Spectrally Selective Hard Pulses (SSHP) for Positive Contrast MRI: Theory and Validation

T. Gupta[1], S. Shah[2], S. Virmani[3], R. Omary[4,5], and A. Larson[1,5]

[1]Radiology and Biomedical Engineering, Northwestern University, Chicago, IL, United States, [2]Siemens Medical Solutions, Chicago, IL, United States, [3]Radiology and Biomedical Engineering, Northwestern University, [4]Radiology, Northwestern University, Chicago, Il, United States, [5]Robert H. Lurie Comprehensive Cancer Center, Northwestern University, Chicago, IL, United States

Introduction: Several approaches have been proposed for signal-enhanced visualization of paramagnetic markers and contrast agents used for catheter tracking, atherosclerotic plaque imaging and stem cell research [1-3]. Recently, Patil *et al* proposed using spatially selective binomial pulses to generate positive contrast from paramagnetic markers [4]. In this work we investigated the use of spectrally selective hard pulses (SSHP) for positive contrast MRI of paramagnetic markers. Our primary focus was to study the effects of specific SSHP-parameters upon marker conspicuity, background suppression and fat suppression.

Theory: (I) Susceptibility-shifted paramagnetic markers exposed to the static magnetic field (B_o) generate a range of dipolar frequency shifts ($\Delta\omega$) within the surrounding tissues. Conspicuity of a paramagnetic marker is directly proportional to the total enhanced surface area contributed by all excited off-resonance (off-res) iso-frequency surfaces surrounding the marker. The enhanced surface area (S_{enh}) around a spherical paramagnetic marker decreases rapidly for iso-frequency surfaces with higher values of $\Delta\omega$:

$$S_{enh} = \frac{4\gamma\pi a^3(\Delta\chi)\, B_o*(0.7698)}{9(\Delta\omega^2)} \qquad \textbf{[Eqn 1]}$$

[a = radius of the paramagnetic sphere, γ = gyromagnetic ratio]

(II) A SSHP sequence contains a series of N short rectangular RF sub-pulses with flip angles Φ_k(k=1 to N) and τ RF spacing (sec) between two adjacent sub-pulses. The applied RF phase alternates between 0 and π radians across the sub-pulse series. The SSHP sequence selectively excites specific off-res targets ($\Delta\omega$) around the paramagnetic marker. These targets can be selected by varying the RF spacing (τ): $\boldsymbol{\tau = (1/4*\pi*\Delta\omega)}$. In addition to exciting the targeted iso-frequency surface, the SSHP pulse also excites frequencies at $\boldsymbol{(\Delta\omega+\Delta\omega*i)}$ **(i=2,4,6,8..)** while suppressing the on-resonant (on-res) frequencies and all off-res frequencies at $\boldsymbol{(\Delta\omega*i)}$.

Materials and Methods: A standard GRE sequence was modified to replace the conventional excitation scheme with composite SSHP pulses using 24 different combinations of N (# of sub-pulses) and τ (RF spacings). For each N=2, 3, 4 and 5, τ was adjusted to target a range of off-res frequencies including 100, 200, 300, 400, 800, 1600 Hz, respectively. The sub-pulse flip angles were individually weighted by binomial pulse ratios of order (N-1) to generate an effective flip angle of 90º. SSHP images of an agar phantom with an imbedded spherical paramagnetic Fe_2O_3 particle were acquired using a Siemens Sonata 1.5T clinical scanner. Sequence parameters: FOV 250x172 mm, Matrix 250x172, Slice/Slab = 16, Slice thickness = 2mm, TR/TE = 80/(2.82ms + (N-1)* τ), BW = 260Hz/Px. MR images and corresponding MATLAB simulations were evaluated for conspicuity, background and fat suppression.

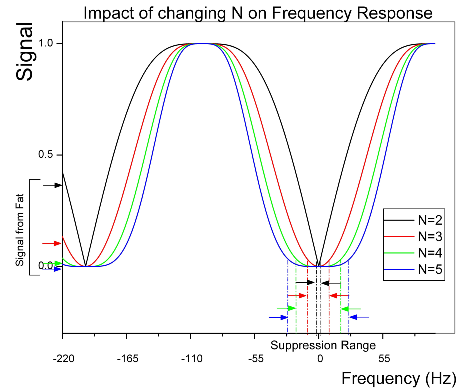

Fig. 1 Frequency response of SSHP at off-res target of 100Hz for series of N = 2, 3, 4, 5 pulses. The suppression range broadens (dashed lines) and the fat signal decreases (colored arrows marking the signal axis at frequency of -220 Hz) with increasing N value.

