Simultaneous T_1 and T_2 Quantification Using Non-Continuous Balanced SSFP Look-Locker Imaging

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

Introduction

T_1 measurement using the Look-Locker (LL) method is accomplished by sampling the transient phase of the magnetization as it recovers to equilibrium after a preparation pulse. The imaging strategy is often dependent on the anatomy of interest. For stationary anatomy, data can be collected continuously during recovery. For dynamic anatomy, such as the heart, data is collected non-continuously and only during a short period (single-phase) of the cardiac cycle (Fig. 1). In both cases, because data acquisition perturbs the recovering magnetization, correction methods are required to calculate the true T_1 from the "apparent" T_1 (T_1*). Such correction methods have been developed for continuous gradient-echo (1) and balanced SSFP (bSSFP) (2, 3) acquisitions. Although several promising cardiac T_1 mapping techniques employ non-continuous bSSFP (4, 5), a correction method specific for this approach has not been reported. The importance of using an appropriate correction can be demonstrated by reviewing bSSFP LL techniques that have used suboptimal models for T_1 estimation. In many cases, the resulting T_1 measurements have exhibited systematic errors and, for cardiac applications, heart-rate dependence. Such models typically ignore T_2 effects, either by using very low flip angles (which significantly compromises the high SNR benefit of bSSFP) or by assuming T_1* = T_1. Because the bSSFP signal evolution is inextricably linked to both T_1 and T_2, the effects of T_2 must be considered. By doing so, the bSSFP LL method can yield both T_1 and T_2 measurements. In a previous study, an analytical expression for the transient state of non-continuous bSSFP was presented (6). The purpose of this study was to utilize that expression to develop a correction method for simultaneous quantification of true T_1 and T_2 using a non-continuous bSSFP LL acquisition. The eventual goal is to apply this method to breath-held cardiac imaging.

Theory

The transient phase (2, 7) of non-continuous bSSFP (Fig. 1) can be expressed by a transformation matrix **A** as (6)

$$\mathbf{A} = \mathbf{E}(T_{rec})\left[\mathbf{R}_z(\pi)\,\mathbf{E}(TR)\,\mathbf{R}_x(\alpha)\right]^{VPS}\mathbf{C}_{ss}$$

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; *VPS* is views per segment; and $\mathbf{C}_{ss}$ denotes steady-state catalyzation. The positive eigenvalue λ of **A**, which is a function of T_1, T_2, and known imaging parameters, describes the exponential evolution of the transient magnetization. It can therefore also be written as $\lambda = \exp(-T_{RR}/T_1^*)$, where T_1* is determined from curve fitting the time point image data acquired during the Look-Locker experiment. Because λ is a function of two unknowns, T_1 and T_2 can be calculated by scanning twice with one imaging parameter changed. In this work, two flip angles (α_1, α_2) were used to solve $\lambda(T_1, T_2, \alpha_i) = \exp(-T_{RR}/T_{1,i}^*)$. Because this method is based specifically on the theoretical model of non-continuous bSSFP, it is expected to provide more consistent results and heart-rate independence.

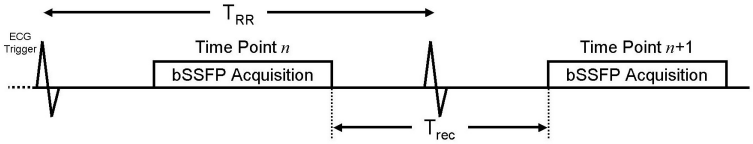

Figure 1. Pulse sequence diagram for single-phase, non-continuous bSSFP. Data acquisition alternates with periods of free relaxation (T_{rec}). Each period of data acquisition represents a time point on the relaxation curve from which T_1* is determined by curve fitting. For Look-Locker acquisitions, a preparation pulse is played out prior to data acquisition only during the first cardiac cycle (not shown). T_{rec} = period of free relaxation; T_{RR} = R-R interval.

Methods

LL imaging (8 time points spaced by T_{RR}) was performed on two phantoms (agarose gel and $MnCl_2$) using saturation-recovery bSSFP with a simulated ECG (Fig. 1). The thigh of a consenting volunteer was also scanned with actual ECG triggering. Each experiment was performed with two different flip angles, generating two relaxation curves from which two T_1* values were determined. These T_1*s were used to create two equations for $\lambda(T_1, T_2, \alpha_i)$ which could be solved simultaneously for T_1 and T_2. To evaluate the robustness of the correction, the VPS and ECG rates were varied in the agarose gel scans. Although the effects of non-ideal slice profiles (which can be substantial for bSSFP (8)) were taken into account, no modifications were made for B_0 or B_1 inhomogeneities.

Results

As an example of the correction method, the measured T_1* values for the agarose gel phantom (scan 1) at 22.5° and 45° were 1755 msec and 1303 msec, respectively. Using the correction, T_1/T_2 was calculated as 2131/35 msec. The true T_1/T_2 as measured by spin-echo imaging was 2152/41 msec. T_1 and T_2 values for all bSSFP LL experiments are shown in Table 1. In all cases, they show very good agreement with actual values.

Acquisition, Heart rate (beats per min)	T_1 (msec)		T_2 (msec)	
	Calculated	Actual[a]	Calculated	Actual[a]
Agarose Gel, 1) 60 bpm[c]	2131	2152	35	41
2) 75 bpm[d]	2122		41	
$MnCl_2$[c], 80 bpm	917	922	124	122
Skeletal Muscle[c], 58 bpm (avg)	1110	1183[b]	34	33[b]

Table 1. T_1 and T_2 values calculated from non-continuous bSSFP.
[a] Phantom values from spin-echo imaging. [b] Values from literature (9).
[c] Two-shot acquisition (VPS=38). [d] Single-shot acquisition (VPS=76)

Discussion

Previous approaches to T_1 mapping using non-continuous bSSFP have neglected the effects of T_2. As a result, such methods are not only unable to quantify T_2, they often exhibit systematic errors in T_1 measurements. This work has demonstrated a new correction method, based on a theoretical model for non-continuous bSSFP, whereby true T_1 and T_2 may be quantified accurately and simultaneously from a LL acquisition. The corrected relaxation times show excellent agreement with actual T_1/T_2 even with different heart rates, VPS, and phantoms/tissue. Future work will involve optimizing the correction method as well as tailoring the acquisition parameters for single breath hold cardiac imaging (e.g., flip angles, number of time points, parallel imaging).

References: 1. Deichmann, JMR, 96:608 (1992). 2. Scheffler, MRM, 49:781 (2003). 3. Scheffler, ISMRM, p.552 (2003). 4. Messrhoghli, MRM, 52:141 (2004). 5. Slavin, SCMR, p.324 (2007). 6. Slavin, ISMRM, p.2210 (2010). 7. Hargreaves, MRM, 46:149 (2001). 8. Sung, MAGMA, 23:85 (2010). 9. De Certaines, MRI, 11:841 (1993).