DEVELOPMENT OF AN MR TECHNIQUE TO INVESTIGATE THE EFFECTS OF RESPIRATION AND MUSCLE CONTRACTION ON THE VENOUS BLOOD FLOW IN THE LOWER LEG

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Aim:
For investigation into the aetiology of Deep Vein Thrombosis (DVT), to develop and optimise MR techniques to investigate the effects of respiration and muscle contraction on the blood flow in the deep veins of the lower limb.

Background:
The need to use Magnetic Resonance imaging to measure the blood flow in the lower limb has been shown by Downie et al [1, 2] in investigating the causes and treatment of Deep Vein Thrombosis. Work using ultrasound [4] has shown the venous return from the leg is dominated by two mechanisms, abdominal pressures due to the respiratory cycle and the calf muscle pump. The velocity of the venous blood is generally low, requiring large encoding gradients, but has faster spurts caused by the muscle contractions. For research into DVT, structural information is required due to the tendency for deformation or collapse of the vein. MR is capable of providing anatomical and flow data in all of the lower limb veins simultaneously using Phase Contrast imaging (PC). This abstract investigates and demonstrates how, with fast gradient performance, high B0 homogeneity and stability of modern systems, images can be acquired during respiratory and other exercise maneuvers at temporal resolution sufficiently approaching 'real time' for venous flow events.

Method:
A new sequence, Interleaved SPiral (ISPLASH), has been developed using PC imaging and interleaved spiral readout gradients [3] and has been validated in-vivo against slower respiratory-gated gradient-echo imaging [7]. It uses water excitation, balanced Velocity ENCoding (VENC) on alternate excitations (VENC (+ve) – VENC (-ve)) of 10 cm/s, upstream arterial saturation, slice thickness 7 mm and has an acquired pixel size of 1x1 mm. The spiral data was re-gridded and by sliding reconstruction [4] (In-house Matlab programs) allowed interpolation between repetitions. The sequence was run continuously for a period of 35 seconds. The number of spiral interleaves used (4/8/12) was investigated with 4 giving sufficient image quality and robustness (in this region of the body) with finest temporal resolution.

A volunteer lay prone, avoiding any unintentional compression of the veins in this initial work, in the scanner (Siemens 1.5T Avanto) with the left leg raised approximately 10 cm, resting the ankle on a foam support, with a pair of carotid surface coils (Machnet) placed gently around the calf. Three separate 35-second scans were collected during the following activities: breathing regularly [4], end-expiratory breath-hold while contracting and relaxing the main calf muscles, Soleus and Gastrocnemius muscles, several times when prompted, and finally end-expiratory breath-hold with leg muscle relaxed. Position data from the subject's respiratory belt sensor and the ECG were recorded during each scan with synchronised timing data for later use. Due to movement of the leg during each contraction of the muscle the reconstructed images required shifting to ensure that the position of the deep vessels was stable. This was achieved using a program (Matlab) that correlates a specified region of interest (ROI) from a reference magnitude image with the same ROI on all other images in the series with a range of pixel shifts. The Posterior Tibial Vein (PTV) and Intra-Muscular Vein (IMV) were manually segmented (CMR Tools) from the magnitude images and the ROIs transferred to the phase images for a mean velocity measurement. For readout with 4 interleaves the time per frame was 320ms, with rate 4 sliding-window reconstruction 80ms between frames.

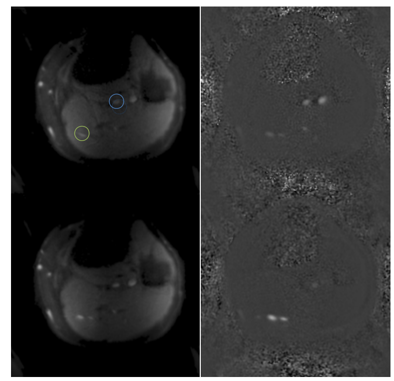

Figure 1: Respiratory magnitude (showing vessels used for measurement) and phase images and muscle contraction magnitude and phase image Blue ROI = PTV; Green ROI = IMV

