Sensitivity and Contrast Enhancement in Magnetic Resonance by the Butterfly Effect and Chaos Control

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Introduction

Recent experimental and numerical studies have revealed that two readily observed effects in solutions with abundant high-gyromagnetic ratio spins – radiation damping and the distant dipolar field (DDF) – combine to generate chaotic dynamics in routine magnetic resonance (MR) experiments [1, 2]. Radiation damping is a macroscopic feedback field that acts back on the spins through the induced current in the receiver coil [3], while the DDF arises from long-range dipolar interactions that persist between distant spins in liquids even after spatial and temporal averaging [4]. The extreme sensitivity of the chaotic spin dynamics to small deviations in initial conditions – the well-known "butterfly effect" – makes the spin systems highly susceptible to the slightest variations in experimental conditions [1, 5]. This work demonstrates numerically and experimentally how the butterfly effect can be exploited in high-field imaging experiments to amplify small magnetization variations. This approach is shown to produce significant sensitivity and contrast enhancement in difference imaging, as represented here by the chemical exchange-dependent saturation transfer (CEST) effect [6].

Methods & Results

A novel periodic control scheme based on radio-frequency (RF) perturbations has been developed to suppress the chaotic dynamics by averaging out the dominant feedback interactions [5]. Surprisingly, by varying the spacing between successive RF pulses, such periodic control schemes not only can suppress but also can enhance the feedback leading to spin chaos. Dynamical features of spin chaos can be characterized by the largest Lyapunov exponents, which describe the rate of exponential divergence of adjacent trajectories. Figure 1 shows the largest Lyapunov exponents calculated for the periodic control scheme shown (inset) as a function of the spacing τ between pulses. In the fast modulation regime, the periodic pulses average out the radiation damping feedback field, which causes the average largest Lyapunov exponent to approach zero, indicating that the system stabilizes. Conversely, varying τ can significantly increase the largest Lyapunov exponent, showing that the chaotic spin dynamics can also be heightened.

The butterfly effect in a chaotic spin system suggests that small variations in MR parameters can be amplified by the interplay between the feedback fields and external periodic RF fields. This is demonstrated in Fig. 2, where significant sensitivity and contrast enhancement for a dilute solute (1 mM ethanol) was achieved by integrating the RF chaos control scheme with the CEST effect. Imaging experiments were carried out on 1 mM ethanol in a 5 mm sample tube with an inserted capillary tube of water (outer diameter of 1 mm) on a Bruker Avance 600 MHz spectrometer equipped with a Micro5 gradient system (1000 mT/m) and a 5 mm $^{13}C/^{1}H$ insert (saddle coil geometry) optimized for proton sensitivity. Spin echo echo planar imaging (EPI) was used to image the magnetization with a matrix size of 128×128, field-of-view of 2×2 cm^2 and slice thickness of 10 mm. No further data processing was applied to the EPI images.

CEST provides a novel source of contrast by amplifying the signal from dilute tissue metabolites via saturation transfer in the presence of water/macromolecule exchange. The CEST effect is of limited use, however, in detecting extremely dilute solutes with few exchange sites or slow exchange rates. Figure 2A shows the difference images obtained from the CEST effect alone: in two successive experiments, saturation of the ethanol resonance produced a decrement of 2% in the water magnetization compared to irradiation applied at the same frequency on the opposite side of the water peak. The limited CEST effect in this sample, however, can be significantly amplified by the RF-enhanced butterfly effect shown in Fig. 2B. The sensitivity of the difference images was improved by a factor of 10 to reach 20% of the water equilibrium magnetization. Furthermore, the contrast between the dilute ethanol solution and the capillary tube containing pure water was highlighted in the enhanced CEST images, as the DDF is a microscopic feedback field sensitive to local structure.

Discussion & Conclusions

Current interest in imaging applications at high fields ensures the viability of enhancing sensitivity and contrast by the butterfly effect as higher fields and more sensitive probes intensify the feedback fields that produce spin chaos. Moreover, enhancement of the butterfly effect can be achieved by applying RF control schemes to perturb the spins into states in which they are most sensitive under the feedback fields to small variations in the MR parameters governing the spins' evolution. Radiation damping can also be heightened by active feedback to the induced current in modified circuits that are already integral components of many commercial spectrometers [7].

Sensitivity and contrast enhancement by the butterfly effect and chaos control takes advantage of the intrinsic spin dynamics and can thus be easily incorporated into existing detection methods. Current efforts are focused on extending the basic RF chaos control scheme to consider the effect of diffusion and other sources of contrast *in vivo* and thereby furnish amplification of other difference imaging methods in biological samples.

References

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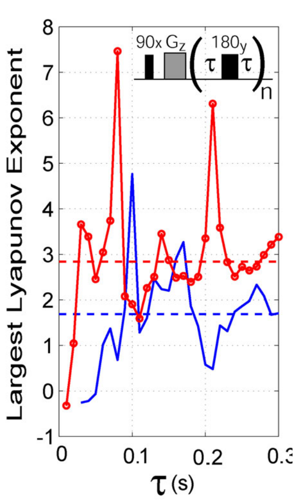

Fig. 1. Average largest Lyapunov exponents as a function of spacing τ between 180° pulses for the periodic control scheme shown. Dotted line shows the average largest Lyapunov exponent for $[(\pi/2)_x - (GT)_z]$. Lyapunov exponents calculated for a field strength of 600 MHz with a radiation damping time constant τ_r = 8 ms (blue) were averaged over 0.9 s, while Lyapunov exponents calculated for 900 MHz with τ_r = 4 ms (red) were averaged over 0.6 s.

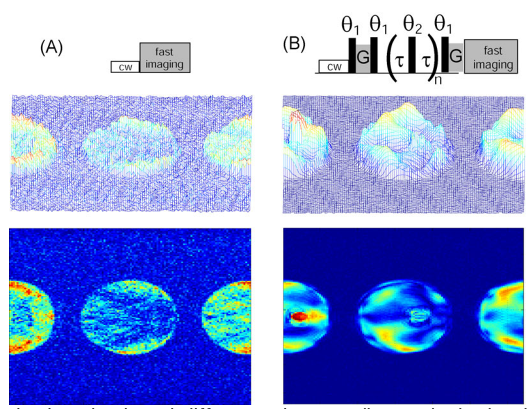

Fig. 2. Mesh plots (top) and difference images (bottom) obtained by spin echo EPI for **(A)** the CEST effect and **(B)** enhanced CEST by the periodic RF control scheme shown. The initial difference in magnetization was prepared by cw irradiation applied at 5 mW for 1s at and opposite the ethanol resonance. θ_1 = 90°, θ_2 = 180°, GT = 5 G·ms/cm, n = 7, and τ = 35.7 ms.