Volumetric measurement of human brain T1 in vivo using pulsed Pseudo Random Amplitude Modulation
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Introduction
Longitudinal relaxation time T1 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 T1 values can improve brain edema diagnosis[2], and even predict disability in early multiple sclerosis[3]. Therefore, an accurate and fast method for T1 quantification would be very useful. In this work, we present a novel method to measure human brain T1 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
The schematic pulsed PRAM sequence diagram is depicted in figure 1. Within each TR, a slab selective inversion RF pulse, denoted by A\(_\alpha\), 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 \(N \times TR\). Let \(\vec{M}\) be the vector of measured signal at \(\{E_{\text{in},m}\}\), \(S\) be the sum of one period of \(A\), the inversion efficiency be \(\alpha\), and two longitudinal decay factors disjointed at inversion pulse be \(E_1 = \exp(-TR - T1/T1)\) and \(E_2 = \exp(-T1/T1)\). The solution to Bloch equation of brain tissue is:

\[
\vec{M} = \alpha A \vec{H}
\]

where the scale factor is \(\sigma = (M_0(1 - E_1)E_2 + M_0(1 - E_2)\cos(\theta)E_{\text{IR}})/(1 - \cos^N(\theta)E_{\text{IR}}^N (-\alpha)^S\) , and

\[
A_n = \begin{pmatrix}
(-\alpha)^{A_1} & (-\alpha)^{A_1} & \cdots & (-\alpha)^{A_1} \\
(-\alpha)^{A_2} & (-\alpha)^{A_2} & \cdots & (-\alpha)^{A_2} \\
\vdots & \vdots & \ddots & \vdots \\
(-\alpha)^{A_N} & (-\alpha)^{A_N} & \cdots & (-\alpha)^{A_N}
\end{pmatrix}
\]

\[
\vec{H} = \begin{pmatrix}
\cos(\theta)E_{T1} \\
\cos^{-1}(\theta)E_{T1}^{-1} + M_0(1 - E_2)/\sigma(-\alpha)^S
\end{pmatrix}
\]

From above equation, one can see the first \(N-1\) points of PRAM reconstruction result \(\vec{H}\) is a geometric sequence with common ration \(\cos(\theta)E_{T1}\). Denote its logarithm slope as \(\beta_1\), 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 power. T1 was estimated by weighted least square fitting procedure on MATLAB platform. The accuracy of estimated \(T_1\) was assessed by T1, flip angle = 15\(^\circ\) and 30\(^\circ\), 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, flip angle = 15\(^\circ\) and 30\(^\circ\), number of average per scan = 10, number of repetitions = 6.

Results
Fig. 2(a) shows the log of the PRAM reconstructed results \(\vec{H}\) as a function of \(n\) for two voxels taken from different bottles. The signal intensity of \(\vec{H}\) decays exponentially with \(n\), the shorter \(T_1\) and the larger \(\theta\), 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\(^\circ\) (data not shown), and the overestimation of \(T_1\) due to b1 reduction increases as \(T_1\) increases.

Conclusion and Discussion
This work describes pulsed PRAM theory for T1 measurement, and validates it on T1 phantoms. The human results further demonstrated the feasibility and high reproducibility of volumetric quantifying T1 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.

References