

Table 1. Comparison of PV measurements on 3D-MRA and 2D-SSFP.

| PV Diameter (mm) | Ostial | 1 cm from Ostium |
|-------------------|---------------|------------------|
| 3D-MRA | 14.6 ± 2.8 | 14.5 ± 3.4 |
| 2D-SSFP (average) | 11.4 ± 2.3*** | 11.9 ± 1.9*** |
| 2D-SSFP (minimum) | 10.2 ± 2.6*** | 11.1 ± 2.1*** |
| 2D-SSFP (maximum) | 12.6 ± 2.1*** | 12.9 ± 1.9* |

Statistics: * = $p < 0.05$, *** = $p < 0.001$.

Conclusion: While 3D-MRA produces excellent anatomic depictions of the pulmonary veins, these images overestimate pulmonary vein size compared to gated studies. This overestimation is likely due to movement of PV across the cardiac cycle in addition to phasic changes, causing blurring of PV margins and ostium on 3D-MRA images. PV dimensions were easily measurable by 2D cine MRI with clear delineation of margins and orifices.

298. Measurement of Skeletal Muscle Perfusion in Normal Volunteers During Reactive Hyperemia: Validation of Gadolinium Enhanced Methods Using MR Plethysmography and Arterial Blood Flow Techniques

Richard B. Thompson,¹ Venkatesh K. Raman,¹ Alexander J. Dick,¹ Guy Shechter,² Robert S. Balaban,¹ Elliot R. McVeigh,¹ Robert J. Lederman.¹ ¹National Heart Lung and Blood Institute, National Institutes of Health, Bethesda, MD, USA, ²Department of Biomedical Engineering, Johns Hopkins University School of Medicine, Baltimore, MD, USA.

Introduction: Obstructive peripheral artery disease affects 15% of adults over age 55, of whom over one-third are symptomatic. Typical manifestations are pain during walking or threat of limb loss. Lower extremity perfusion measures would be useful in the development of novel biological treatments. However, no robust global or regional measurements are available. Measurement of circumferential muscle swelling with venous occlusion strain-gauge plethysmography (SG-P), the prevailing standard for non-invasive measurement of limb perfusion, is limited by significant systematic underestimation of flow (Saltin B, Am. J. Cardiol. 62: 30E–35E (1988)). SG-P also provides only global as opposed to regional flow information. Finally, lower extremity perfusion measures are best obtained during post-ischemic reactive hyperemia (RH), which is less

susceptible to fluctuations in vascular tone than resting blood flow measurements. The short duration of RH (peak flows typically lasting several seconds) imposes demands on the temporal resolution of MR-based perfusion measures. We present here an investigation of several lower-extremity perfusion measures that might serve as attractive tools for diagnosis and assessment of response to treatment, such as investigational therapeutic angiogenesis.

Purpose: We validate blood flow in skeletal muscle during reactive hyperemia (RH) measured by gadolinium (Gd-DTPA) inflow-enhanced MR with MR plethysmography (MR-P) and real-time phase-contrast (PC) MRI.

Methods: In four normal volunteers, post-ischemic RH in the calf was induced by 5 minutes of thigh-cuff inflation to supersystolic pressures (180–220mmHg) to occlude arterial inflow. Immediately following arterial cuff deflation, a second thigh-cuff was inflated to occlude venous outflow (40mmHg). Both cuffs were inflated/deflated using an automated plethysmography system (D.E. Hokanson, Bellevue, WA). MR imaging was performed on a Siemens 1.5 T Sonata scanner (Siemens Medical Systems, Erlangen, Germany) using a standard head coil. A series of two post-ischemic RH experiments were used with each volunteer for comparison of flow measurement techniques. In the first, PC-MRI was used to measure bulk blood flow in the popliteal artery during the hyperemic flow period. Following a 15 minute recovery period, the flow response to RH was measured with interleaved saturation recovery Gd-DTPA (Magnevist, Berlex, Wayne, NJ) inflow and MR-plethysmography high spatial resolution anatomical imaging experiments. Due to the transient nature of RH, the bulk blood flow was measured with a real-time PC-MRI pulse sequence, targeting flow in the popliteal artery at the level of the knee. The Gd-DTPA saturation recovery ($T_i = 160$ ms) and MR-P exams were both FISP pulse sequences: FOV = 24 × 19 cm, slice thickness = 10 mm, flip angle = 60 degrees, TR = 5.0 ms/3.4 ms, TE = 2.5 ms/1.7 ms, BW = 20 kHz /150 kHz, matrix = 64 × 64/192 × 154, respectively.

The interleaved experiments were run continuously for 2 minutes beginning 20 seconds prior to the arterial cuff release, with a temporal resolution of 890 ms for both acquisitions. One minute after arterial cuff inflation, the Gd-DTPA (0.1mmol/kg) was injected to allow contrast equilibration in the blood pool. Arterial cuff release (with simultaneous venous cuff inflation) begins a square-wave input of contrast agent concentration in the arterial blood and concurrent swelling of the calf. An ankle cuff was inflated to 200mmHg prior to all arterial cuff inflations to exclude pedal flow from the measured hyperemic response.

