Non-contrast-enhanced imaging of lower limb veins: improved imaging using multiple flow preparations

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Target audience Physicists and clinicians interested in venous imaging or deep vein thrombosis

Purpose

MRI can be used for multi-contrast imaging of venous thrombo-embolism (VTE) including imaging of both the thrombus and the lumen, or for mapping the leg veins prior to surgery. Acceleration-Dependent Vascular Anatomy for Non-Contrast-Enhanced MR Venography (ADVANCE-MRV)[1] has been recently proposed for lumen imaging. It is based on a flow-dependent angiography method[2], where vascular images are obtained by subtracting bright-vein (acceleration-sensitised) images and dark-vein (velocity-sensitised) images to give vein-only images with good suppression of arteries and static tissues such as thrombus. Initial work[3] demonstrated that the venous signal suppression can oscillate as a function of the flow velocity and the first moment of the motion-sensitisation gradients (MSG), which leads to non-uniform vein signal in regions where the intra-voxel flow dispersion is low. Improved uniformity was obtained by combining multiple images with different degrees of flow suppression, but this increased the total scan time. This study aims to investigate in volunteers whether improved vein signal uniformity (reduced oscillation) can be obtained by applying multiple flow suppression modules in one acquisition, and to demonstrate the method, for the first time, in patients with deep vein thrombosis (DVT).

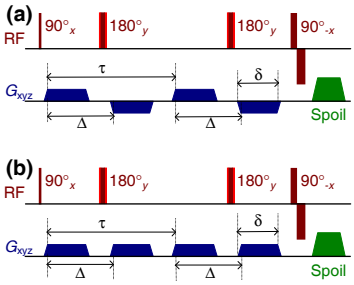

Fig. 1: modules for (a) velocity sensitisation and (b) acceleration-sensitisation. The sensitisation gradients are shown in blue.

Methods

ADVANCE-MRV uses the velocity- and acceleration-sensitising flow-preparation modules shown in Fig. 1. The velocity sensitisation module (Fig. 1a) has a signal dependence[3] of $S=S_0\cos\phi\,\mathrm{sinc}(\beta_x\Delta x)\mathrm{sinc}(\beta_y\Delta y)\mathrm{sinc}(\beta_z\Delta z)$, where $\phi=\gamma\mathbf{m}_1.\mathbf{v}_0$ is the mean phase change within a voxel (due to the effective first gradient moment $\mathbf{m}_1$ and the mean velocity $\mathbf{v}_0$), $\beta_{x,y,z}$ represents the velocity dispersion along the x, y and z directions, and Δx, Δy and Δz are the voxel dimensions. Assuming the worst case of no dispersion (all $\beta_{x,y,z}=0$) the signal reduces to $S=S_0\cos\phi$ (Fig. 2a). By combining 2 or 3 sequential flow-preparation modules before the image readout, and changing $\mathbf{m}_1$ by successive factors of 2, reasonable flow suppression can be achieved over a range of velocities (Fig. 2b). In real cases, the suppression will be better than this simulation due to intra-voxel flow dispersion.

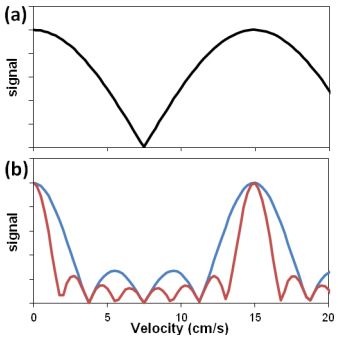

Fig. 2: Simulated signal magnitude as a function of velocity with (a) one and (b) two or three flow-preparation modules, to achieve moderate signal suppression for a wider range of velocities. Dispersion within the voxel is assumed to be zero.

Following ethical approval and informed consent, the upper legs of 6 healthy volunteers, and 2 patients with acute lower limb DVT (proven by compression ultrasound) were imaged at 1.5 T (GE Healthcare, Waukesha, WI). The cardiac trigger delay was chosen to position the first flow-preparation module at peak arterial flow. The readout was 3D balanced-SSFP (coronal oblique, flip angle 65°, TE/TR=1.7/3.7 ms, ASSET factor 2, acquisition matrix 256×256 or 288×288, FoV 35–40 cm).

