Journal of Cardiovascular Magnetic Resonance

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Analysis of the transient phase of balanced SSFP with non-continuous RF for cardiac imaging

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from 13th Annual SCMR Scientific Sessions
Phoenix, AZ, USA. 21-24 January 2010

Published: 21 January 2010

Journal of Cardiovascular Magnetic Resonance 2010, **12**(Suppl 1):P230 doi:10.1186/1532-429X-12-S1-P230

This abstract is available from: http://jcmr-online.com/content/12/S1/P230

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. The example considered here, Look-Locker-based T_1 mapping, begins with an ECG trigger, and is followed by magnetization preparation, a bSSFP imaging segment, and a recovery time prior to the subsequent ECG trigger. Multiple time points are acquired, separated by the R-R interval T_{RR}. The description of the continuous-RF transient phase is not applicable in this case.

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*).

Methods

The pulse sequence is shown in Figure 1 and is periodic, beginning with data acquisition (a segment of N views) and ending with a recovery time $T_{rec} = T_{RR}\text{-}N \times TR$ before the next segment. Let $\mathbf{M}_T(n)$ be the transient magnetization prior to time point n, and assume the magnetization at the subsequent time point is reduced to $\lambda\mathbf{M}_T(n)$ [1,2]. The transient response may then be written

$$\mathbf{M}_{\mathrm{T}}(n+1) = \lambda\mathbf{M}_{\mathrm{T}}(n) = \mathbf{A}\mathbf{M}_{\mathrm{T}}(n).$$

This work will show that

$$\mathbf{A} = \mathbf{E}_{\mathrm{Trec}}[\mathbf{R}_z\mathbf{E}_{\mathrm{TR}}\mathbf{R}_x]^N\mathbf{B}$$

where $\mathbf{R}_{x,\,z}$ are rotation matrices for RF excitation/alternation, $\mathbf{E}_t$ represents relaxation during time t, and $\mathbf{B}$ denotes steady-state catalyzation. The equation $\mathbf{AM}_T(n) = \lambda\mathbf{M}_T(n)$ can be solved for the real eigenvalue $\lambda_{eig}(T_1, T_2)$ of $\mathbf{A}$, which is a function of T_1, T_2, and known imaging parameters. Because it describes the exponential evolution of the transient magnetization, λ can also be written

$$\lambda_{image} = \exp(-\mathrm{T}_{\mathrm{RR}} / \mathrm{T}_1{}^*).$$

T_1* can be determined from fitting the time point images acquired during the transient phase. With an appropriate pulse sequence, $\lambda_{eig}(T_1, T_2) = \lambda_{image}$ can be solved for T_1 and T_2.

Results

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.

Conclusion

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&T_2 for cardiac imaging while obviating such assumptions in acquisition or post-processing.

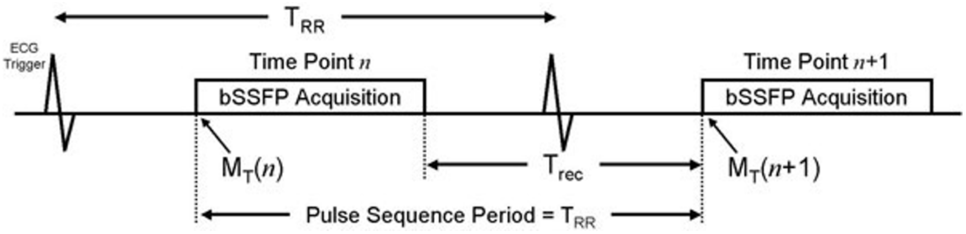

Figure 1
Pulse sequence diagram, $M_T(n)$ is the transient magnetization prior to data acquisition at time point *n*.

References

1. Scheffler : *MRM* 2003, **49:**781.
2. Hargreaves : *MRM* 2001, **46:**149.