Clinical prostate T1 quantification using a magnetization-prepared spiral technique

W. Foltz[1], M. Haider[2,3], P. Chung[1], A. Bayley[1], C. Catton[1], V. Ramanan[4], D. Jaffray[1], G. Wright[4], and C. Ménard[1]
[1]Radiation Medicine Program, Princess Margaret Hospital, Toronto, Ontario, Canada, [2]Medical Imaging, University Health Network, Toronto, Ontario, Canada, [3]Medical Imaging, University of Toronto, [4]Sunnybrook Research Institute, Toronto, Ontario, Canada

Introduction: Current efforts in T1 quantification are motivated by a need to quantify exogenous contrast concentration dynamics from signal time-courses, plus characterization of partial oxygen pressures and hemorrhagic pathology (1,2). This research describes the optimization of a magnetization-prepared spiral imaging for clinical T1 quantification of the prostate gland. Termed T1prep, the method provides time-efficient multi-slice coverage of the entire gland without compromising robustness, as demonstrated via in vitro quality testing and pilot clinical studies.

Methods: A magnetization-prepared vascular oximetry technique, termed T2prep (2), was adapted for T1-prepared acquisitions using a non-selective adiabatic inversion followed by a delay of duration TI. Slice selection and spatial encoding are performed using a spectral-spatial pulse and spiral imaging gradient. Multi-slice imaging is performed by repetitive slice selection and spatial encoding at frequent intervals (~ every 20ms in different slices). A second delay of value TI' trails a final spoiler gradient. After the TI' delay, a BIR-4 adiabatic half-passage pulse is applied to null the residual longitudinal and transverse magnetization. By preserving a constant summation of TI+TI' across variable TI, the period of longitudinal recovery is kept independent of TI selection for any TR. Also intrinsic to T1prep is RF cycling to reduce data sampling to 2 TI only. Simply, the inversion pulse is applied on every other sequence iteration only and the difference signal is extracted. The difference signal is the decaying component of T1 relaxation (3) and T1 regression is reduced to the robust linear fitting of a logarithmically-transformed monoexponential decaying signal with TI values of 14 and 1014ms. It is unnecessary to increase TI values by increments of the imaging interval duration (~20ms) for adjacent slices because the slope of a linear fit depends only on the TI separation rather than on the absolute TI values.

Multi-slice T1prep reproducibility testing used a 750ml MnCl2-doped water volume within a standard head coil (1.5T GE Signa). T1prep acquisitions (TI = 13, 1013ms, 1.1x1.1x6mm voxels) were then repeated at RF amplifier mis-tunings between ±20%. T1prep accuracy was tested using 7 serial dilutions of Gd-DPTA in 2cc eppendorff tubes within a doped water bath (T1 between 400 and 2200ms). T1prep (TI of 14, 414, 814, 1214, 1614, 2014ms) was compared to gold standard inversion-recovery spin-echo acquisitions (TI of 50, 400, 800, 1200, 1600, 2000, 4000ms).

Clinical pilot studies involved 15 patients with low and intermediate risk localized prostate cancer and no prior treatment history. The MRI examination was performed on a 1.5T GE Signa with patients positioned supine and a torso-phased array, including full gland coverage using standard diagnostic FSE imaging and the quantitative T1 acquisition (TI = 14, 1014ms; TR=4400ms, 1.1x1.1mm resolution over a 20cm FOV, 6mm slice thickness, 5min duration). Data analysis involved regions of interest (ROIs) corresponding to the central gland (CG), uninvolved peripheral zone (PZ), and tumor-dense bearing (T) regions, delineated on FSE images by an experienced radiation oncologist using MIPAV (NIH, Bethesda, MD). ROIs were applied to T1prep signal images and manually adjusted to account for evident motion. T1 regression to a monoexponential decay used Origin software. Significance testing used Student's t-test at a threshold of 0.05.

Results: Using a centrally-placed ROI in each of 10 6-mm slices, T1prep preserved the T1 standard deviation (σT1) of the multi-slice acquisition on the order of 1% for RF offsets between ±20%. The method also demonstrated excellent agreement with the gold-standard inversion-recovery approach. Bland-Altman analysis highlighted an increasing bias using T1prep as sample T1 approached and lengthened beyond the latest TI of 2014ms. However, T1 agreement was within 0.5% for T1 values of less than 1500ms.

From clinical acquisition, the mean zonal T1 values were 1327±60ms (n=14) and 1355±191ms (n=11) for CG and PZ respectively. Inter-patient heterogeneity was significant, with mean CG T1 ranging from 1149 to 1482ms, and mean PZ T1 ranging from 1039 to 1486ms. Nine tumor-dense ROIs were delineated (volume of 665±432mm3). Tumor T1 values were 1187±149ms (minimum: 1051ms; maximum: 1406ms). Tumor T1 were significantly shorter than the CG (T1 difference 70±77ms, p=0.024) and approached significance with PZ (T1 difference of 119±164ms, p=0.081).

From voxel-based analysis within individual ROIs, intra-patient T1 heterogeneity were 16±1% for CG, 20±4% for PZ, and 18±6% for tumor. From Monte Carlo simulation of a monoexponential decay, T1 standard deviation (σT1) from thermal noise reduces below 5%, 2.5%, 2%, 1.5%, and 1% for SNR values of 35, 70, 90, 115, and 170. From histogram analysis, 95% of the delineated voxels presented with SNR values of 32 (CG) and 29 (PZ) or more at a TI of 14ms, so that a voxel-based analysis will be quite prone to thermal noise. At least 10 voxels must be included in a ROI to maintain thermal noise variability within 2%. A ROI must then contain at least 13 voxels to reduce noise contributions below 1.5%. 95% of SNR values at the second TI were greater than 15 for CG and 13 for PZ, so that regressions were not biased by the noise baseline in magnitude images.

Summary and Conclusions: A magnetization-prepared spiral imaging strategy has been adapted for time-efficient RF-insensitive clinical prostate T1 quantification. Clinical investigation in patients with low and intermediate risk prostate cancer demonstrated equivalence between CG and PZ T1, and a significantly reduced tumor T1. SNR analysis identified a minimum-useful sampling volume for thermal-noise-insensitive T1 quantification, and identified SNR thresholds to guide protocol design for future voxel-based analysis as an adjunct measure supporting quantitative perfusion.

References: (1) Dale et al *J Magn Reson Imaging*, 2003; (2) Foltz et al. *Magn Reson Med*, 2006; (3) Hsu et al. *Magn Reson Med*, 2006.

Figure (a) Multi-slice reproducibility for RF offsets between ±20% for T1prep (experimental, circle) and standard VFA (simulated, triangle); (b) Bland-Altman comparison between T1prep and a gold standard inversion-recovery spin-echo method; (c) representative FSE, T1w-prep (TI=1014ms), and T1prep map (windowed between 800 and 1600ms). An arrow demarcates the location of a small peripheral-zone tumor.