Quantitative Study of TX/RX-efficiency of X-Nuclear MRS/MRI at High/Ultrahigh Field

Hannes M. Wiesner[1], Wei Luo[2], Qing X. Yang[3], Xiao-Hong Zhu[1], Scott Schillak[1], and Wei Chen[1]

[1]*Center for Magnetic Resonance Research, Department of Radiology, University of Minnesota Medical School, Minneapolis, Minnesota, United States,* [2]*Department of Engineering Science and Mechanics, Pennsylvania State University College of Medicine, Hershey, Pennsylvania, United States,* [3]*Center for NMR Research, Department of Radiology, Pennsylvania State University College of Medicine, Hershey, Pennsylvania, United States*

Introduction: *In vivo* MRS and MRI can benefit significantly from high/ultrahigh field in improving detection sensitivity and spectral resolution. Owing to the different behaviors of RF wave properties at low versus high field, the RF B_1 fields of transmission (B_1^+) and reception (B_1^-) become dependent upon the operation (or Larmor) frequency at high field, especially for ^{1}H spin. This frequency dependence has a critical impact on the MR sensitivity, RF power deposition, SAR, and their spatial distributions at high field. Although numerous research efforts have been dedicated to understand the complexity of B_1 fields on proton MRI at high/ultrahigh field, it is still elusive about the B_1 implication on X-nuclear MRS/MRI. The present study aims to quantitatively investigate and compare the transmission and reception efficiencies of four common spins of ^{1}H, ^{31}P, ^{23}Na and ^{17}O at 7T.

Theory: The MR signal (S) for a given spin can be described by the following equations [1-4]:

$$S \propto \rho \cdot B_1^- \sin(\alpha) \quad \text{Eq [1]}; \qquad \alpha = \gamma \cdot pw \cdot B_1^+ \cdot V \quad \text{Eq [2]}; \qquad \left|B_1^+\right| = \frac{\left|B_x + iB_y\right|}{2} \quad \text{Eq [3]}; \qquad \left|B_1^-\right| = \frac{\left|B_x - iB_y\right|}{2} \quad \text{Eq [4]}; \qquad \alpha\text{-Ratio} = \left(\frac{\gamma_X}{\gamma_H}\right)\left(\frac{B_{1,X}^+}{B_{1,H}^+}\right)\left(\frac{V_{90^o,X}}{V_{90^o,H}}\right)\left(\frac{Q_X}{Q_H}\right) \quad \text{Eq [5]}$$

where ρ is the spin density; α is the RF excitation pulse flip angle; γ is the gyromagnetic ratio; *pw* is the RF pulse width; *V* is the RF pulse driving voltage; B_x and B_y are the B_1 component along x and y axis in the rotating frame; α-Ratio is the flip angle ratio between X-nuclear spin to ^{1}H spin. B_1^- determines the reception sensitivity and B_1^+ determines the transmission efficiency or the RF pulse voltage required for achieving a desired flip angle. According to Eq. [2], the *V* value required for achieving a desired α with a constant *pw* could become inversely proportional to γ if B_1^+ was considered to be frequency independent. This could imply that a much larger RF driving voltage is needed for low-γ spins to achieve the same α. Nevertheless, our results from the present study clearly show a much smaller voltage is required for low-γ nuclei at 7T, suggesting that B_1^+ must be different at high field among various nuclei with distinct RF operation frequencies. In this study, the quantitative relation between B_1^+ and *V* among ^{1}H, ^{31}P, ^{23}Na and ^{17}O nuclei at 7T was determined and compared, and the reception efficiency of B_1^- and its difference among these heterogeneous spins were also investigated.

Methods and Materials: Four surface loop coils with identical diameter of 6 cm were made using 2mm copper wires with two equally split, tuning capacitors and matching circuit. The tuning capacitances were adjusted to different Larmor resonance frequencies at 297.2 MHz for ^{1}H, 120.3 MHz for ^{31}P, 78.63 MHz for ^{23}Na and 40.29 MHz for ^{17}O spin, respectively. Coil losses with disconnected cable were characterized by Q-measurements of a standard 3-point method (-3db width) using a calibrated Network analyzer and a pickup coil. Two spherical plastic phantoms with ~5.5 ml solution were prepared with equal sodium concentration (77 mM): one with de-ionized water and 0.45% NaCl for measurements of ^{1}H, ^{23}Na and ^{17}O signals; another one with de-ionized water and NaH_2PiO_4 for ^{31}P signal; they were positioned at the center of the surface coils. MR signals (FIDs) were collected under fully relaxed conditions with a single-pulse-acquire sequence (hard RF pulse with a fixed *pw* of 500 μs) on a 7T whole-body actively shielded magnet (Siemens AG, Erlangen, Germany). The RF pulse driving voltages were varied in a range of 0 to 30v for calibrating the 90° flip angle voltage (V_{90^o}) via regressing the MR signals to the sinusoidal function using the Curve Fitting toolbox of Matlab (The Mathworks, Natick, MA). Coils of same dimensions including sample and configuration lying on the x-z plane were modeled using the XFdtd software (XF7, Remcom Inc., State College, PA) for calculating B_1^+ (driven by 1 W and can be converted to per volt) and B_1^- (by 1 Amp) profiles along the y-axis at the coil center (x,z=0).

