4D Vessel-Encoded Arterial Spin Labeling Angiography

T. W. Okell[1], P. Schmitt[2], X. Bi[3], M. A. Chappell[1,4], R. H. Tijssen[1], K. L. Miller[1], and P. Jezzard[1]
[1]FMRIB Centre, Department of Clinical Neurosciences, University of Oxford, Oxford, Oxfordshire, United Kingdom, [2]MR Application & Workflow Development, Siemens AG, Healthcare Sector, Erlangen, Germany, [3]Cardiovascular MR R&D, Siemens Healthcare, Chicago, IL, United States, [4]Institute of Biomedical Engineering, University of Oxford, Oxford, Oxfordshire, United Kingdom

Introduction: X-ray digital subtraction angiography is generally considered to be the gold standard for obtaining vessel selective angiograms of the cerebral vasculature, providing vital information about the morphological and functional status of brain feeding arteries in patients with cerebrovascular disease. However, this method carries risks to the patient from the catheterization procedure and contrast agent injection and is labor intensive. It has recently been demonstrated [1] that vessel-selective dynamic angiograms can be obtained non-invasively and without the use of contrast agents by combining a vessel-encoded pseudo-continuous arterial spin labeling (VEPCASL) preparation [2] with a time-resolved FLASH readout. However, the reduction of the ASL contrast caused by this spoiled gradient echo scheme necessitates limiting the number of RF pulses used during the dynamic readout to prevent poor SNR in later time frames. This reduced readout efficiency means that only dynamic 2D acquisitions are feasible within a clinically relevant scan time. The recycling of transverse magnetization in balanced steady-state free precession (bSSFP) ensures that the progressive reduction of ASL contrast is much less severe, allowing a greatly accelerated acquisition. In this study the VEPCASL preparation module was combined with a 4D bSSFP readout that has previously been shown to generate high quality (non-selective) dynamic ASL angiograms [3,4].

Sequence Design: The 4D VEPCASL angiography sequence consists of a WET pre-saturation module [5], a one second VEPCASL pulse train to fill the majority of the cerebral vasculature with labeled blood [1] and a 4D bSSFP readout catalyzed by ten RF pulses with linearly increasing flip angles [3]. A constant flip angle of 40° is used and the acquisition gated to the cardiac cycle to reduce pulsatility artefacts. Eight VEPCASL cycles are used: two are non-selective (tag and control), two encode left-right, two encode anterior-posterior and two encode obliquely to label diagonally opposed vessels. Using eight cycles (rather than six [1]) increases the rank of the encoding matrix and improves generation of vessel-specific angiograms for both right and left internal carotid arteries (RICA and LICA) and right and left vertebral arteries (RVA and LVA). These complementary pairs of cycles can be subtracted before further image processing to reduce sensitivity to scanner drift and subject motion. In this study, slice and phase resolution was reduced (relative to [3]) to reduce the total scan time to approximately 18 mins (depending on the subject's cardiac cycle), yielding a voxel size of 1x1.2x4 mm within a field of view of 220x177x64 mm and temporal resolution of 59 ms with 12 time frames. The sequence can also be used in dynamic 2D mode where phase encoding is performed along one direction only, yielding a single 2D image for each time frame. Using identical in-plane resolution this reduces the scan time to approximately 1.5 mins. Here we show results obtained both with the full 4D and dynamic 2D readout strategies.

Methods: Four healthy volunteers with no known neurological deficit were recruited and scanned under a technical development protocol agreed with local ethics and institutional committees. Experiments were performed on a 3T Siemens TIM Trio scanner using a 12 channel head receive coil and body coil for transmission. A 3D time-of-flight (TOF) acquisition was used for vessel localization and labeling plane selection, followed by 4D VEPCASL angiography and an identical acquisition in dynamic 2D mode, both at the level of the circle of Willis. Pre-processing of the VEPCASL angiography data included brain extraction using BET [6] and subtraction of complementary pairs of VEPCASL cycles, as mentioned above. Vessel specific angiograms were calculated using a maximum *a posteriori* solution to the Bayesian framework of [7] with two vessels per class, which can adapt to motion between scans and boost SNR. Due to the long VEPCASL labeling duration used, the first acquired time frame corresponds to the arteries filled with labeled blood, with subsequent time frames showing the washout of this bolus. Visualization of the inflow of blood was simply achieved by subtracting each time frame from the second (the first frame had some minor artefacts due to transient bSSFP signal oscillations).

