Selective Excitation of Dissolved $^{129}$Xe

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Target Audience
Hyperpolarized MR spectrally selective pulse designers

Purpose
Short RF pulses for frequency selective excitation of dissolved $^{129}$Xe

Introduction
Hyperpolarized $^{129}$Xe is a promising contrast medium that is capable of probing physiological parameters owing to its solubility in tissues [1-2]. When dissolved, the $^{129}$Xe resonance shifts approximately 200 ppm from the gas signal, with distinct separation of the signals from the dissolved ($^{3}$Xe) and gas ($^{5}$Xe) phase resonances. Previous studies have used long excitation pulses to selectively excite $^{3}$Xe resonances, assuming a minor ~1-2$^\circ$ perturbation of the larger $^{5}$Xe peak. However, owing to the low solubility of $^{129}$Xe in blood coupled with the a small blood volume to air space ratio in the lung, the intensity of $^{5}$Xe is approximately two orders of magnitude lower than the intensity of $^{3}$Xe. This means that even a 1$^\circ$ flip angle on the $^{3}$Xe peak will result in $^{3}$Xe and $^{5}$Xe signals of equal magnitude. Non-Cartesian trajectories are often needed to capture the short T$_2^*$ of the $^{3}$Xe (< 2ms [3]), this sizeable off-resonance $^{3}$Xe peak can create undesirable imaging artifacts. However, longer, more frequency selective RF pulses are suboptimal due to the T$_2^*$ dephasing during the pulse. Ideal excitation pulses for imaging $^{3}$Xe should have very low side band excitation coupled with short pulse length to minimize in-pulse T$_2^*$ relaxation [4]. Spectroscopists have used composite pulses extensively for water suppression which may be ideally suited for $^{3}$Xe imaging. In this work, we compare standard RF excitation pulses with shaped and composite pulses based on their spectral selectively and performance in relation to T$_2^*$ relaxation.

Methods
Simulated excitation pulses and profiles are in Fig 1. The shortest pulse in this study (500 μs hard pulse) is least affected by T$_2^*$ dephasing and produces transverse magnetization M$_{xy}$=0.86M$_0$ on resonance (red). However, despite having a nominal bandwidth of 2 kHz, the $^{3}$Xe signal is only ½ an order of magnitude lower than $^{5}$Xe. The 1.8ms long Hamming-windowed sinc pulse provides only half the total M$_{xy}$ and gives poor side band excitation as well. An 800 μs, 6 element optimized composite pulse delivers M$_{xy}$=0.72M$_0$ but has $^{3}$Xe excitation over five orders of magnitude less than $^{5}$Xe (black). Fig 2 shows spectra experimentally acquired with these two pulses, normalized to the highest dissolved spectral peak showing a dramatic excitation difference at $^{3}$Xe. With hard pulse excitation the gas is nearly an order of magnitude higher than either dissolved peak. With composite pulse excitation, the gas peak is nearly undetectable. Inset in the figure is a 100x magnification of the y-axis to show the residual excited gas peak. Measured excitation is 2 orders of magnitude lower than the dissolved peak, corresponding to a 4-5 order of magnitude suppression.

Discussion
Excitation with a composite pulse precludes slice selectivity, necessitating three dimensional encoding but this also eliminates the requirement for a slice refocusing pulse, which reduces effective echo time. If spectral selectivity is required, the minimum phase SLR pulse performs well in regards to side band suppression, however, the length of this pulse reduces signal in an already low SNR regime. The phase toggled implementation of the composite pulse generates no excitation at the tuned frequency, while generating a wide excitation band off resonance. This allows for the precise tuning to the resonance of gas to enable minimum excitation at this frequency. Even in the presence of B0 inhomogeneity, this pulse has >4 orders of magnitude suppression over a 600Hz range.

Conclusions
Standard excitation pulses perform poorly for the selective excitation of $^{3}$Xe, especially at lower fields where their resonance separation is small. While minimum phase SLR pulses can provide up to 3.5 orders of magnitude suppression and deliver high tip angles, tuned composite pulses can be made very short, delivering a higher percentage of M$_0$ to the transverse plane and provide sharp resonance notches that are ideal for suppressing narrow line shapes such as in the case of $^{5}$Xe.

References

Figure 1: Time domain envelope of RF excitation pulses (left) and their resulting profile including T$_2^*$ in pulse relaxation (right). Far right (beyond dashed lines) is log magnitude to emphasize small differences. $^{3}$Xe is at 0Hz and $^{5}$Xe is 3.5kHz (purple line). The short dissolved $^{129}$Xe T$_2^*$ puts difficult criteria on RF pulse length as seen by the M$_{xy}$(0Hz) as pulse length increases. Suppression of signal from is very strong for both shaped and composite pulses.

Figure 2: Spectra of $^{3}$Xe (at 0Hz) and $^{5}$Xe (at 3500-4200 Hz) using a hard pulse excitation (red) and a 6 element, 800us composite pulse (black), inset is 100x magnification in amplitude.