ$ pulse and different τ times. For $\tau = 0$, the initial image reveals no observable contrast (Fig. 1a). Between $\tau = 70$ -80 ms, the water signal in the outer tube decreases significantly, while the signal in the inner capillary appears hyperintense (Fig. 1b). As τ is increased above 80 ms, the positive contrast for the inner capillary decreases while the surrounding water regains signal intensity. At $\tau = 100$ ms, the contrast has inverted, yielding negative contrast for the inner capillary (Fig. 1c). Evolving solely under T_1 effects revealed no contrast with increasing τ (not shown). For this phantom, the contrast enhancement thus comes from amplification under the butterfly effect of variations in a combination of MR parameters, including chemical shift and proton exchange rate.

Figure 2(a-d) examines the contrast enhancement arising from the chaotic spin dynamics in the carrot leaf stalk. For $\tau = 0$, the images following a $\theta = 120^\circ$ (Fig. 2a) or 90° hard pulse (Fig. 2c) and gradient show contrast only between the cortex and the vascular bundles. At $\tau = 125$ ms, the contrast inverts to highlight specific regions within the vascular bundles. Snapshots of the contrast at $\tau = 400$ ms are shown for both flip angles in Figs. 2(b,d). The bright spots reflect the bicollateral nature of the vascular bundles and correspond to the phloem, the tissue transporting organic material. T_1 -weighted images show that variations in T_1 can highlight the phloem within the vascular bundles (not shown) but only on much longer time scales (~ 1 s). We thus conclude that the butterfly effect amplifies sensitivity to as yet indiscernible T_1 variations at $\tau = 400$ ms, leading to the enhanced contrast features seen in Fig. 2.

Discussion and Conclusion

We have demonstrated a method for amplifying small spatial variations in MR parameters and initial magnetization distribution through the butterfly effect and chaos control. Experiments in phantoms reveal that the resulting contrast enhancement may be tailored to reflect the spatial distribution of a combination of MR parameters. Experimental results on a carrot petiole indicate the possibility of highlighting vascular tissue in plants through the sensitivity of the joint feedback fields to intrinsic variations in T_1 , which would otherwise be imperceptible at short times.

For practical applications, it may be desirable to enhance contrast arising from a specific physical origin. This can be achieved through difference imaging, in which all contributions to the image contrast other than changes in the parameter of interest are subtracted out. Current efforts are focused on extending our amplification scheme to diffusion effects and other sources of contrast as well as to difference imaging methods such as CEST and MTC in biological samples. This technique may thus open new opportunities for enhancing spatial variations in chemical shift and proton chemical exchange rates in such clinical applications as early tumor detection. As higher fields and more sensitive probes with active feedback circuits become available in MRI, the butterfly effect and chaos control should become increasingly sensitive to small spatial differences in the full range of MRI contrast sources.

[1] Lin YY *et al.*, *Science* **290**:118, 2000. [2] Bloembergen N *et al.*, *Phys. Rev.* **95**:8, 1954. [3] Warren WS *et al.*, *Science* **281**:247, 1998. [4] Huang SY *et al.*, *Phys. Rev. Lett.* (in press).

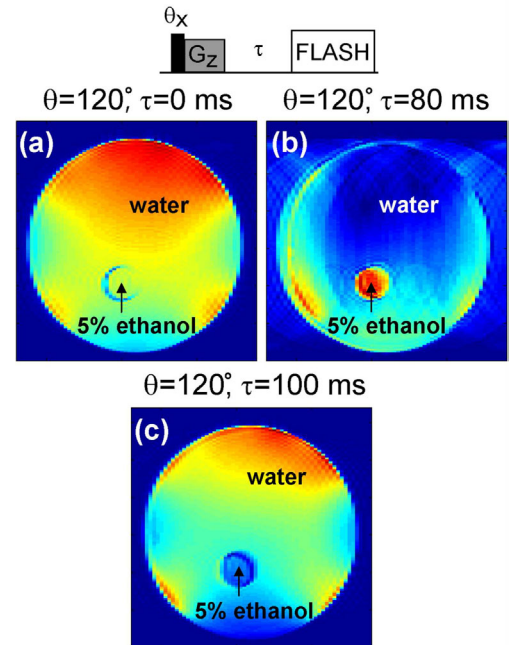


Fig. 1. Images of a water phantom at 14.1 T ($\tau = 5.35$ ms) containing an inner capillary of 5% ethanol solution as a function of flip angle θ and evolution time τ in the preparation sequence shown above. FOV 1 cm, matrix size 512 \times 128.

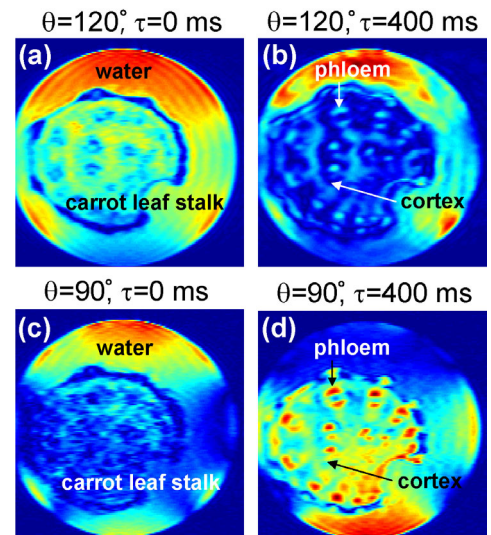


Fig. 2. Images of a carrot leaf stalk immersed in water as a function of flip angle θ and evolution time τ in the preparation sequence shown in Fig. 1. FOV 0.83 cm, matrix size 512 \times 64.