Volumetric measurement of human brain T1 in vivo using pulsed Pseudo Random Amplitude Modulation

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Introduction

Longitudinal relaxation time T_1 has been extensively used to differentiate tissues. After it was quantitatively correlated with water content [1], several studies have shown that the water content and iron concentration derived from T_1 values can improve brain edema diagnosis[2], and even predict disability in early multiple sclerosis[3]. Therefore, an accurate and fast method for T_1 quantification would be very useful. In this work, we present a novel method to measure human brain T_1 in vivo using pulsed Pseudo Random Amplitude Modulation (PRAM) [4]. Both phantom and human results confirm that this method agrees well with the conventional inversion recovery method. Without fast imaging acceleration, the scan time per slice (128x128 matrix size) on human brain is 1.5s.

Theory

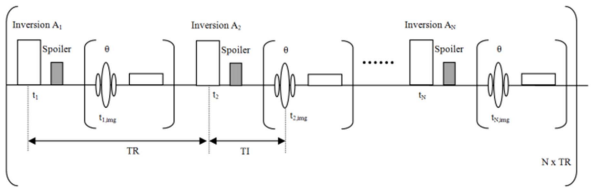

Figure 1: Schematic pulsed PRAM sequence diagram

The schematic pulsed PRAM sequence diagram is depicted in figure 1. Within each TR, a slab selective inversion RF pulse, denoted by A_n, is applied to imaging slices, followed by a spoiler and gradient-echo readout module. $\{A_n\}$ is a binary sequence of length N, in which $A_n = 1$ if inversion pulse ON and 0 otherwise. The same pattern is repeated every N x TR. Let $\vec{\boldsymbol{M}}$ be the vector of measured signal at $\{t_{n,img}^{-}\}$, S_A be the sum of one period of A_n, the inversion efficiency be α, and two longitudinal decay factors disjointed at inversion pulse be $E_1 = \exp(-(TR - TI)/T_1)$ and $E_2 = \exp(-TI/T_1)$. The solution to Bloch equation of brain tissue is:

$$\vec{\boldsymbol{M}} = \sigma \boldsymbol{A}_{\boldsymbol{\alpha}} \vec{\boldsymbol{H}}$$

where the scale factor is $\sigma = \left(M_0(1-E_1)E_2 + M_0(1-E_2)\cos(\theta)\,E_{T_1}\right)/(1 - cos^N(\theta)\,E_{T_1}^N\,(-\alpha)^{S_A})$, and

$$\boldsymbol{A}_{\boldsymbol{\alpha}} = \begin{pmatrix} (-\alpha)^{A_1} & (-\alpha)^{\sum_{k=1-1}^{1} A_k} & \cdots & (-\alpha)^{\sum_{k=1-(N-2)}^{1} A_k} & (-\alpha)^{S_A} \\ (-\alpha)^{A_2} & (-\alpha)^{\sum_{k=2-1}^{2} A_k} & \cdots & (-\alpha)^{\sum_{k=2-(N-2)}^{2} A_k} & (-\alpha)^{S_A} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ (-\alpha)^{A_N} & (-\alpha)^{\sum_{k=N-1}^{N} A_k} & \cdots & (-\alpha)^{\sum_{k=N-(N-2)}^{N} A_k} & (-\alpha)^{S_A} \end{pmatrix} \qquad \vec{\boldsymbol{H}} = \begin{pmatrix} 1 \\ \cos(\theta)\,E_{T_1} \\ \vdots \\ \cos^{N-1}(\theta) E_{T_1}^{N-1} \quad + \frac{M_0(1-E_2)}{\sigma(-\alpha)^{S_A}} \end{pmatrix}$$

From above equation, one can see the first N-1 points of PRAM reconstruction result $\vec{\boldsymbol{H}}$ is a geometric sequence with common ration $\cos(\theta)\,E_{T_1}$. Denote its logarithm slope as β_1, then T_1 can then be solved as:

