High Resolution Imaging and Artery-Vein Separation of Contrast-Enhanced MR Angiography in the Lower Extremity Using Vasovist Blood Pool Agent

M. S. Wang[1], D. R. Haynor[2,3], G. J. Wilson[4], R. M. Hoogeveen[5], M. G. Hartmann[6], J. H. Maki[2,3]

[1]Bioengineering, University of Washington, Seattle, WA, United States, [2]Radiology, University of Washington, Seattle, WA, United States, [3]Radiology, Puget Sound VAHCS, Seattle, WA, United States, [4]Philips Medical, Bothell, WA, United States, [5]Philips Medical, Best, Netherlands, United States, [6]Epix Pharmaceuticals, Cambridge, MA, United States

Introduction: Blood pool agents allow longer scan times to be used for high resolution imaging in the equilibrium phase (EP). Standard first-pass imaging parameters are not optimal for EP imaging because there is no longer a time constraint on the optimal image acquisition window. Also, equilibrium T1 is longer than in the dynamic phase. Our goal is to optimize MR parameters to obtain high resolution and contrast-to-noise (CNR) images in the EP using a blood pool agent. Since both arteries and veins are enhanced in the EP, computational tools were developed to separate the arterial and venous vasculature while minimizing user interaction.

Methods: A phase II study was conducted to optimize MR acquisition parameters for high resolution vascular imaging using the Vasovist™ (Epix Pharmaceuticals, Cambridge, MA; Schering AG, Berlin, Germany) blood pool agent. Six healthy volunteers and 5 patients with known peripheral occlusive vascular disease (PVOD) were administered 0.03 mmol/kg of Vasovist. Imaging was performed using a Philips NT 1.5T system (R11) with a 4 channel phased array coil.

Optimize high resolution imaging: T1 relaxation times of blood and muscle after Vasovist administration were measured in all subjects using the Look-Locker (LL) Inversion Recovery – Turbo Field Echo (IR-TFE) sequence, performed immediately after the arterial phase and 1 hour after contrast administration. T2* of blood doped with Vasovist to achieve the average T1 relaxation time was estimated *ex-vivo* using gradient echo sequences acquired at multiple TEs. In healthy subjects, the lower extremity calf was imaged at resolutions from 1 mm to 0.4 mm to determine the spatial resolution needed for differentiating arteries from veins. MR imaging parameters that influence SNR were examined [1]. TR was increased within clinically acceptable scan times (5-7 minutes). Bandwidth was decreased by increasing TE. The increase in TE was limited to prevent T2* shortening effects. The optimal flip angle for maximizing CNR was calculated. Signal in blood and muscle were plotted as a function of flip angle at TR's ranging from 5 to 20 ms using the average T1 values measured in-vivo (Fig 1).

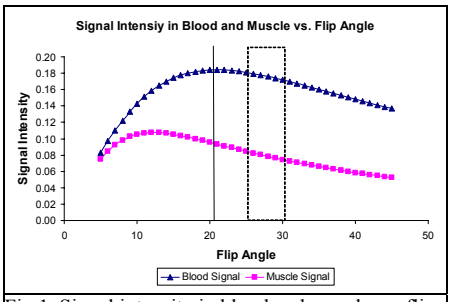

Fig 1. Signal intensity in blood and muscle vs. flip angle is plotted for TR of 15 ms and using average T1 values of blood and muscle measured in-vivo.

Post-processing technique for artery-vein separation: High resolution EP images of the peripheral thigh and calf were acquired using a T1-FFE sequence (TR/TE 15 ms/5 ms, flip 20°, matrix 432x712x80, FOV 440x308 mm^2, slice thickness 0.6 mm). Velocity data was acquired using a 3D quantitative phase contrast (q-flow PC) sequence with cardiac-gating to acquire central k-space after peak systole (TR/TE 13 ms/5 ms, flip 20°, matrix 368x436x48, FOV 440x308 mm^2, slice thickness 1 mm, VENC 40 cm/s). Vessel centerlines in the EP image were detected using a multi-scale vesselness filter [2]. The centerlines were labeled as artery or vein based on flow direction and magnitude from the q-flow PC data. Automatic seeds for initializing the segmentation algorithm were obtained from the labeled centerlines and incorporated into a Bayesian probabilistic framework based on a Markov random field (MRF) model. Graph cuts optimization [3] was used to find the maximum *aposteriori* probability of the Markov random field model to separate the arterial and venous vasculature. The segmentation results were refined to smooth vessel edges using a narrowband level set filter [4].