Results and discussion: Figure 1A displays the MR measurement results, showing the relationship between MR signal and RF reference voltage for four nuclei at 7T. The required V_{90^o} increased with low-γ nuclei compared to ^{1}H, but not inversely proportional to γ. Figures 1B and 1C show the simulation results of B_1^+ and B_1^- profiles along the y-axis, indicating distinctive frequency dependences and much higher B_1^+ and B_1^- efficiencies for low-γ nuclei, in particular, ^{17}O spin. Table 1 summarizes the results of V_{90^o} and Q measurements, simulated B_1^+ at the coil center (x,y,z=0), γ values of four nuclei, and their ratios normalized by the corresponding ^{1}H values.

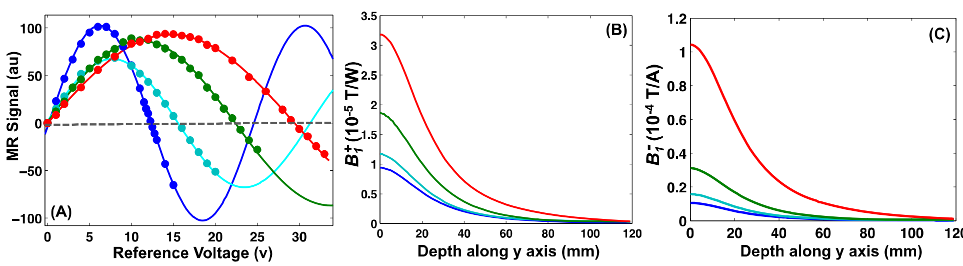

Figure 1 (A) Relation between MR signal and RF voltage (full circles: experimental measures, lines: sinusoidal fitting. (B) B_1^+ and (C) B_1^- profiles. Red color for ^{17}O; green color for ^{23}Na, cyan color for ^{31}P and blue for ^{1}H spin, respectively.

Theoretically, the flip angle (=90° used herein) ratios between two nuclei should be 1 according to Eq. [5]. Table 1 shows that the mean α-Ratio values were within 1.0±0.1 from all nuclei, suggesting high accuracy of experimental and B_1 simulation results. In comparison with ^{1}H, the required V_{90^o} for X-nuclear spins was substantially lower than that predicted from their γ-ratio, for instance, only 2.4 times higher V_{90^o} was needed for ^{17}O while their γ-ratio alone predicts 7.4. This is mainly due to the higher B_1^+ efficiency of ^{17}O at 7T, which is 3.4 times better than ^{1}H. Thus, the requirements of RF driving voltage, RF power and SAR are significantly reduced for low-γ nuclei at high/ultrahigh field.

Table 1 Summary of results

Nuclei	γ (10^7rad/s/T)	B_1^+ (10^5T)	$V_{90°}$ (v)	Q	γ-Ratio	B_1^+-Ratio	$V_{90°}$-Ratio	Q-Ratio	α-Ratio
^{1}H	26.75	0.94	6.18	384	1.00	1.00	1.00	1.00	**1.00**
^{31}P	10.83	1.17	7.79	620	0.40	1.24	1.26	1.61	**1.03**
^{23}Na	7.08	1.86	11.20	367	0.26	1.98	1.81	0.95	**0.91**
^{17}O	3.63	3.18	14.72	383	0.14	3.38	2.38	1.00	**1.09**

Strikingly, the reception efficiency of the surface coil for low-γ nuclei is superior compared to the ^{1}H at 7T as demonstrated in Fig. 1C. The average B_1^- efficiency between y=0 to 6 cm (one diameter of the surface coil) was 1.4, 2.8 and 10.3 times better for ^{31}P, ^{23}Na and ^{17}O, respectively, as compared to ^{1}H. This finding supports the *in vivo* observation of superior ^{17}O MR sensitivity for detecting brain tissue water at high/ultrahigh field despite of extremely low ^{17}O natural abundance of 0.037% and low γ ratio [5].

Conclusion: Several conclusions can be drawn from this study for understanding the pros and cons of X-nuclear MRS/MRI at high/ultrahigh field. In general, low-γ nuclei require a large RF pulse voltage (or power) to achieve the same flip angle as compared to ^{1}H. Nevertheless, their power demand at high field is significantly less than the prediction based solely on the γ-ratio due to the compensation effect of their high B_1^+ transmission efficiency. Moreover, low-γ nuclei have a much better reception efficiency than that of ^{1}H spin at high/ultrahigh field, leading to superior detection sensitivity for *in vivo* application of X-nuclear MRS/MRI.

Acknowledgements: This work is supported in part by NIH grants NS057560, NS041262, NS070839, P41 EB015894, S10 RR026783.

References: [1] Alecci *et al. MRM* **46**, 379-385 (2001). [2] Collins *et al. MRM* **47**, 1026-1028 (2002). [3] Yang *et al. MRM* **47**, 982-989 (2002). [4] Hoult, D. I. *JMR* **213**, 344-346 (2011). [5] Lu *et al. MRM* **69**, 1523-1527 (2013).