$$T_1 = \frac{TR}{\ln(\cos(\theta)) - \beta_1}$$

Method

All measurements were carried out on a 3T Siemens Trio scanner with 12-channel head coil. 15-cycles PRAM sequences with standard gradient echo readout for phantom and echo-planar imaging readout for human were implemented employing a 15.36 ms hyperbolic secant inversion pulse. T_1 was estimated by weighted least square fitting procedure on MATLAB platform. The accuracy of estimated T_1 was assessed by T_1 obtained from inversion recovery sequences with the same readout kernel. *Phantom studies:* A T_1 phantom was constructed consisting of five Gadolinium-solution bottles with concentration varying from 0 to 1mM. The imaging parameters were: TR = 250 ms, TE = 4 ms, matrix = 128x128, FOV= 256x256 mm^2, slice thickness = 5 mm, flip angle = 15^o and 30^o, number of repetitions = 6. *Human Study*: A healthy volunteer was recruited under approved IRB protocol. The imaging parameters were: TR = 430 ms, TE = 49 ms, matrix = 128x128, FOV= 256x256 mm^2, slice thickness = 5 mm, slice number = 4, flip angle = 15^o and 30^o, number of average per scan = 10, number of repetitions = 6.

Results

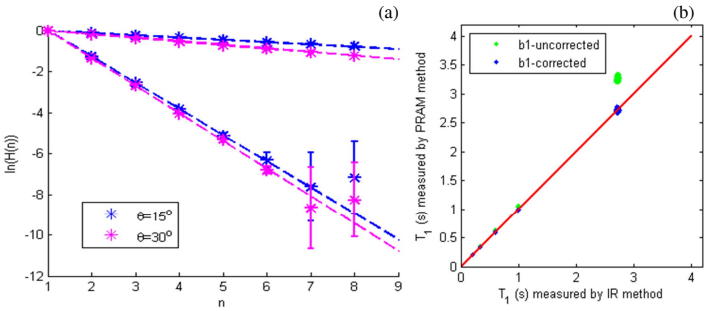

Figure 2: Phantom results. (a) PRAM reconstructed $\vec{\boldsymbol{H}}$. Only first eight points are shown. (b) Scatter plot of T_1 obtained from PRAM θ=15^o v.s. from IR

Fig. 2(a) shows the log of the PRAM reconstructed results $\vec{\boldsymbol{H}}$ as a function of n for two voxels taken from different bottles. The signal intensity of $\vec{\boldsymbol{H}}$ decays exponentially with n, the shorter T_1 and the larger θ, the faster decay rate, as predicted by theory. Figure 2(b) shows a scatter plot of the average T_1 measured by the PRAM method versus the T_1 measured by the inversion recovery method. The b1-corrected data (blue points) using double-angle method [5] falls on the unit slope line, demonstrating a nearly perfect agreement (R = 0.99994). The overall b1 field is 12^o (data not shown), and the overestimation of T_1 due to b1 reduction increases as T_1 increases.

Human results are shown in Fig. 3. The estimated T1 value is approximate 850 ms for white matter and 1400 ms for gray matter, consistent with previously reported values [6]. And the standard deviation is approximate 5% for white matter and 8% for gray matter. The average overestimation of T_1 of whole brain due to b1 in homogeneities is 2.27% (data not shown)

Conclusion and Discussion

This work describes pulsed PRAM theory for T_1 measurement, and validates it on T_1 phantoms. The human results further demonstrated the feasibility and high reproducibility of volumetric quantifying T_1 within relatively short time using pulsed PRAM. For better quantification, whole brain coverage incorporated with parallel imaging and an optimized protocol will be developed in future work.

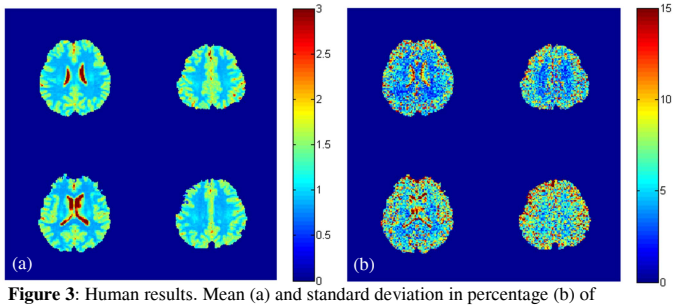

Figure 3: Human results. Mean (a) and standard deviation in percentage (b) of b1-corrected T_1 over six repetitions

References

[1] MacDonald HL, et al. The British journal of radiology 1986;59(700):355-357. [2] Andersen, C. Acta Neurochir 139(3): 249-255; [3] Manfredonia F, et al. Arch Neurol 2007;64(3):411-415. [4] Zou X, et al. GRC 2012. [5] Insko EK, et al. J Magn Reson Ser A 1993;103:82-85. [6] Rooney WD, et al. Magn Reson Med 2007;57(2):308-31