PC-MRI flow data was normalized for muscle mass estimated from three-dimensional calf images. Gd-DTPA flow was calculated using the mean transit time (MTT), calculated directly from the inflow enhanced data, assuming a distribution volume (extracellular volume) in skeletal muscle of 0.08 (Donahue KM et. al., MRM 34: 423–432 (1995)) ($F = \text{Volume}/\text{MTT}$). The MTT was calculated using the impulse response, which is the time-derivative of the inflow signal intensity curve (Fig. 1a). MR-P cross sectional areas were automatically calculated using B-spline snakes that tracked the outer fat boundary in time, without user interaction. Partial volume (PV) correction for fat and bone was done for all volunteers. MR-P data was also processed with an assumption of 3D-isotropic growth rather than 2D-planar growth (factor = 1.5). All data analysis was done using MATLAB (Mathworks, Natick, MA).

Results: Examples of raw measured flow data, for volunteer 3, is shown in Fig. 1. Figure 1a displays a sample gadolinium inflow signal intensity curve and the corresponding calculated impulse response for a 20 cm² ROI from the gastrocnemius muscle. The flow rate for this sample ROI is $F = 0.08/(6.6 \text{ sec}/60 \text{ sec}/\text{min}) = 73 \text{ mL}/100 \text{ mL muscle}/\text{min}$. The PC-MRI flow curve is shown in Fig. 1b, where the peak flow rate is 16ml/s, corresponding to a flow rate of $16 \text{ ml}/\text{s} * 60 \text{ sec}/\text{min}/1620 \text{ ml} = 59 \text{ mL}/100 \text{ mL muscle}/\text{min}$, where 1620ml is the measured muscle volume. Figure 1c displays the percentage change in calf cross-sectional area over time, with a peak rate of 27mL/100mL muscle/min. Multiple venous cuff inflations/deflations, shown in Fig. 1c, allow the recovery from hyperemia over time to be measured (not reported here). Figure 2 displays the RH blood flow measured with the three methods in each of the four volunteers. The Gd-DTPA flow values are averaged for the entire muscle mass, although S/N is sufficiently high (>100) to allow single voxel (.14 ml) flow analysis. MR-P values are shown; i) as measured directly, ii) with a correction

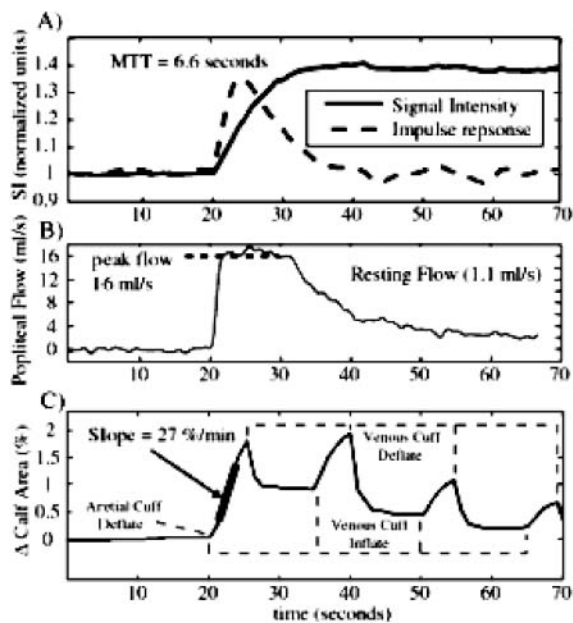


Figure 1.

for partial volume effects, and iii) for an assumption of isotropic swelling.

Conclusions: Skeletal muscle blood flow measured with gadolinium inflow-enhanced MRI during reactive hyperemia agrees with bulk flow values measured with real-time phase-contrast MRI. There is sufficient S/N (>100) with gadolinium inflow studies to do regional flow analysis in skeletal muscle, allowing comparison of flow between muscle groups.

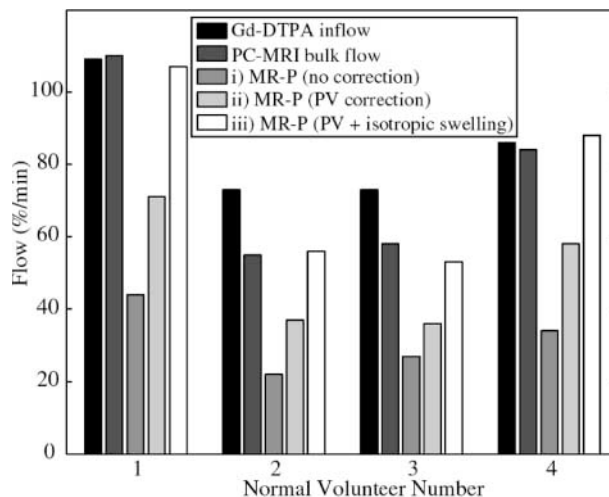


Figure 2.