Analysis of the Transient Phase of Balanced SSFP with Non-continuous RF for Cardiac Imaging

G. S. Slavin[1]
[1]Applied Science Laboratory, GE Healthcare, Bethesda, MD, United States

Introduction The transient phase of balanced SSFP (bSSFP) is the period during which magnetization approaches steady state. The transient phase of non-ECG-gated, continuous-RF bSSFP has been characterized by a simple exponential decay with a time constant that is a flip-angle-weighted average of T_1 and T_2 (1). Cardiac imaging applications, however, often utilize bSSFP with non-continuous RF excitation where bSSFP data is collected only during a short period of the cardiac cycle. For example, a Look-Locker-based cardiac T_1 mapping sequence (Fig. 1) begins with an ECG trigger, and is followed by magnetization preparation (on the first cardiac cycle only), a bSSFP imaging segment, and a recovery time T_{rec} prior to the subsequent imaging segment. Multiple time points (i.e., inversion times, TI) are acquired, separated by the R-R interval T_{RR}. Another example, magnetization-prepared bSSFP, would utilize a preparation pulse and TI for each cardiac cycle. In this case, T_{rec} would be the time between the end of the bSSFP acquisition and the next preparation pulse. The continuous-RF transient phase as described in reference 1 is not applicable in these cases.

Purpose The goal of this work was to develop an analytical expression for the transient phase of bSSFP with non-continuous RF excitation. The resulting equation can be applied to Look-Locker acquisitions to provide true quantification of T_1 (and T_2), rather than an "apparent" T_1 (T_1*) for cardiac imaging.

Methods The Look-Locker pulse sequence is shown in Figure 1 and is periodic (after the initial preparation pulse). It begins with a data acquisition segment (with N views per segment) and ends with a recovery time $T_{rec}=T_{RR}-N\times TR$ before the next segment. Let $\mathbf{M}_T(n)$ be the transient magnetization at time point n (2). Assume that the magnetization at the subsequent time point $\mathbf{M}_T(n+1)$ is a scaled version of $\mathbf{M}_T(n)$; i.e, $\lambda\mathbf{M}_T(n)$ (1). The transient response may then be written as $\mathbf{M}_T(n+1)=\lambda\mathbf{M}_T(n)$. Because this resembles an eigenvalue equation, it may also be written as $\mathbf{A}\mathbf{M}_T(n)=\lambda\mathbf{M}_T(n)$. $\mathbf{A}$ is a transformation matrix that describes the change of the transient magnetization from segment to segment and can be derived from matrix modeling of one period of the pulse sequence. This work will show that the transformation matrix can be expressed as

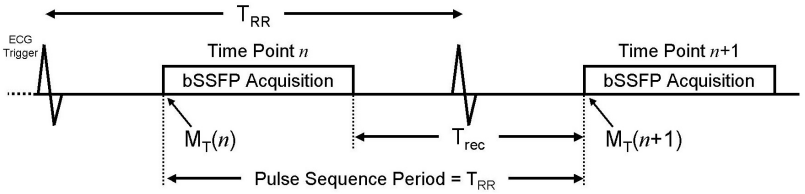

Figure 1. Pulse sequence diagram. $\mathbf{M}_T(n)$ is the transient magnetization prior to data acquisition at time point n. Magnetization preparation pulses may be played out between the ECG trigger and the bSSFP acquisition. For Look-Locker acquisitions, a preparation pulse is played out only during the first cardiac cycle of each Look-Locker experiment. For magnetization-prepared acquisitions, a preparation pulse is played out every cardiac cycle.

$$\mathbf{A}=\mathbf{E}(T_{rec})\left[\mathbf{R}_z(\pi)\mathbf{E}(TR)\mathbf{R}_x(\alpha)\right]^N\prod_{i=M}^{1}\mathbf{R}_z(\varphi_i)\mathbf{E}(\tau_i)\mathbf{R}_x(\alpha_i)$$

where $\mathbf{R}_x$ and $\mathbf{R}_z$ are rotation matrices for RF excitation and phase modulation, respectively; $\mathbf{E}(t)$ represents relaxation during time t; and the product term (Π) denotes steady-state preparation using any series of M pulses. The equation $\mathbf{A}\mathbf{M}_T(n)=\lambda\mathbf{M}_T(n)$ can be solved for the real positive eigenvalue λ_{eig} of $\mathbf{A}$, which is a function of T_1, T_2, and known imaging parameters. Although $\mathbf{A}$ can be expressed compactly above, λ_{eig} is more complex because the exponent N is usually greater than 20. Since λ describes the exponential evolution of the transient magnetization, it can also be written as $\lambda_{image}=\exp(-T_{RR}/T_1^*)$. T_1* is determined from fitting the time point image data acquired during the transient phase (i.e., during the Look-Locker experiment). Because λ_{eig} is a function of two unknowns, the equation $\lambda_{eig}(T_1, T_2)=\lambda_{image}$ can be solved for T_1 and T_2 by scanning twice with one parameter changed (e.g., flip angle).

Results A Bloch simulation of the pulse sequence in Figure 1 was performed, and T_1* was determined by curve fitting. T_1, T_2, and T_1* were then calculated using $\lambda_{eig}(T_1, T_2)$ and showed perfect agreement. An agarose gel phantom (T_1=2242 msec) was scanned using a ten-point bSSFP Look-Locker sequence. Imaging was performed twice with flip angles of 45° and 22.5°. A T_1* value was determined for each of the two ten-image datasets, one for each flip angle. This produced two equations for $\lambda_{eig}=\lambda_{image}$. Solving these simultaneous equations yielded a T_1 of 2367 msec.

Discussion Previously reported cardiac T_1 mapping techniques using bSSFP have employed various assumptions and approximations to estimate T_1. This work presents an analytical expression for the transient phase of non-continuous-RF bSSFP. It provides the ability to directly quantify T_1 for cardiac imaging while obviating any assumptions in acquisition or post-processing. Future work will involve continued evaluation on materials with a range of T_1 and T_2 values and the development of a single-breath-hold scan for clinical cardiac imaging. This method can also be used to calculate an optimal inversion time for magnetization-prepared scans based on imaging parameters.

References 1. Scheffler, MRM, 49:781 (2003). 2. Hargreaves, MRM, 46:149 (2001).