Optimizing Saturation-Recovery Measurements of the Longitudinal Relaxation Rate Under Time Constraints

J-J. Hsu[1], G. H. Glover[1], and G. Zaharchuk[1]

[1]Lucas Center for Imaging, Stanford University, Stanford, California, United States

Introduction. The oxygen level of brain tissue and cerebrospinal fluid (CSF) are related; thus CSF oximetry can allow insight into brain regional oxygenation. All existing clinical methods of oximetry are highly invasive, requiring either microelectrode or optode insertion. The non-invasiveness of MRI oximetry is hence desirable. It has been shown recently [1] that the oxygen concentration of CSF can be determined by MR longitudinal relaxation rate R_1 measurement. The saturation–recovery (SR) method is a common technique for tissue, which derives R_1 by curve-fitting the data points acquired with different *recovery times*. But CSF has long T_1 ($T_1 = 1/R_1$); consequently, when the recovery times that are optimal for imaging tissue ($T_1 \sim 1$ s) are scaled for CSF ($T_1 \sim 4$ s), the total scan time can be too long to be clinically feasible. Despite earlier efforts [2] to optimize the SR method, very little is known about the feasibility and optimization for long-relaxation substances. To overcome the scan-time obstacle of translating CSF oximetry to the clinic, Monte Carlo computer simulation was performed in this work to determine the recovery times that generate optimal accuracy and precision of SR R_1 measurements under strict constraint on constant total scan time. With the optimization, 3D, high resolution, whole brain SR scans completed in a scan time of 10 min can generate R_1 measurements of CSF in agreement with the best literature results, as described below.

Methods. In the interest of clinical feasibility, the present work focuses on two- and three-point SR methods with the sum of the recovery times (SRT) subject to a constant. The SR equation is given by $M(\tau) = M_{eq}[1-\exp(-\tau R_1)]$, where $M(\tau)$ and M_{eq} represent the magnetization at recovery time τ and at thermal equilibrium, respectively. Time is expressed in unites of the true T_1 and the value of R_1 is in units of $1/T_1$ unless a physical unit is attached. **§*Computer Simulation.***—The distribution of R_1 values obtained by solving or curve-fitting the SR equation was simulated by using a large number of computer-synthesized signals for various SNR levels. A distribution was established for each vertex on a Cartesian grid of recovery-time spacing $0.05T_1$. Then the ideal set of the recovery times was determined as the one that minimizes the standard deviation (SD) of the distribution. The signals were synthesized as the SR equation plus noise. The noise was generated by a zero-mean, normally-distributed random number generator of standard deviation defined by the given signal-to-noise ratio (SNR). **§*SR MRI with XETA.***—3D imaging by the SR method was implemented by repetition of a fast spin-echo (FSE) train. Each repetition was delayed by the desired amount of recovery time τ. The FSE train had a large number of refocusing rf pulses (146 pulses) and very short pulse spacing (6.8 ms); therefore, each pulse train is effectively a saturation (90°) pulse. The FSE train had an echo time of ~500 ms, more than five times longer than the transverse relaxation time T_2 of brain tissue but much shorter than the T_2 of CSF; thus the MR signals recorded arise almost entirely from the CSF. This T_2-weighting effect reduces the partial-volume-effect error. 3D XETA [3], an advanced FSE pulse sequence, was employed in this work; each 3D image contained 84 2-mm thick, 22×22 cm, sagittal slices; each slice had resolution of 0.86×0.86×2.0 mm or 1.5×10^{-3} c.c., reconstructed from data that was 85% undersampled in the phase encoding direction. XETA images of different τ were acquired as separate scans.

