Balanced Binomial-Pulse Steady-State Free Precession (BP-SSFP) for fast, inherently fat suppressed, non-contrast enhanced angiography

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Introduction: In balanced SSFP for angiography, blood and muscle are inherently differentiated via the T2/T1 contrast. Fat signal suppression, however, relies on contrast preparation or chemical shift manipulation. The disadvantages of the former include regular interruption of the steady state MR signal, and fat signal regrowth during data acquisition. The latter can be divided into multiple versus single echo methods. Multiple echoes, while offering superior fat and water signal separation by iterative estimation, may significantly increase scan time [1]. A conventional single echo strategy places a 1/TR null band at the chemical shift frequency of fat and is inflexible in terms of TR and stopband width. A more flexible alternative, called Water-Excitation SSFP, was introduced by Lin et al. [2]. This technique leaves the fat magnetization on the longitudinal axis after each steady state excitation by using a binomial spectral-spatial RF pulse [3]. While the fat signal suppression is independent of the choice of TR, there is a minimum TR related to the fat/water chemical shift, which can be longer than desired especially for the 1-2-1 binomial pulse at 1.5T. In this work, we present a generalized design of the 1-2-1 binomial pulse SSFP sequence, and the trade-off between TR reduction, water SNR, and water/fat CNR. We apply our method to obtain fast, non-contrast enhanced MR angiograms of the popliteal artery.

Design: The behaviour of the generalized 1-2-1 binomial pulse is explained in Figure 1.

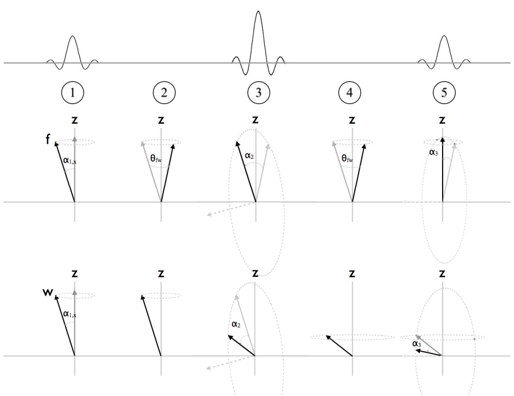

Figure 1: Pictorial description of the generalized 1-2-1 binomial pulse.
Top: timing diagram of the three subpulses (not to scale). Middle: evolution of the fat magnetization vector, **f**, at 220 Hz off-resonance at 1.5T. Bottom: evolution of the resonant water magnetization, **w**.
(1) The first subpulse points along the x-axis (into the page), and tips both **f** and **w** by α_1.
(2) Off resonant spins precess away from **w**. In particular, $\theta_{fw} = 2\pi \cdot \Delta\upsilon_{fw} \cdot \tau_{fws}$ is the phase of **f** in the transverse plane after τ_{fws}, the fat/water separation time. $\Delta\upsilon_{fw}$ = 220 Hz, is the fat/water frequency offset at 1.5T
(3) The second subpulse points along $\mathbf{f}_{(2)}$ x $\mathbf{w}_{(2)}$ and tips **f** by α_2 to where **w** was, and tips **w** toward the transverse plane by α_2 as well.
(4) **f** precesses like in (2).
(5) The final subpulse points along $\mathbf{f}_{④}$ x **z** and returns **f** to equilibrium while tipping **w** by α_3.
τ_{fws} is the time between subpulses. τ_{rf} = ½ τ_{fws} is the duration of each subpulse [4]. Note that the conventional 1-2-1 pulse sets τ_{fws} = ½ / $\Delta\upsilon_{fw}$, which corresponds to setting $\theta_{fw} = \pi$. The slice selective gradient has been omitted in the diagram, but the duration of each oscillating lobe is $\tau_{gz} = \tau_{rf}$. Therefore, the total time of the binomial pulse excitation is, τ_{ex} = 3 τ_{fws}. By adjusting the phase and off-resonant frequency of the subpulses, we can reduce τ_{fws} by up to 50% and still maintain fat signal equilibrium while exciting water. This is equivalent to a theoretical TR reduction of approximately 3.4 ms. Due to RF amplifier restrictions, however, we demonstrate a reduction of 2.8 ms.

