Design of ramped RF excitation pulses with built-in out of slab saturation for 3D - TOF angiography

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INTRODUCTION – In clinical practice, imaging of the intracranial arteries, such as the Circle of Willis (CoW), is performed most frequently with 3D TOF angiography. This noninvasive technique uses a T_1-weighted RF-spoiled gradient echo (SPGR) sequence, typically in conjuction with multiple overlapping slabs (MOTSA) and RF slab excitation pulses with ramped excitation profile (TONE) to reduce blood saturation effects and to improve signal homogeneity of the vessel lumen. An additional proximal or distal SAT RF Pulse is usually added to explicitly eliminate arterial or venous blood signal, respectively. To achieve good blood saturation, the SAT band should be shifted with respect to each imaging slab and played out every TR with a corresponding gradient spoiler gradient to efficiently suppress even fast flowing blood. The addition of these additional SAT pulses, in turn, dramatically increases the scan time. Previous work by Cunningham *et al*. [1] showed that by concatenating a rectangle excitation profile with saturation bands on both sides can reduce scan time of triggered CE-MRA. A similar approach can be taken for TOF MRA. In this work, we leverage Shinnar-Le-Roux (SLR) transform to combine a minimum-phase small tip angle ramped excitation pulse with a one-sided saturation band to either suppress the venous/or arterial signal in 3D TOF acquisitions.

THEORY – The forward SLR transform reduces the RF pulse design problem to the design of two polynomials, A_N and B_N, whereby, B_N relates via the Fourier transformation to the RF excitation profile. Here, BIDEAL reproduces the desired slice profiles. Defining the desired in-and out of slice ripples, the Parks-McClellan algorithm for linear phase FIR filter design with an equally ripple filter was used to find approximated minimal phase polynomials, BMIN, of the ideal polynomial BIDEAL. Note, the maximal phase polynomial, $B_{SAT}(n)$ is simply the reversed minimal phase polynomial, $B_{MIN}(N-n)$, where n = 0 .. N. Then, as described in [2], A_N is computed with the aim of minimizing the energy of the resulting RF. Note, that minimal energy corresponds to a minimal phase across the slice. Finally, using these polynomials, the inverse SLR transform generates the approximated RF waveform to achieve both slab selection and inflow saturation simultaneously [2, 3].

MATERIALS & METHODS

• *Pulse Design:* Two polynomials B_{SAT} and B_{EXC_RAMP} (duration = 4ms, TBW = 68), for SAT and MOTSA pulse, respectively, were defined in Matlab (Mathworks, Natick, MA). To reduce peak B_1, B_{SAT} was designed as a maximal phase saturation pulse (in-slice ripple=0.1%, out of slice ripple=0.001%) and $B_{EXC\text{-}RAMP}$ as a ramped minimal phase excitation pulse (in slice ripple=0.01%, out of slice ripple=0.1%). Out-of-slab saturation was realized by modulation a phase term on B_{SAT} . This pulse scrambles the phase of the spins across the saturation slice to eliminate the need for a big crusher gradient. Both pulses were scaled according to their desired flip angles (α_{SAT}= 90°, $\alpha_{EXC\text{-}RAMP}$ = 15-30°) and then simply summed up. A_N was computed and the inverse SLR transform applied to generate the RF Waveform [2]. A second RF Pulse was designed with α_{SAT}= 0° but otherwise identical pulse parameters. Both slab profiles are basically identically besides the built-in saturation slab, which is shown on the right of Figure 1. • *Experiment:* Flow phantom and volunteer studies were performed on a 1.5T GE Signa Excite unit (GE Healthcare) with an 8-channel receive-only head coil. An axial 3D RF spoiled gradient echo sequence (SPGR) (*FOV=23cm, 256x256, TR/TE=14/2.5msec, 26 slices, 1.5mm slice thickness*) was prescribed with the aforementioned pulse to image the CoW. Two consecutive scans were performed, first with the built-in saturation band and then without. All imaging parameters were kept the same between the scans.

