Steady-State Motion-Induced Contrast Using DANTE Pulse Trains: A Novel Approach to Black Blood Imaging

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Background: There are three principal methods employed for effective moving-blood suppression in order to assess vessel wall anatomy and pathology. They operate by either minimally perturbing static spins in the imaging plane whilst crushing moving spins outside the imaging plane, such as for spatial pre-saturation approaches; or by flipping the static spins back to the longitudinal direction following static-spin-specific preparation, such as for the DIR [1] and MSDE [2] approaches, which crush moving blood by inversion-recovery nulling and pseudo-diffusion encoding, respectively. None of them, however, can be adapted as an ideal module for multi-interleaved acquisition, which requires regular repetition of the preparation module. Here, we show the novel use of DANTE (a rapid series of low flip angle RF pulses interspersed with gradients) pulse trains as motion-sensitive preparation, manipulating both the static and moving spins optimally and simultaneously and differentiating them via their different steady state signal behaviors. We show that this approach is highly compatible with regularly repeated preparation modules, and preserves a high CNR of static tissue vs blood. Steady-state contrast between moving blood and static tissue is established during DANTE preparation because flowing spins are largely (or fully) attenuated due to phase dispersion accrued while flowing along the applied gradient (similar to quadratic RF cycling). This is in contrast to static tissue, whose longitudinal magnetization is mostly preserved. This progressive saturation of flowing spins is insensitive to spin velocity (above a low threshold) and can be quantified with a simple M_z decay model [3].

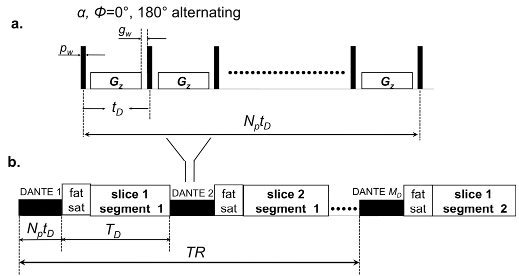
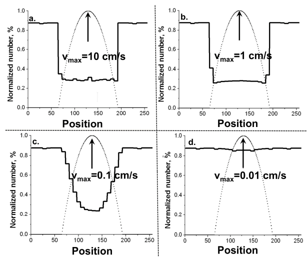


Fig 1. DANTE multislice interleaved acquisition

Objectives: We aim to develop a DANTE BB module with short duration (e.g. 64ms) that can be repeated 5-6 modules/sec in combination with a multi-slice image acquisition. This compares with 1-2 modules/sec for DIR and MSDE, respectively. We also hypothesize that the low SAR of the DANTE preparation will facilitate these rapid repetition rates.

Methods: The proposed DANTE-BB imaging sequence is shown in Fig. 1, indicating both the DANTE preparation module itself, as well as the proposed method for embedding it within an imaging readout method, such as a TSE. N_p is the number of pulses applied in the DANTE module. T_D in Fig. 1b represents the inter-DANTE module delay time reserved for the readout module. Eight healthy volunteers (male, ages 24-35 years) underwent carotid artery wall MR imaging, acquired using a 3T Siemens Verio scanner with a 4-ch Siemens neck coil. For quantitative comparison [2] we define the SNR as SNR=0.695S/σ, where S is signal intensity and σ is standard deviation of the noise. The contrast-to-noise ratio (CNR) is defined as $CNR_{ml} = SNR_{muscle} - SNR_{lumen}$ where 'ml' indicates muscle-lumen. The definition for CNR_{eff} is then given by $CNR_{eff} = CNR_{ml} / (T_{SA})^{1/2}$ where T_{SA} is the average scan time for each slice. Protocol parameters are listed in Table 1.



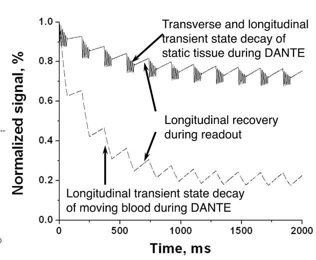


Fig. 2: Velocity sensitivity Bloch Fig.3:Steady-state contrast simulation.

