# Design of Velocity Selective Inversion Pulse for VSASL using the Shinnar-Le Roux Algorithm

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**Introduction:** The tagging pulses in Velocity Selective Arterial Spin Labelling (VSASL) [1] are purely Velocity-Selective (VS), rendering VSASL potentially resistant to transit delay effects and suitable for use in cases with slow blood flow. Many different approaches have been used to design VS pulses [1-4], including saturations and inversions. Here we propose a method to improve the velocity selectivity of VS inversion pulses by using the Shinnar-Le Roux (SLR) algorithm [5].

**Method:** The SLR algorithm converts the problem of RF pulse design into that of FIR filter design [5]. In our case, the pulse design problem is equivalent to a high-pass filter design. We designed a low-pass inversion pulse using the SLR algorithm and appended it to a non-selective inversion to yield the desired high-pass slice profile. Identical bipolar gradients of trapezoidal shapes are applied during each interval between two RF hard pulses to produce velocity encoding while satisfying the hard pulse approximation in SLR algorithm [5]. A pulse with 6 samples that inverts spins below a given cut-off velocity was generated using the SLR algorithm. A composite 90x-180y-90x non-selective inversion pulse provides the initial inversion. To reduce the total pulse duration and reduce sensitivity to off-resonance effects, we used as few RF samples as possible and shortened all hard pulses by maximizing their amplitudes. The total duration of the pulse was 14.5ms. The design targets were: Mz =1 for velocities below $\pm$13.6cm/s and Mz =-1 for velocities above $\pm$13.6 cm/s, within a velocity range of $\pm$50cm/s; Passband ripples no greater than 0.5%. The pulse and gradient waveforms are shown in Fig.1. The simulated velocity slice profile and the pulse performance versus B1 magnitude are shown in Fig. 2.

**Experiments:** Phantom experiments were conducted on a 1.5 T GE Signa Excite Scanner (GE Healthcare, Milwaukee, WI). The designed VS pulse was added to the beginning of a standard SE sequence as a preparatory pulse prior to the 90$^o$ excitation pulse. First, a static phantom study was conducted to observe the frequency selectivity of the designed pulse. A constant gradient took place of the bipolar gradients and was applied concurrently with the designed hard pulses. The experimental frequency slice profile is compared with simulation result in Fig 3. In addition, flow phantom studies were conducted using the same sequence. A pump was used to generate flow and a water-filled tank was used to make the flow in the imaging plane more continuous. Bipolar gradients were applied along the z axis to encode spins flowing in the –z direction. Flow phantom experimental results are shown in Fig. 4 and Fig. 5.

**Results:** Simulation results shown in Fig.2 demonstrate that (1) the flip angle; (2) the velocity selectivity; (3) the pass-band ripples all correspond well to the design targets. Results of static phantom studies shown in Fig. 3 illustrate that the frequency selectivity of the pulse corresponds well to the design target. Results of flow phantom studies shown in Fig. 4 and Fig. 5 verify that the designed pulse (1) can invert flowing spins within a large velocity range; (2) can leave static spins untagged.

**Discussion:** We have presented a novel design method for designing velocity selective inversion pulses, and shown a design example. Simulation results demonstrate that the pulse has very smooth inversion slice profile and good resistance to B1 inhomogeneity. Phantom studies verified the frequency selectivity and the velocity selectivity of the pulse. All results imply that the pulse is potentially suitable for tagging in VSASL to enhance the image SNR. In addition, our design method enables the pulse designer to explicitly trade-off among important parameters such as slice thickness, pulse duration and pass-band ripple.

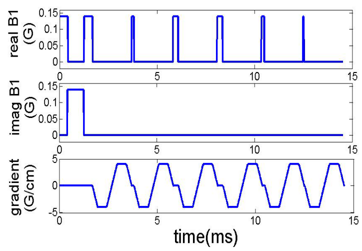


***Figure 1.** RF and gradient waveform. First three hard pulses make up the 90x-180y-90x non-selective inversion. The rest hard pulses together with bipolar gradients fulfill velocity selective inversion. RF and gradients have no overlap in time.*

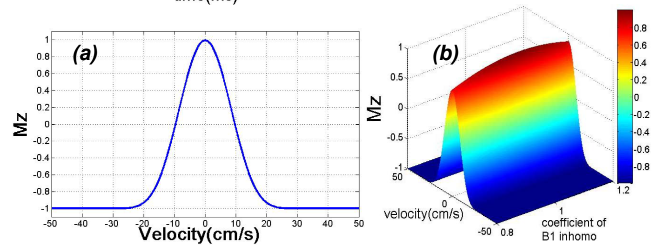


***Figure 2.** Pulse performance in simulation. (a) Velocity slice profile. (b) Resistance to varying B1 ranging from 0.8 to 1.2 its original value.*

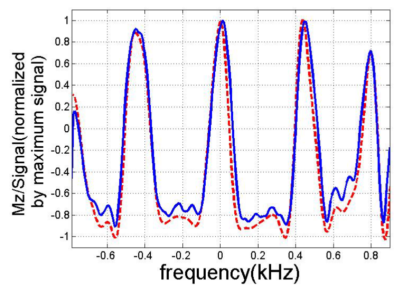


***Figure 3.** Excellent agreement is shown between simulated (red dashed line) and experimentally measured (blue solid line) frequency slice profiles. Less inversion is seen in experiment due to T1 relaxation.*

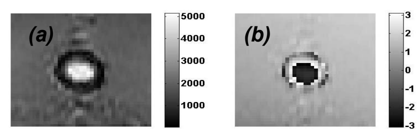


***Figure 4.** Images from flow phantom experiments. The designed pulse was used as a preparatory pulse prior to a standard SE sequence. The circle corresponds to a tube containing phantom flowing in –z direction with a speed of 20.9cm/s; the rest areas correspond to static water. In (a), the amplitude image, signal intensity is bigger for phantom than water. In (b), the phase image, the phase of flowing phantom is opposite to that of static water.*

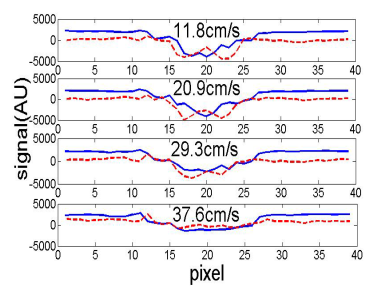


***Figure 5.** Signals on a horizontal line going through the center of the tube. Mx (blue solid line) and My (red dashed line) signals show that the pulse inverted spins with four different average velocities shown in the figure. Unknown phase error caused the My signal not to be perfect zero.*

**References:**
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