The single-prep and multi-prep strategies were compared in detail by acquiring images with 21 evenly-spaced gradient moments from 0–2.0 $\mu Ts^2/m$ in one volunteer; signal was measured from ROIs drawn in representative locations in the veins.

In all volunteers, single- and multi-prep datasets were acquired with $\mathbf{m}_1$ of 1.2, 0.6 and 0.3 $\mu Ts^2/m$ for the first, second and third preps. Triple-prep datasets were acquired in four of the volunteers. An experienced radiologist, blinded to the acquisition method, compared the signal uniformity between pairs of these datasets, viewing the individual slices not MIPs. Signal levels were also compared between the methods (and were comparable intra-subject as all gains were consistent). The radiologist also reviewed the patient studies, defining the extent and location of thrombus for comparison with ultrasound.

Results

Fig. 3 shows the typical variation of vein signal with $\mathbf{m}_1$ for a central region of a volunteer's femoral vein. Substantial oscillations are seen as a function of velocity sensitisation for a single flow preparation (which leads to non-uniform signal in the subtraction venograms, since the oscillation frequency and amplitude varies with location/local flow velocity). For dual or triple preparation, these oscillations are reduced and signal suppression is more consistent.

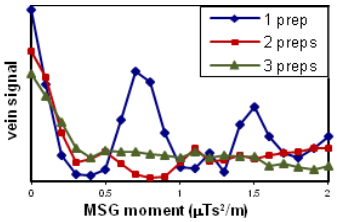

Fig. 3: Variation of vein signal suppression with motion sensitisation gradient, in a region of low flow dispersion. Multiple preps reduce the oscillations and improve signal suppression compared to single prep.

Fig. 4 shows a single slice from a subtraction venogram acquired using 1–3 flow preparation modules in a volunteer. Non-uniformities in the vein signal occur for the single-prep strategy, due to inconsistent signal suppression in the dark-vein image, but the multi-prep images show much greater uniformity within the lumen.

In the qualitative uniformity assessment, the dual-prep strategy were preferred to single-prep in 5/6 cases, and they were considered equivalent for the sixth case. Triple prep was preferred to single prep in 4/4 cases and to dual prep in 3/4 cases. Signal measurements showed very similar mean signals for single- and dual-prep (average change –0.5%) but the addition of a third prep pulse reduced signal levels by an average of 17.5%.

From these results, the dual-preparation scheme was deemed to be optimal and was thus used for subsequent imaging in patients. Fig. 5 shows venograms in the affected leg for two DVT patients. In these patients, the distal occlusion of the femoral vein can be clearly seen, and was consistent with the thrombus locations determined by ultrasound.

Discussion

An important requirement of potential vein imaging methods is a reasonably uniform signal in unobstructed veins, even in regions of only weak flow dispersion such as the centre of the vessels. This method offers improved uniformity without an increase in total scan time. In all cases where non-uniformity was apparent, the addition of a second preparation module improved the vein signal uniformity substantially. Adding a third preparation gave only small further uniformity improvements but reduced signal levels; dual preparation thus appears to offer a good compromise between optimising uniformity and signal. With greater coverage, this method may also have value in pre-surgical venous mapping.

Conclusion

This study demonstrates that the uniformity of vein images acquired with ADVANCE-MRV can be improved by using multiple flow-preparation modules, and also shows the feasibility this approach to detect acute lower limb DVT; further evaluation of its diagnostic performance is planned.

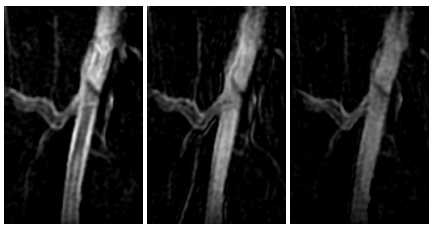

Fig. 4: Volunteer images acquired with one, two and three preps respectively (left to right). Venous signal voids are greatly reduced by using multiple flow preps.

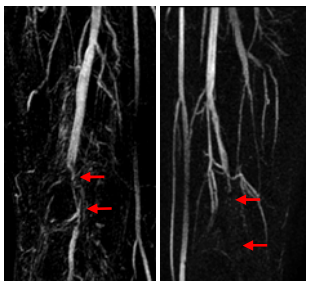

Fig. 5: MIPs of Dual-prep images from two patients with DVT, showing occlusion of the femoral vein by thrombus (arrows).

References

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