Table 1: Common parameters for read-out 2D TSE image protocols
FOV = 150 × 150 mm, matrix size 256 × 252 interpolated to 512 × 512, slice thickness = 2mm, Numer of average =1

	TR (ms)/TE(ms)	receiver bandwidth (Hz/pixel)	Turbo factor	slices/gap	Concatenation groups	Acq time (mins)	BB module TI=780ms
DIR	~1000/13 (ECG triggered)	130	9	5/100% sequential	N/A	2.5	DIR, Siemens product module
iMSDE[2]	2000/ 9.5 (no ECG)	247	12	6/100 % interleaved	2	1.5	G_z=20mT/m, Gduration=4.4ms
DANTE	2000/13 (no ECG)	130	7	22/no gap interleaved	2	2.5	flip angle (FA) α = 7°-9°; Np=64; time duration between DANTE pulses, t_D=1 ms; G_z=18mT/m; gradient duration≈1 ms.

Results: *Velocity sensitivity and steady-state contrast simulation*: Bloch simulations (Fig. 2) suggest that the attenuation of signal from moving spins is relatively independent of flow velocity for values above 0.1 cm/s (1 mm/s). This velocity insensitivity of the DANTE preparation enables effective BB contrast in the delineation of lumen and plaque (or vessel wall). Fig. 3 shows the Bloch simulation of the steady-state signal behaviour of static tissue and moving blood when employing the DANTE module in a multi-slice interleaved acquisition (simulation parameters: t_D=1ms, N_p=64, T_D=120ms, α=7°, $T_{1tissue}$=700ms, $T_{2tissue}$=70ms, T_{1blood}=1500ms). Figure 3 shows that the blood signal attains a low amplitude about 2 seconds into the sequence due to progressive saturation. Meanwhile this BB effect will persist as blood travels through the imaging slice/slab during imaging. This means that brief periods of blood flow within plane, or turbulent flow patterns, which usually cause problems in conventional methods, should also be effectively suppressed. This is another important factor that contributes to effective blood suppression. *Fast BB multi-slice 2D TSE in vivo imaging*: 22 2D contiguous slices were reconstructed into a 3D image using multiple planar reconstruction (MRP). Note that although the velocities of CSF and blood differ by a factor of ten, they are equally suppressed in Fig. 4c. This is further evidence for the velocity independence of the DANTE module

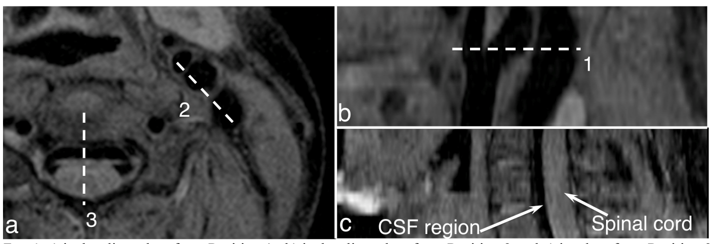


Fig. 4. a) is the slice taken from Position 1. b) is the slice taken from Position 2 and c) is taken from Position 3

	SNR_{lumen}	CNR_{tis_lum}	T_{SA}	CNR_{eff}
DANTE	2±0.2	11.7±2	9 slice/min	35±2
DIR	4±0.5	11±1	2.1 slice/min	14±2
MSDE	2.1±0.1	6.6±2	4.6 slice/min	17±2

Table 2: Comparison of T_1 weighted results between DANTE and conventional methods

Conclusions Before considering scan time DANTE has comparable lumen suppression to MSDE, which is the best technique currently available for suppressing lumen signal. Meanwhile, DANTE also has comparable CNR to the best-known technique for high CNR (DIR). Once scan time is considered, the overall improvement of the DANTE method over the existing methods is considerable. 2D multi-slice DANTE-BB TSE shows that the DANTE preparation is a very promising BB technique.

Acknowledgements and References We thank the NIHR Oxford Biomedical Research Centre for grant funding. [1] Edelman RR, et al. (1991) Radiology. 181:655–660. [2] Wang J, et al. (2007) Magn. Reson. Med. 58(5):973-81.[3] Li L, Miller K and Jezzard P (2011) manuscript in revision.