

Improvements to NCE-MRA: Vascular Anatomy by Non-Enhanced Static Subtraction Angiography (VANESSA)

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Introduction

Non-contrast enhanced (NCE) methods allow arteries or veins to be imaged without the need for an exogenous contrast agent; this avoids the constraints associated with a small available acquisition time window and safety concerns related to Nephrogenic Systemic Fibrosis. A recently demonstrated new method [1] uses a modified motion-sensitized driven-equilibrium (MSDE) preparation sequence [2,3] as a controllable flow suppression module. A vascular image is formed by subtracting a dark-blood image, obtained with flow suppression, from a bright-blood image, obtained with the motion-sensitising gradients turned off. By using a 3D approach and adjusting the strength of these gradients, it is possible to image with isotropic resolution either fast flowing vessels, such as arteries, slow flow, such as veins, or both.

Although this method initially demonstrated good potential in volunteers, a high background signal was often seen in MIPs, arising primarily from lipid. Also, further investigations revealed inconsistencies in vessel definition linked to the variability of flow immediately after the cardiac trigger. The aim of this work was to develop this MSDE approach further, addressing these limitations, and to evaluate the technical performance of the optimised approach in normal volunteers. The resulting method is termed ‘Vascular Anatomy by Non-Enhanced Static Subtraction Angiography’ (VANESSA).

Materials/Methods

The lower legs of 8 healthy volunteers were imaged using a 1.5 T Signa HDx scanner (GE Healthcare, Waukesha, WI). Ethical committee approval and informed consent were obtained. The pulse sequence was cardiac triggered (PPG) and consisted of a modified MSDE preparation [2,3] and fat suppression followed by a 3D balanced SSFP readout.

Fig. 1 shows the MSDE preparation sequence: the degree of flow suppression was controlled by the motion suppression gradients (MSG). TE_{eff} was 25 ms, and MSG duration was 8ms. A set of images was acquired in sagittal orientation, to demonstrate a series of modifications, introduced cumulatively. The initial set of acquisitions (a) used a simple MSDE prep and half-Fourier acquisition. This was followed by acquisitions using: (b) a composite tipup pulse ($270^\circ_x 360^\circ_x$ replacing the final 90°_x) [4]; (c) a full Fourier readout replacing half-Fourier; (d) a composite refocusing pulse ($90^\circ_x 180^\circ_y 90^\circ_x$ replacing 180°_y) [4]; and (e) suppression of lipid magnetisation during the MSDE module, using a 90° fat-saturation pulse immediately before MSDE, instead of a fat-inversion pulse before the bSSFP readout; this avoids the appearance of stripe artefacts in the subtracted images. This demonstration was carried out using the arrangement previously found to give the highest extraneous background signal—sagittal acquisition of one leg using gradient moments of 0, 0.5 and $20 \times 10^{-6} \text{ s}^2/\text{m}$.

Sequence parameters were: TE/TR 1.8/3.8 ms; flip angle 65° ; matrix $256 \times 94 \times 80-100$; acquired resolution $1.3 \times 1.3 \times 1.4 \text{ mm}^3$. An initial delay of 100 ms was applied after the PPG trigger, to place the MSDE preparation at approximately peak arterial flow. The readout covered one k_x-k_y plane per heartbeat, using linear phase-encode ordering (with an additional 100ms delay for the half-Fourier scans, to maintain the time at which the centre of k-space was acquired). Vascular images (one showing mostly arteries, the other showing veins also) were obtained by subtracting the zero-moment data from the other two sets.

After this initial set of acquisitions, a further set of images was acquired in coronal orientation, to allow an assessment of vessel visibility and image quality. These images covered both legs, and used all of the above modifications (b)–(e). A set of 5 different gradient moments was acquired (0, 0.5, 1, 2, $20 \times 10^{-6} \text{ s}^2/\text{m}$) leading to 4 subtracted image sets with different flow sensitivities. Image parameters were as above but with matrix $256 \times 230 \times 80$ and parallel imaging (ASSET, factor 2); the total scan time was 400 heartbeats.

The image quality was evaluated, over the ‘functional FOV’, which is slightly smaller than the acquired FOV due to the impact of field inhomogeneities on the bSSFP readout. Using both raw and MIP images, an experienced radiologist assessed the ability of the 4 subtracted datasets, together, to depict the principal arterial and deep vein segments in both left and right calves: popliteal (Pop), anterior tibial (AT), posterior tibial (PT), peroneal (Per). For each vessel segment, the visibility of a contiguous whole vessel (yes/no/partial) and image quality (0=almost invisible, 1=poor, 2=moderate, 3=good, 4=excellent) were scored. An additional score was given for image artefacts (scale 0–3, where 3 = severe enough to impair diagnosis).

