Preparing the Magnetization for Magnetization Prepared SSFP

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Introduction: Balanced steady-state free precession (SSFP) sequences provide a high signal-to-noise ratio (SNR) that is practically independent of the repetition time (TR). Important applications of SSFP include the use of magnetization preparations for quantitative imaging or to create contrast enhancement such as inversion recovery or tagging. In these applications, imaging during the transition to steady-state is essential to capture the induced contrast. Furthermore, the window of acquisition tends to be short such that steady-state is never reached. Unfortunately, SSFP is notorious for oscillatory behavior with long decay constants during the transition to steady-state, necessitating catalyzation methods that appropriately tailor the magnetization to avoid oscillations. Furthermore, the application of these catalyzation sequences can lead to an off-resonance dependent weighting on the acquired signal modifying the expected image contrast. This work presents an analysis of the weighting function and a preparatory sequence to correct the magnitude scaling of the magnetization and avoid image contrast corruption.

Theory: The basic physics for the transient behavior of the magnetization during SSFP-type sequences was described by Jaynes [1] as long ago as 1955 with excellent analyses provided more recently by Hargreaves [2] and Le Roux [3]. These works show that the transient behavior in SSFP is governed by the eigenvalues and eigenvectors of the magnetization state transition matrix (e.g. A in [2] or [4]). For non-oscillatory transients, the residual (i.e. $\mathbf{M_k}$-$\mathbf{M_{ss}}$) must lie in the direction of the eigenvector corresponding to the real-valued eigenvalue of the matrix. For $T_1,T_2>>TR$, this direction lies almost exactly (within a few degrees) along the direction of the $\mathbf{M_{ss}}$ vector itself at TE, subtending an angle ψ to the z-axis, satisfying: $\tan(\psi(\Delta\theta)) = \tan(\alpha/2)/\cos(\Delta\theta/2)$ where α is the imaging flip angle and $\Delta\theta$ is the angle precessed by an off-resonance isochromat per TR (Fig 2a). To avoid oscillatory transients, it is necessary to initialize (a.k.a. catalyze) each isochromat to its ψ: this can be considered to be a problem of spectral-spatial pulse design and has been addressed previously [2,3]. However, an ideal catalyzation that orients the isochromats to ψ will introduce an initial off-resonance dependent modulation of the acquired signal by $\sin(\psi(\Delta w))$. The modulation will decay to M_{ss} at a rate, T, controlled by the real eigenvalue and approximated by $1/T = \cos^2(\psi)/T_1 + \sin^2(\psi)/T_2$ [3,5]. This rate of decay is always between T_1 and T_2, so this weighting will persist throughout early imaging. In the context of magnetization prepared sequences, the signal becomes: $S(\Delta\theta) = M_P \cdot \sin(\psi(\Delta\theta))$ where M_P is the desired magnetization prepared signal level as given by inversion or saturation recovery preps, for example. To obtain an accurate measure of the prepared magnetization, the sinusoidal spectral weighting should be removed. This can be achieved using an initial magnitude scaling preparation to flatten the spectral response. It can be shown that a suitable response can be obtained by applying a pair of RF pulses TR apart, with flip angle, $\pm\xi$ given by $\xi = (90-\alpha/2)/2$ followed by a gradient crusher (Fig 1). The theoretical response required for a flat spectral response in shown in Fig 2c (solid line). We suggest this magnitude scaling sequence be applied before a linear ramp of flip angles specified by $\alpha_i = (\alpha/2N)\cdot(2i+1)$ where *i=0...N-1* and *N* is the number of pulses in the ramped series (a variant of the sequence proposed in [6]). Thus, not only will the oscillatory response be minimized but the off-resonant dependent signal weighting will be removed.

Methods: Simulations were written in C++ to characterize and calculate the angle ψ. Simulation of magnetization responses was achieved using a 4-vector description of the magnetization similar to that described in [4] that allows for rapid prototyping of magnetization behavior.