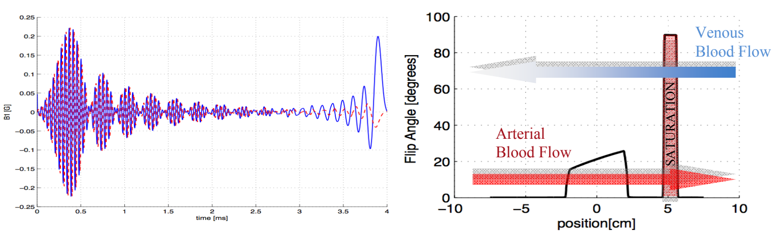

Figure 1: Designed RF pulse waveform (imaginary in red, real in blue) after inverse SLR transform and B1 scaling for a duration of 4ms, time-bandwidth-product of 68 and the corresponding simulated pulse profile (right).

RESULTS – Excellent inflow saturation of the superior signal was achieved with the designed RF pulse in phantom and volunteer studies (Fig. 2 and 3). A total scantime reduction of 30% (TR decreased from 20ms to 14ms) was achieved by simply avoiding a separate saturation RF pulse and saturation gradient spoilers. No image degradation was noticed using the built-in saturation band. However, the distance between the built-in saturation band and the ramped excitation slab plays an important role to avoid signal contamination from the saturation band transition zone 'bleeding' into the slab profile, which might otherwise cause unwanted artifacts. As a general rule, the tradeoff between achieving an efficient saturation *vs*. avoiding unwanted signal corruption could be applied here in the same fashion as it would be for standard methods (e.g. when using separate pulses for excitation and saturation).

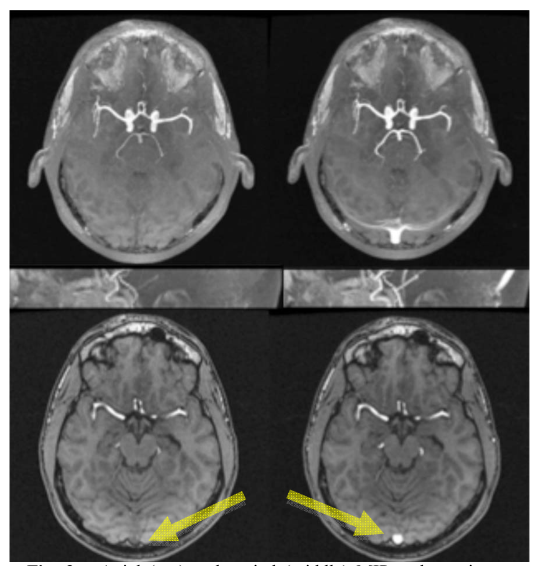

Fig. 3 – Axial (top) and sagital (middle) MIP and raw images (bottom) of the ramped excitation pulse with the built in saturation band (left) and the non-saturated case (right). The venous in-flow is successfully suppressed with the built-in saturation slab. This is best noticeable in the sagittal sinus (yellow arrow).

CONCLUSION & DISCUSSION:

Our results indicate that this concatenated RF pulse is very effective in saturating superior inflow without the use of additional gradient spoilers and thus shortens the overall TR time. Since both polynomials are summed up in the design process, an important key factor to avoid signal contamination is to keep the out-of-slice ripples for both B-polynomial's low, especially that for the saturation part. While our design focused on venous saturation, inferior or bilateral saturation bands could be added to the MOTSA pulse. Even negative slopes could be designed without any scan-time or peak-B1 penalties. In this regard, this pulse concatenation approach is also very valuable for performing TOF-venograms where the effective saturation of the arterial signal is even more crucial due to the slow venous flow. The fusion of the SAT and MOTSA pulse does not allow a simple scaling of B1 to alter the flip angle of the MOTSA pulse. However, the computational time of the design process is quite short (<14sec, Intel 2.16Ghz), and a forthcoming project is therefore to incorporate on-the-fly design of these RF pulses on the MR host computer.

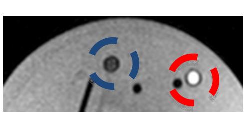

Fig. 2 – A flow phantom with Gd-doped water to mimic T_1 of blood was used to validate the saturation performance. Inflowing Gd-doped-water on the right (red circle) (bottom), return flow on the left (blue).

References: [1] C. H. Cunningham, RF pulses with built-in saturation sidebands, Proc. Intl. Soc. Mag. Reson. Med. 11 (2004) , [2] Pauly, J.M., et al., Parameter relations for the Shinnar-Le Roux selective excitation pulse design algorithm, IEEE TMI, 1991:10:53-65. , [3] P. Le Roux, "Exact synthesis of radio frequency waveforms," in Proc. 7th SMRM, Aug. 1988, p. 1049.

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