Methods: *Phantom experiment:* A 3D 1-2-1 BP-SSFP sequence was implemented on a GE Signa 1.5T. The spectral response was measured by scanning a ball phantom with a constant 0.1 G/cm gradient in the frequency encoding direction to create a spatial off-resonance axis. This was repeated for $\theta_{fw} = \pi\cdot\{0.5, 0.55, 0.6, \ldots 1.0\}$ to create an off-resonance response map. *In vivo experiment:* A healthy, 29 year old male volunteer was imaged without the aid of contrast agents. The popliteal arteries in both legs were simultaneously visualized using an 8-channel cardiac coil, with a 28-cm FOV, and 1-mm isotropic resolution. This was performed for $\theta_{fw} = \pi\cdot\{0.5, 1.0\}$, corresponding to TR = {5.384, 8.136} ms, and Scan time = {4:07, 6:52} mins. Water signal intensity (WSI) was measured by averaging a ROI in the artery. Fat signal intensity (FSI) was similarly measured in tibial bone marrow. Noise intensity (NI) was measured from a background region. The following quantities were calculated: (1) SNR = WSI / NI; (2) CNR = (WSI-FSI)/NI; and, (3) Water/Fat signal ratio (WFSR) = WSI / FSI.

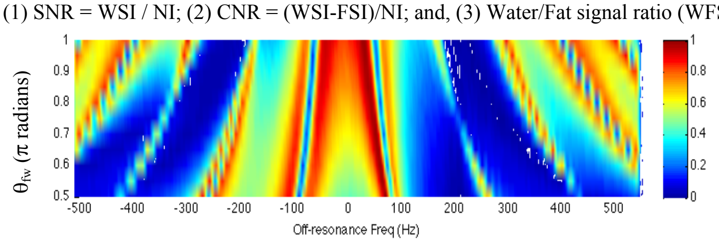

Figure 2: Off-resonance response to 1-2-1 excitation.

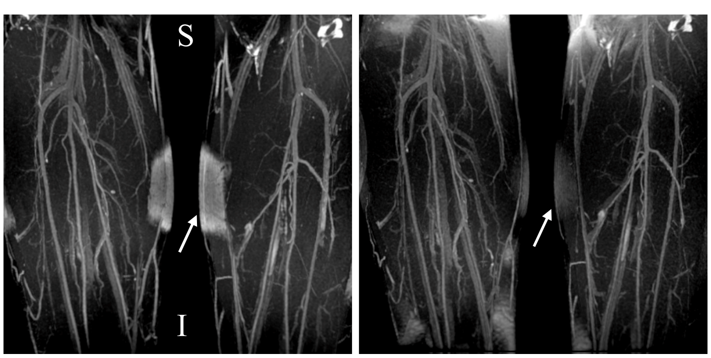

Figure 3: Non-contrast enhanced MRA of the popliteal arteries shown as max. intensity proj, images. (left) normal 1-2-1 pulse, $\theta_{fw} = \pi$, TR = 8.136 ms, Scan time = 6:52 mins.; (right) modified 1-2-1, θ_{fw} = ½ π, TR = 5.384 ms, Scan time = 4:07 mins.

Results: Figure 2 shows several interesting features. First, when θ_{fw} is not equal to π, the frequency response is asymmetric. Second, signal in the passband decreases with θ_{fw}. Third, there exist narrow frequency bands of high signal intensity near multiples of 1/TR. In general, the fat signal suppression is very high. The signal ratios between on- and 220-Hz off-resonance is approximately 17:1 and 9:1 for $\theta_{fw} = \pi$ and ½ π , respectively. Figure 3 shows that significant banding artifacts (solid white arrow) are avoided using our technique to reduce the TR, which also reduced the scan time by nearly 3 minutes. For $\theta_{fw} = \pi$, SNR = 7.2, CNR = 5.9, and WFSR = 5.6. For θ_{fw} = ½ π, SNR = 6.7, CNR = 5.4, and WFSR = 5.3.

Discussion: The signal dropoff due to decreasing θ_{fw} is due to a loss of efficiency in the RF pulses. Referring back to Figure 1, as the phase separation between **f** and **w** tend toward ½ π from π, the phases of the RF subpulses 2 and 3 change as well. Consequently, there is less RF power tipping **w** toward the transverse plane; some power is wasted in changing the phase of **w**. We have derived a formula for increasing the flip angles of the binomial pulse to counteract this effect, and are in the process of testing it. The high intensity bands near 1/TR in Figure 2 are also a concern under investigation. These bright bands may be responsible for eroding the stopband, leading to the in vivo WFSR being lower than that measured in the phantom results.

Conclusion: We have presented a novel technique for achieving short 1-2-1 spectral spatial excitation. We combined this technique with a SSFP sequence to achieve a short scan time, provide steady-state fat suppression, maintain high SNR, and restrict banding artifacts for peripheral MRAs.

References: [1] Reeder et al. MRM, 2005; [2] Lin et al. JCMR, 2008; [3] Meyer et al. MRM, 1990. [4] Zur et al. MRM, 2000.