Results: The angle ψ, as determined from simulations, matched the theoretical formulation excellently and is shown in Fig 2a as a function of off-resonance precession angle, $\Delta\theta$. The effective weighting function applied to the magnetization-prepared magnetization is shown in Fig 2b. Effectively, isochromats that precess (π+2πk) radians in one TR are affected in the greatest degree by the weighting function: they have the largest initial signal after ψ-catalyzation, but ultimately have the smallest steady-state magnetization. The desired and obtained responses of the magnitude scaling sequence are shown in Fig 2c.

Discussion: The widespread use of balanced SSFP has lead to a variety of applications that though producing significantly different contrast from the original form as a steady-state imaging sequence still reap the benefits of increased SNR in coherent imaging. In particular, generation of enhanced contrast via magnetization preparation and imaging throughout the transient behavior are now widely applied. Catalyzation sequences in many forms have been suggested to remove the oscillatory behavior robustly in the presence of inhomogeneities. In the ideal, these sequences will impart a weighting on the measured magnetization. To correct for that weighting the sequence proposed here could be pre-pended, resulting in a truly off-resonance-independent catalyzation sequence. Further applications to relaxometry [7] would also be of interest. Finally, in IR-prepped cardiac applications where contrast is used to reflect the viability of tissue, the application of this sequence should remove uncertainties introduced by field inhomogeneities across the heart.

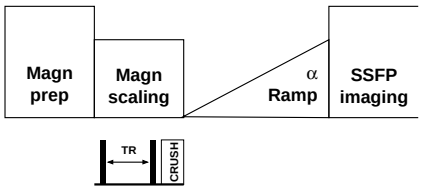

Figure 1: Proposed magnitude scaling sequence used to remove off-resonance dependent weighting.

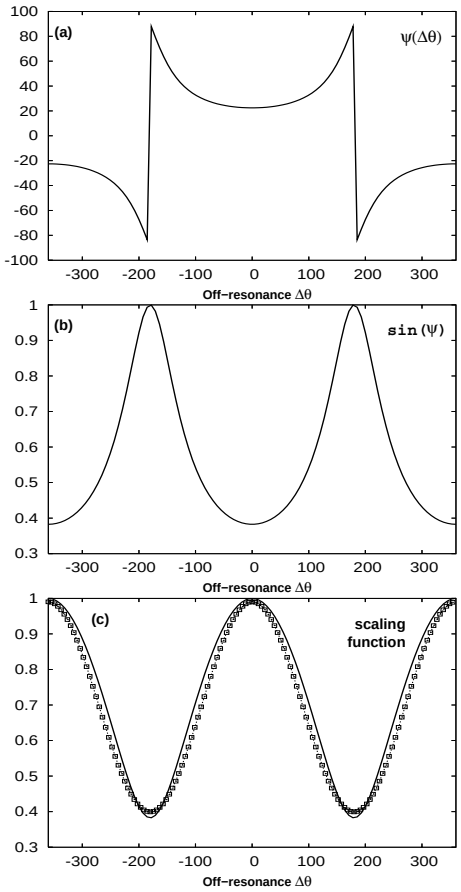

Figure 2: (a) The application of successful catalyzation sequences used in balanced SSFP strives to place magnetization along the direction determined by eigenvalue analysis, characterized by the angle ψ. Unfortunately, in the process of reducing oscillatory responses, ideal catalyzation sequences also apply a $\sin(\psi)$ off-resonance dependent weighting (b). The weighting, which affects most the highly off-resonant spins should be compensated for when applying magnetization prepared sequences that image during the transition period. To do so, a magnitude scaling step applying a $\sin^{-1}(\psi)$ weighting is used (c). In (c) the thick line represents the theoretical desired magnitude scaling response function while the dotted line demonstrates the achievable magnetization profile with the suggested preparatory sequence in Fig 1.

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