Vessel	Pop	AT	PT	Per
Artery	3.4 [2–4]	4 [4–4]	4 [4–4]	4 [4–4]
Vein	3 [2–4]	1.9 [1–3]	2.8 [1–4]	2.5 [1–3]

Table 1: Image quality scores (scale 0–4) for arteries and veins: mean [min–max].

Results

Substantial improvements in image quality were seen consistently in all subjects due to modifications (b)–(e). Fig. 2 shows an example of the progressive changes for the series with $0.5 \times 10^{-6} \text{ s}^2/\text{m}$: similar improvements were seen for the $20 \times 10^{-6} \text{ s}^2/\text{m}$ series. The use of a composite tipup pulse is essential for good vessel visualisation, and the other modifications cause a reduction in the background signal, although the composite refocusing pulse has only a small impact.

Fig. 3 shows a MIP of coronal acquisitions for an example volunteer. Across the 8 subjects, all 64 arterial segments were fully visualised, while 48 vein segments were fully and 16 were partially visualised. Table 1 shows the mean and range of scores for various the arteries and veins. 56/6/2/0/0 arteries and 8/27/21/8/0 veins were scored as 4/3/2/1/0 respectively. Artefact levels were scored as 0 (none) for 7/8 subjects and 1 (mild) for one subject.

Discussion & Conclusions

Good arterial image quality was consistently obtained using this sequence, in part due to the placing of the MSDE preparation at the point of peak arterial flow, while the centre of k-space was acquired during the slower flow of diastole. The sequence modifications (b)–(e) described above also improved image quality and robustness, while substantially reducing the background signal from fat. In previous work, off-resonance effects reduced the consistency of half-Fourier reconstruction and the flip angles of the non-selective pulses, leading to residual signal in the subtraction; in this work these effects were removed by full Fourier acquisition and suppression of fat magnetisation during the MSDE preparation.

All arteries were graded as having excellent image quality in all subjects, with the exception of the popliteal arteries. The depiction of the popliteal arteries was reduced slightly, by comparison, since they were near the edge of the field of view, and influenced by the effects of inflow through magnetic field inhomogeneities, which affects the baseline bSSFP image quality. This could be reduced by the use of higher-order shim, by delaying the acquisition window fully into diastole, or using an alternative readout, e.g. FSE or GRE. Venous image quality, while mostly acceptable, was less consistent, and future work will look at ways of improving this.

It was possible to acquire images with several flow sensitivities at isotropic resolution, all within an acceptable scan time (~6 minutes). In patients this should provide the opportunity to obtain information, not only about the presence or absence of stenoses/occlusions, but also on flow patterns throughout the vascular tree.

References

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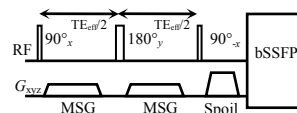


Fig. 1: MSDE preparation. The MSG area is varied to adjust the flow suppression. With no MSG, bright-blood images are obtained.

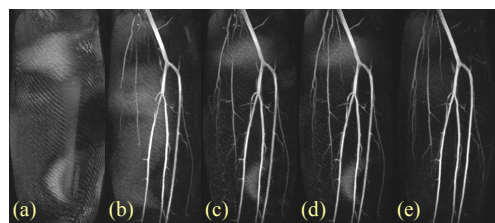


Fig. 2: Coronal MIPs of the sagittal series with $0.5 \times 10^{-6} \text{ s}^2/\text{m}$ in an example volunteer, showing cumulatively introduced modifications to improve image quality and reduce background signal: (a) initial series; (b) composite tipup; (c) full Fourier; (d) composite refocusing pulse; (e) fat-sat for MSDE.

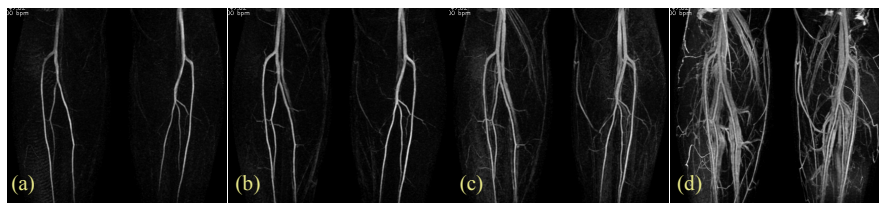


Fig. 3: MIPs of the coronal vascular images for an example volunteer. The applied gradient moment, and thus the degree of flow sensitivity, increases from left to right.