Sodium MRI of the Human Brain Using Projection Acquisition in the Steady-State with Coherent Magnetization (Na-PACMAN)

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Introduction: Sodium MRI is interesting not only because its signal source may facilitate the assessment of sodium ion concentrations, but also because sodium's relaxation mechanism is different than proton's, providing another tool for in-vivo exploration. Unlike the dipole-dipole interaction for proton NMR, sodium relaxation is derived from the electric quadrupole moment of the nucleus and its alignment in an electric field gradient; and is linked not only to macromolecular density but also to anisotropy (through T_{2f}) (**1**). In the human brain T_{2f}* assumes a very large range of values from < ~1 ms to 65 ms (T_{2f} comprises 60% of the transverse relaxation); T_{2s}* ranges from ~17 ms to 65 ms, and T_1 from ~37 ms to 65 ms (at 4.7 Tesla). Previous sodium MRI techniques have attempted to use sodium's unique relaxation as a means to selectively detect intracellular ions (**2**). However, the relaxation mechanism itself may be useful in the exploration of disease, providing different contrast than proton and quantitative sodium concentration imaging. The purpose of this work is to propose a sodium MRI technique, Projection Acquisition in the steady-state with Coherent MAgNetization (Na-PACMAN), for the generation of high-quality, strongly T_{2f}* weighted sodium images.

Methods: The Na-PACMAN sequence is a steady-steady projection imaging sequence for sodium MRI in which the transverse magnetization is refocused following readout and added to the relaxing longitudinal magnetization by the subsequent RF pulse (**Figure 1**). For short T_{2f}* environments the transverse magnetization associated with T_{2f}* is of little consequence at TR, but as T_{2f}* increases above ~7ms, T_{2f}* begins to have a very significant impact on the amount of signal produced. Na-PACMAN also generates strong T_{2f}* relaxation weighting over TE (especially for shorter T_{2f}* values). Large flip angles (90°) and longer RF pulse lengths (2.5 ms – yielding a TE of 1.3 ms) are used to enhance this weighting. Longer RF pulse lengths also enable short TR (25 ms) under specific absorption rate (SAR) constraints; a short TR value is required to increase the number of acquisitions and reduce noise variance. Under SAR the three parameters (flip angle, RF pulse length, and TR) that govern relaxation weighting and SNR are interdependent. Projection acquisition is used so that TE is not increased excessively by additional delay following the RF pulse (with significant signal reduction consequence in short T_{2f}* environments). Na-PACMAN was implemented on a 4.7T Varian Inova scanner, and tested with healthy volunteers. 4000 twisted projections were implemented to fully cover k-space to an extent of 200 1/m x 200 1/m x 67 1/m. 10 averages were acquired for a total scan duration of ~ 17 minutes.

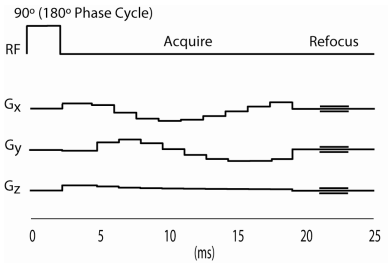

Figure 1: The Na-PACMAN pulse sequence makes use of long, non-selective 90° RF pulses and gradient refocusing to generate high SNR sodium images with strong T_{2f}* relaxation weighting. Projection imaging is required to limit TE, concomitantly determined by the RF pulse length, which also facilitates TR reduction under specific absorption rate (SAR) constraint.

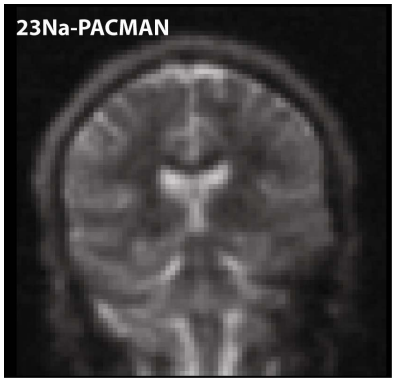

Figure 2: The Na-PACMAN sequence generates high SNR sodium images. For the image presented distinct signal differences are observed between white and gray matter, suggesting more rapid T_{2f}* relaxation in the dense, and ordered white matter environment.

Results and Discussion: The Na-PACMAN sequence produces very high-quality sodium images (**Figure 2)** with an SNR of ~140 in CSF, ~45 in gray matter (hippocampus), and ~22 in white matter (corpus callosum). Given that the tissue sodium concentration has been measured as 13% greater in white matter than gray matter (**3**), **Figure 2** highlights a significant sodium relaxation dependence (assumed to be predominantly T_{2f}*, as measured differences in T_{2s}* (**4**) and differences in T_1 are expected to have little impact). It should be pointed out that the steady-state relaxation weighting (ignoring T_{2f}* over TE weighting) generated with the Na-PACMAN sequence is similar to that generated with proton balanced steady-state free-precession, i.e. T_1/T_2, but is also somewhat dependent on the value of T_1 itself, as TR is not << T_1 and T_2. As described, the Na-PACMAN sequence is expected to generate T_{2f}* relaxation weighting when T_{2f}* values are short (through TE), and T_{2f}* relaxation weighting when T_{2f}* values are long (through magnetization refocusing), covering the full range of T_{2f}*. The dramatic range of T_{2f}* and its connection with macromolecular anisotropy may complement tissue sodium concentration studies in neurological disease associated with loss of macromolecular density and order.

References: (1) Woessner, D.E., Concepts in MR 13, 294 (2001) **(2)** Pekar, J., et. al., JMR 72, 159 (1987) (**3**) Ouwerkerk, R., et. al., Radiology, 227, 529 (2003) (**4**) Bartha, R.B., Menon, R.S., MRM 52, 407 (2004).