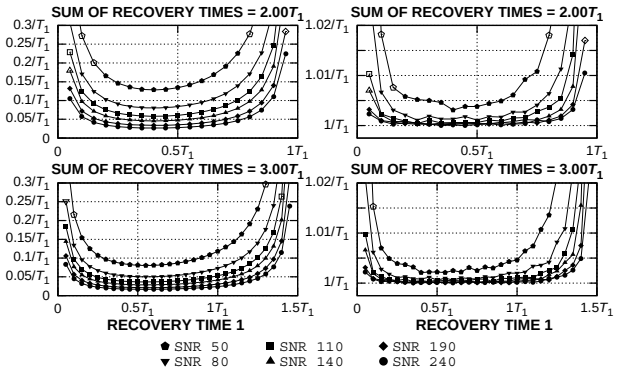

Figure 1 The standard deviation (SD, left column) and the mean (right) of the computer simulated distribution of R_1 for the two-point method. The SD and the mean represent precision and bias, respectively. Recovery time 2 can be derived by subtracting the sum by recovery time 1.

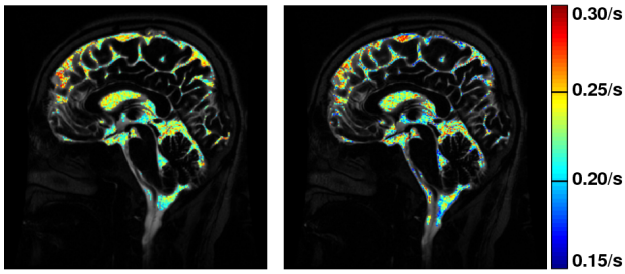

Figure 2 Sample slices of the 3D CSF R_1 maps acquired at 1.5 T by the two-point SR method with the optimal recovery time pair $(0.4, 1.6)T_1$ (left) and a suboptimal pair $(0.6, 1.4)T_1$ (right).

Table I Mean R_1 values (and SDs; in s^{-1}) of CSF at 1.5 T.

	Lat. Ventricle	Subarachnoid Space
Subj. I, Day 1	0.225 (0.016)	0.233 (0.038)
Subj. I, Day 3	0.223 (0.022)	0.244 (0.046)
Subj. II	0.213 (0.019)	0.220 (0.039)
Zaharchuk et al. [1]	0.226±0.004	0.247±0.011

Results and Discussion. It was determined in preliminary scans at 1.5 T that the SNR of interest is in the range of 50–240. The simulation was performed for SRT of $1.5T_1$ to $3T_1$; these conditions can reduce the scan time considerably and have adequate SNR for R_1 measurement. Figure 1 shows sample results of the simulation for the two-point method. In general, the minimal SD occurs at the same or approximately the same set of the recovery times despite the SNR. For the two-point method, the ideal recovery times are $(0.4, 1.6)T_1$ and $(0.55, 2.45)T_1$, for SRT of $2T_1$ and $3T_1$, respectively. For the three-point method, the recovery times are $(0.25, 0.30, 1.45)T_1$ and $(0.40, 0.40, 2.20)T_1$, for SRT of $2T_1$ and $3T_1$, respectively; it is very interesting that two of the recovery times should be set the same or approximately the same and shorter than the third one, which has not been reported in earlier work using analytical formulae. The accuracy of setting the recovery times to their exact values for optimal R_1 precision is not critical if the SNR is high. Under a common constraint of SRT, the two-point method is more efficient than the three-point method because the improvement in accuracy and precision by the latter is only marginal (~0.5%). Figure 2 shows sample CSF R_1 maps using our method. The total scan time was 9 min 55 s. The advantage of the optimization might not be easily discernable in this figure. Nevertheless, by adding computer generated noise to the XETA images and recalculating R_1, it is confirmed that the R_1 results of the optimal recovery times are always more stable under noise influence. The R_1 measurements are in agreement with earlier literature results as shown in Table I, which demonstrates the clinical feasibility of applying two-point SR method for R_1 mapping for CSF.

Acknowledgements. This work is supported by NIH RR09784 and the Richard Lucas Foundation. **References:** [1] G Zaharchuk *et al.*, Acad Radiol **13**, 1016 (2006). [2] See, for example, GH Weiss *et al.*, J Magn Reson **37**, 369 (1980); ED Becker *et al.*, *ibid.* **37**, 381 (1980); H Hanssum and H Rüterjans, *ibid.* **39**, 65 (1980); SJ Doran *et al.*, *ibid.* **100**, 101 (1992); RJ Kurland, Magn Reson Med **2**, 136 (1985). [3] GE Gold *et al.*, Am J Roentgenol **188**, 1287 (2007).