Tissue water dynamics in acute ischemic stroke by $T_{1\rho}$ and $T_{2\rho}$ MRI using adiabatic pulses

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Introduction

Early and unambiguous diagnosis of acute cerebral ischemia is accomplished by several MRI techniques exploiting endogenous parenchymal contrasts, including diffusion and $T_{1\rho}$. Rotating frame longitudinal $T_{1\rho}$ MRI contrast, obtained with an on-resonance continuous wave (CW) spin-lock pulse, is a particularly sensitive MR index of tissue pathology associated with hyperacute ischemia and at the same time it provides information from long-term tissue outcome [1]. $T_{1\rho}$ MR signal decay is strongly influenced by slow molecular fluctuations occurring close to the condition of $1/\tau_c=\gamma B_1$. Several physical processes influence molecular motion at this time scale including exchange, diffusion and dipolar interactions. Similarly, the transverse $T_{2\rho}$ rotating frame relaxation, as obtained by means of adiabatic pulses, is influenced by slow molecular motion [2,3]. Exchange and dipolar interaction induced rotating frame relaxations depend on the amplitude and frequency modulations of the adiabatic full passage (AFP) pulses such as hyperbolic secant (HSn) pulses [2,3]. Despite the complexity of tissue relaxation, simple two-site exchange (2SX) model which includes dipolar relaxation at sites A (macromolecule-interacting water) and B (bulk-like water) coupled by the equilibrium exchange provides a commonplace model for the tissue relaxation. Within the 2SX model the respective intrinsic relaxation rate constants, $R_{1\rho,A}$ and $R_{1\rho,B}$, for the sites A and B are population averaged and are dependent on the choice of adiabatic pulse modulation function. Thus by changing adiabatic pulse shapes the weighting of the MR signal can be altered and inherent rotational correlation times (for the dipolar interaction) as well the exchange correlation time between these sites can be computed [3]. The aim of this work was to take advantage of the aforementioned unique features of rotating frame relaxations during adiabatic pulses to probe alternations of the water spin dynamics during evolving tissue pathology in the early moments of acute ischemic stroke.

Methods

Male Wistar rats were anesthetized with 1.5 - 2 % isoflurane in 70/30 N_2O/O_2 for permanent middle cerebral artery occlusion (MCAo) [4]. MRI experiments were performed in a horizontal 4.7 T magnet interfaced to a Varian Inova console. MRI scans were acquired at two time points 60 to 170 minutes and 170 to 280 minutes from induction of ischemia. The transversal imaging plane (thickness 1.5 mm) was positioned 4 mm from the surface of the brain. A quadrature half-volume coil was used in transmit/receive mode. Fast spin-echo (FSE) readout (TR 2.5 s, 64 x 128 pixels, echo spacing 10 ms, FOV 2.56 x 2.56 cm^2) was used for $T_{1\rho}$ and $T_{2\rho}$ MRI. D_{av} was quantified using a SE sequence incorporating four bipolar gradients along each axis with four b-values ranging from 0 to 1370 s/mm^2 (TR 1.5 s, TE 55 ms, 64 x 128 pixels, FOV 2.56 x 2.56 cm^2). Absolute $T_{1\rho}$ images were acquired using AFP pulses with eight different HS1 to HS8 modulation functions (train of 4 - 32 AFPs, pulse duration 2 ms, no inter pulse delay) (Fig. 1) [5]. Corresponding $T_{2\rho}$ images were obtained with AFP-pulses using an adiabatic half passage in front and after the AFP train. The previously described 2SX model was fitted into the measured rotating frame relaxation data in least squares sense using Levenberg-Marquardt algorithm. The free parameters used were correlation time $\tau_{c,A}$, populations P_A, P_B, and the exchange correlation time, τ_{ex}. The correlation time $\tau_{c,B}$ of 10^{-12} s^{-1} was used for free water compartment.