Results: 4D VEPCASL angiography produced clear angiograms in all subjects with a high degree of vessel specificity. Fig. 1 shows typical results in one subject after inflow subtraction and axial maximum intensity projection (MIP), with each brain feeding artery represented by a different color. The normal filling of arteries beyond the circle of Willis is apparent, with a small level of collateral flow from both ICAs to the ipsilateral posterior cerebral arteries via the posterior communicating arteries. Also shown in Fig. 1 is the equivalent dynamic 2D acquisition acquired in a fraction of the scan time. It is apparent that the smaller vessel delineation is not as clear due to reduced SNR but the main features of the angiogram are clear. However, the full 4D data set also allows reformatting in any arbitrary plane: Fig. 2 demonstrates coronal and sagittal MIPs using the same data set. Some residual artefacts are evident, particularly due to motion of the eyes and a small shift in the bSSFP bands near the auditory canal and frontal sinuses, perhaps due to a small amount of B0 drift during the acquisition.

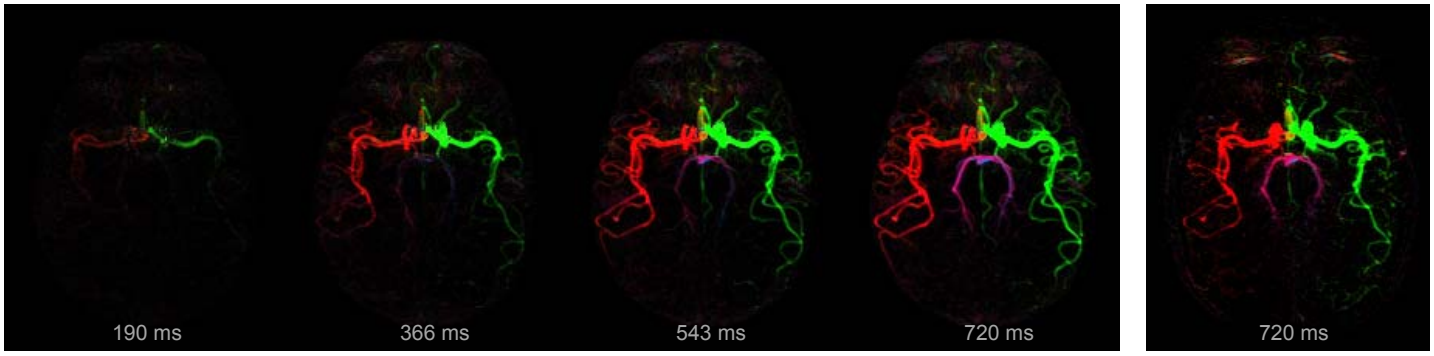

Figure 1: Selected frames from the 4D VEPCASL angiography sequence after separation of the vascular components, inflow subtraction and axial MIP (left). The time shown is that since the end of the VEPCASL pulse train. A single equivalent frame from the shorter 2D dynamic acquisition is also shown (right). Color is used to represent the origin of the blood signal (red = RICA, green = LICA, blue = RVA, purple = LVA).

Discussion: Highly vessel specific 4D angiograms of the four major cerebral arteries were produced non-invasively using the proposed technique. The considerably faster dynamic 2D mode reveals many of the major features, but at reduced SNR and without the ability to reformat in any plane. However, the full 4D acquisition may currently take too long for a standard clinical protocol, as well as being more susceptible to motion artefact.

Figure 2: Coronal (left) and sagittal (right) MIPs of a single time frame (acquired 130.5 ms after labeling) from the same 4D VEPCASL angiography data set as Fig. 1 (without inflow subtraction).

In future work we hope to speed up this acquisition by pushing the parallel imaging acceleration, use of non-cartesian trajectories and compressed sensing. A variable flip angle approach is also likely to benefit the visualization in later time frames [3] but further work must be undertaken to optimize such a scheme for VEPCASL.

Acknowledgements: *The authors are grateful for financial support from the UK Stroke Association and the Medical Research Council.*

References:

[1] Okell, T.W. Magn Reson Med, 64 (2010): 698–706
[2] Wong, E.C. Magn Reson Med, 58 (2007): 1086-1091
[3] Schmitt, P. ISMRM (2010): #402
[4] Bi, X. Magn Reson Med, 63 (2010): 835-841
[5] Golay, X. Magn Reson Med, 53 (2005): 15–21
[6] Smith, S.M. HBM 17 (2002): 143-155
[7] Chappell, M.A. Magn Reson Med, 64 (2010): 1529–39