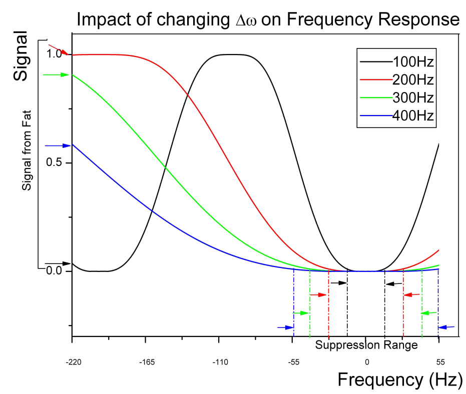

Fig. 2 Frequency response of SSHBP with N=4 for $\Delta\omega$ =100, 200, 300, 400 Hz. The suppression range broadens (vertical dashed lines) with increasing $\Delta\omega$. The fat signal (colored arrows marking the signal axis at frequency of -220 Hz) is lowest for $\Delta\omega$ = 100Hz.

Results: Each of the 24 N-τ combination SSHP pulses generated a characteristic dipolar signal enhancement pattern around the paramagnetic Fe_2O_3 particle (**Fig.3**). SSHP pulses with higher N values resulted in a broader suppression range (**Fig.1**), as a result on-res protons and Bo inhomogeneities were more effectively and homogenously suppressed at higher N values (**Fig.3**). Suppression range also increased with increasing $\Delta\omega$ (**Fig.2**). Figure 3 shows rapidly declining conspicuity with increasing N and increasing off-res target $\Delta\omega$. This is due to (a) increasing suppression range at higher N and $\Delta\omega$ values and (b) decreasing S_{enh} with increasing $\Delta\omega$ [Eqn 1]. According to MATLAB simulations, fat suppression increased with increasing N due to overall increased background suppression (**Fig.1**). Furthermore, for $\Delta\omega$=110Hz, frequencies around 220Hz ($\Delta\omega$*[i=2]) should be completely suppressed in addition to on-res protons as described above. Amongst our selected $\Delta\omega$ targets, 100 Hz was closest to 110 Hz, consequently fat suppression was maximum at $\Delta\omega$ =100Hz (**Fig.2**). According to graphical simulations, fat signal was slightly lower for $\Delta\omega$ =1600 Hz. However, S_{enh} (being inversely proportional $\Delta\omega^2$) was minimal at 1600Hz resulting in very low signal contribution from these protons and consequently, poor image quality due to low SNR within these images (**Fig.3**).

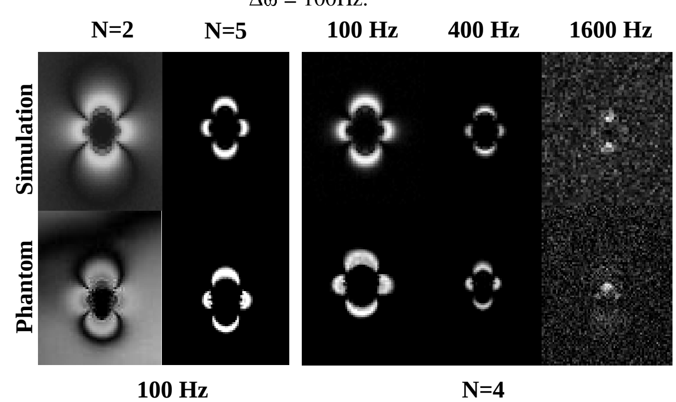

Fig. 3 SSHP simulation (top row) and agar phantom (bottom row) images of Fe_2O_3 particle. For a constant off-res target=100Hz, background suppression increases and conspicuity decreases as N increases from 2-5 (from the left: col. 1 and 2). For a constant N=4, conspicuity decreases rapidly with increasing off-res target value (col.3, 4 and 5). Low Senh at 1600 Hz iso-frequency surface leads to low signal contribution (col. 5).

Discussion: Incorporation of SSHP pulses in standard GRE sequences offers a promising method for positive contrast MRI. N, τ and $\Delta\omega$ may be individually optimized for applications requiring high fat suppression (e.g. abdominal imaging), homogenous background suppression (e.g. high-field imaging) or greater conspicuity (e.g. iron-labeled cell tracking). Further developments are needed to demonstrate the utility of this technique for *in-vivo* clinical applications. **Future directions:** (1) TSE based application of binomial hard pulses, (2) addition of spectrally selective FATSAT pulse to further saturate fat signal [4], (3) application of non-exact binomial flip angles for increased background suppression at lower N values [5].

References: **[1]** Seppenwoolde *et al*, Magn Reson Med 50:784-790 (2003) **[2]** Stuber *et al*, Proc Intl. Soc. Mag. Reson. Med. 13(2006) **[3]** Mani *et al*, Magn Reson Med 56:1096-1106 (2006) **[4]** Patil *et al,* Proc Intl. Soc. Mag. Reson. Med. 14(2007) **[5]** Schick, MAGMA 1: 158-168 (1993)