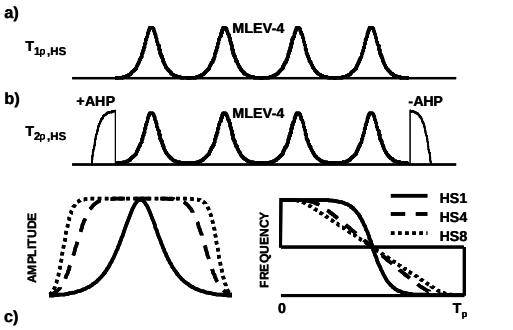

Fig.1: Preparation pulse shapes used: a) $T_{1\rho}$ and b) $T_{2\rho}$. (T_{SL} = 8ms) AHP = Adiabatic Half Passage. c) Amplitude and frequency plots for HSn (n=1,4,8) pulses.

Results

Severe ischemia was evident in all animals, as ipsilateral D_{av} decreased irreversibly by 39.9 ± 1.4 % (mean ± SD). $R_{1\rho}$ and $R_{2\rho}$ data obtained with HSn (n = 1 to 8) pulses, acquired at two time points (Fig. 2), showed that progression of ischemia led to increased difference in $R_{1\rho}$ and $R_{2\rho}$ values between ipsi- and contralateral sides. All relaxation rate constants were significantly decreased in the ischemic brain at both time points, except for $T_{1\rho,HS1}$ ($p=0.098$). Fitting the two-site exchange model [3] into the relaxation data indicated that the relative size of the free water pool (site B) increased during ischemia in a time-dependent manner ($p<0.01$ at time point 2). The rotational correlation time $\tau_{c,A}$ drastically decreased ($p<0.05$) during ischemia, indicating increased mobility of the bound water fraction. Furthermore, the exchange correlation time τ_{ex} was increased ($p<0.05$).

Conclusions

The results show that both $T_{1\rho}$ and $T_{2\rho}$ MRI reveal cerebral ischemia. We show that sensitivity of rotating frame MRI contrast can be modified using adiabatic approaches, and that modeling the rotating frame relaxation data may provide insight into progression of ischemic pathology. Modeling data are consistent with known features of acute stroke including edema and lytic tissue processes.

Table I: Fitted model parameters of water pools for contralateral and ipsilateral sides measured by the HSn $T_{1\rho}$ and $T_{2\rho}$ pulses at two time points (mean ± SEM).

	P_A	P_B	τ_A (s)	τ_{ex} (s)
Contra	0.37 ± 0.06	0.63 ± 0.06	(6.4 ± 4.6) x 10^{-10}	(6.6 ± 1.3) x 10^{-5}
Ipsi Tp 1	0.36 ± 0.18	0.64 ± 0.18	(4.0 ± 5.0) x 10^{-10}	(7.3 ± 0.7) x 10^{-5}
Ipsi Tp 2	0.34 ± 0.16	0.66 ± 0.16	(4.1 ± 5.2) x 10^{-10}	(7.1 ± 0.8) x 10^{-5}

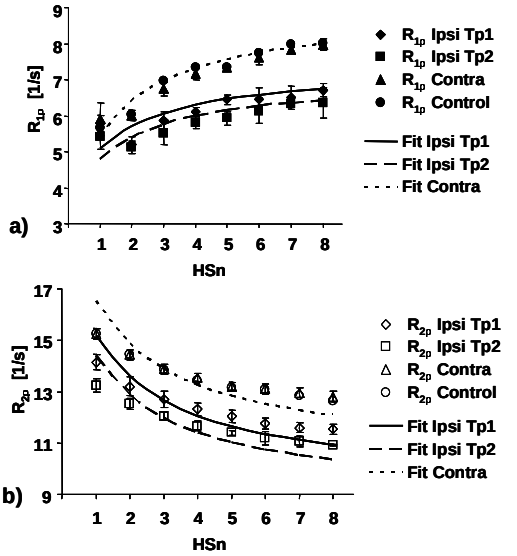

Fig.2: a) $R_{1\rho}$ and b) $R_{2\rho}$ values (mean ± SD) measured with HSn (n = 1 to 8) pulses for ischemic ('ipsi') and contralateral ('contra') brain (N=3) and a control rat. The fitted lines for each time point (Tp) were calculated using the measured $R_{1\rho}$ and $R_{2\rho}$.

References:

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