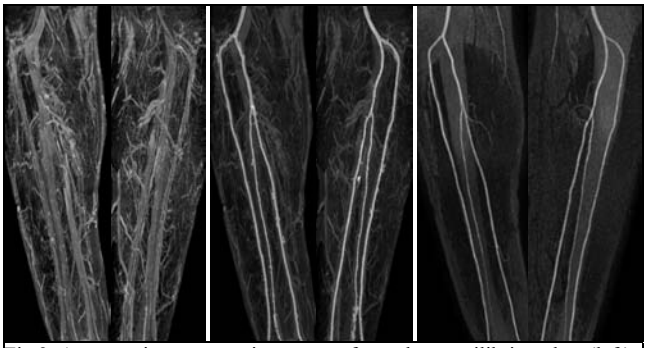

Fig 2. Artery-vein segmentation was performed on equilibrium data (left) of a patient with PVOD. The segmented arterial image (center) had noticeably higher CNR and image resolution compared to the dynamic phase image (right) when imaged at an in-plane resolution of 0.5 mm.

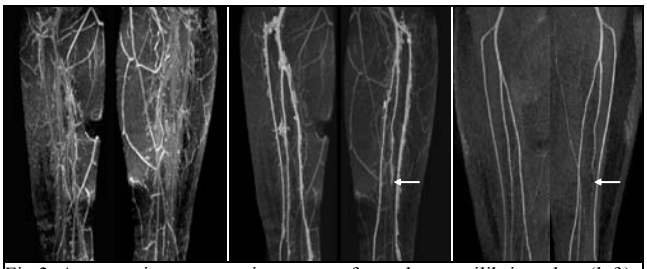

Fig 3. Artery-vein segmentation was performed on equilibrium data (left) in a patient with more severe PVOD. Due to insufficient in-plane resolution (0.6 mm), closely overlying veins were mislabeled as arteries, and the diseased left peroneal artery was not correctly classified in the arterial image (center). This diseased peroneal artery is also poorly visualized on the dynamic phase image (right).

Results: Average T1 relaxation times immediately after the arterial phase and one hour after contrast administration were 214±58 ms and 226±42 ms ms in blood and 640±24 ms and 660±26 ms in muscle. At resolutions of 0.5 mm and better, major arteries were separated from adjacent vessels by at least 1 pixel at most locations. Since there was no gain in vessel conspicuity at resolutions greater than 0.5 mm, and there was a noticeable loss in SNR, we considered 0.5 mm to be the optimal spatial resolution for our blood pool imaging protocol. At the average T1 of 221 ms and a long TR of 15 ms, the Ernst angle for optimal signal intensity in blood is 21°. However, there is more image contrast between blood and muscle at higher flip angles, ranging from 27-30° (Fig. 1). The combined effect of reducing bandwidth, increasing TR, and increasing parallel imaging SENSE factor (SF) was examined. A 50% increase in normalized SNR was measured by reducing bandwidth from ±59 kHz to ±13 kHz, increasing TR from 11 to 16 ms, and increasing SF from 3 to 4.5. Artery-vein segmentation was performed on high resolution EP data in healthy subjects and patients. The result from a patient with PVOD imaged at an in-plane resolution of 0.5 mm is shown in Fig 2. The main infra-popliteal arteries and veins were correctly classified by the segmentation algorithm. The segmented arterial image had noticeably higher CNR and image resolution, particularly in the peroneal arteries compared to the dynamic phase image. Segmenting data acquired at a lower in-plane resolution (0.6 mm) was more difficult, for a patient with more severe PVOD, as shown in Fig 3. In this case, some close lying veins were mislabeled as arteries. Due to insufficient in-plane resolution and poor filling, the diseased distal left peroneal artery (indicated by arrows) was not well visualized in the segmented arterial image.

Discussion: We focused on how to best utilize blood pool agents for high-resolution imaging, and methods for accurately separating arteries from veins. Based on the measured T1 values, the window for EP imaging is greater than 1 hour of contrast administration. To optimize a pulse sequence for high-resolution EP imaging, MR parameters (flip angle, TR, bandwidth, and SF) need to be chosen properly. Optimal blood pool imaging requires extremely high spatial resolution. High CNR between vessel and muscle is needed for the algorithm to accurately detect vessels. Adding a tailored q-flow PC image sequence provides arterial and venous flow magnitude and direction, which helps to automate the detection and labeling of vessel centerlines as artery or vein, hence minimizing user interaction. We found that in-plane resolutions greater than 0.5 mm appear necessary to segment arteries and veins and to detect stenoses in peripheral vessels that are 2-3 mm in diameter. Imaging at even higher in-plane resolution will enable the smaller branches and diseased vessel segments to be more clearly delineated, although increased SNR will likely be required. This could be achieved with better coils or higher doses of contrast.

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