Results and Discussion:
The blood mean velocity was dominated by the respiratory cycle while the leg is at rest (Fig 2). During end-expiratory breath-holding the mean velocity in the deep vessels was dominated by the cardiac cycle (Fig 3.). During muscle contractions the blood mainly travels through the IMV, Gastrocnemius Vein, (Fig 4), within the contracting muscle (Fig 1), which has low flow whilst the leg is at rest (Fig 2,3). This is seen as a large velocity spike upon contraction, with higher peak velocities than seen under regular respiration in the deep vessel, followed by a small reversal in flow with relaxation of the muscles (Fig 4). The arrhythmia of the volunteer shows the velocity of the blood in both veins is probably being drawn in by atrial filling via the IVC, and is delayed by approximately one second (Fig 3). Previous applications of real-time MR flow imaging have been in the great vessels [5,6], here we have adapted and optimised the design suitable for the FOV and resolution needed for lower limb veins which are typically 5-10 mm in diameter. Spiral imaging has the advantage of more reliable flow signal than EPI. Although zone-selective EPI [5] may offer higher temporal resolution its SNR and flow-signal reliability may be lower than spiral [3].

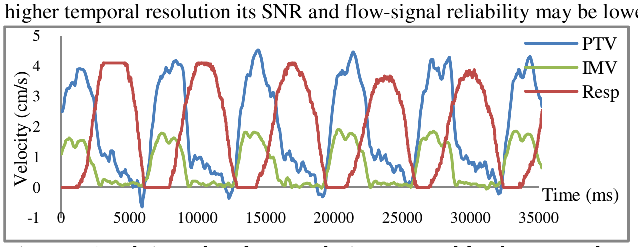

Figure 2: 'Real-time' plot of mean velocity measured for the PTV and IMV with respiratory trace for regular breathing scan (Resp trace shows inspiration upward on graph)

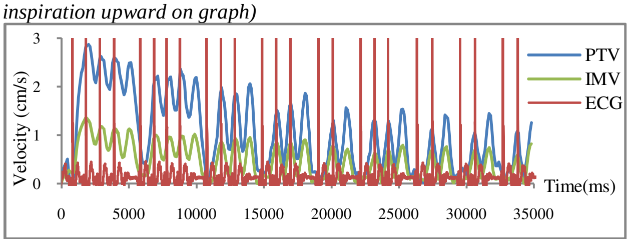

Figure 3: Mean Velocity measurements for PVT and IMV with ECG trace during breath-hold scan (vertical lines are R- wave triggers from gating system but the sequence ran continuously)

Conclusion:
This new application of 'real time' flow imaging for measuring the velocity of blood flow in the lower limb allows investigation into the effects of the respiratory and cardiac cycles and also the muscle pump on the venous blood velocities in the lower leg. The flow in the deep veins is confirmed to be predominantly respiratory based with muscle contractions pushing the flow into more superficial vessels located within the contracting muscle (as they aren't compressed by the muscle contraction, quite the opposite). Future work is planned for further optimisation and reduction of each image acquisition time partly by utilising T-SENSE [4] and using an initial reference image for phase subtraction instead of balanced velocity encoding gradients [3].

References: [1] S. Downie, et al, JMRI 26:80-85 (2007), [2] S. Downie, et al, AJP – Heart Circ Physiol 294:2112-2120 (2007), [3] P.D. Gatehouse et al, MRM 31:504-512 (1994), [4] J. Miller, et al, J Physiol 563:925-943 (2005), [5] R. Nezafat et al, MRM 54(6):1557-1561(2005), [6] V.E. Hjortdal et al, circ 108:1227-1231(2003), [7] ISMRM 2009 Abstract Submitted.

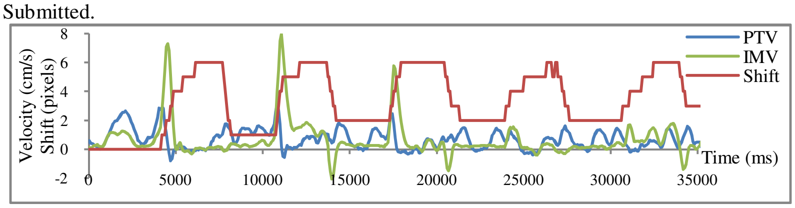

Figure 4: Mean velocity measurements for the PTV and IMV with pixel shifts (–y direction) during a breath hold with muscle contraction scan