Optimisation of Oxygen-Enhanced Imaging in the Kidney

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Introduction: Oxygen-enhanced MR imaging (OE-MRI) has been used in various studies to investigate oxygenation in arterial blood, abdominal organs and tumours by measuring a signal change upon the breathing of 100 % O_2, which is due to the paramagnetic T_1-shortening properties of dissolved molecular O_2 in blood and tissue plasma [1- 3]. Blood flow and oxygenation in the kidneys is known to be inhomogeneous [4] and previous oxygen-enhanced studies have shown regionally varying signal change [5]. The magnitude of oxygen-enhanced signal change is small, yet few attempts have been made to optimise any imaging sequence for this particular application and no comparisons have been made between the abilities of different sequences to demonstrate signal change in abdominal organs or tumours. In this work we have investigated the contrast to noise ratio offered by two sequences commonly used in OE-MRI: Inversion-prepared Half Fourier Turbo Spin Echo (IR-HASTE) and Spoiled Gradient Echo (SPGR), and then using simulations we have optimised both for use in OE-MRI of the kidneys. We then compared their abilities in vivo in a single subject. Finally we carried out a dynamic OE-MRI study in the kidneys of a small group of healthy volunteers and created parameter maps showing ΔPO_2 and wash-in time on a voxel-by-voxel basis. **Simulations:** Typical T_1 changes due to breathing 100 % O_2 for a selection of abdominal organs were taken from literature [5]. Simulations were carried out using Matlab 7.5 (The Mathworks Inc, Natick, MA, USA) to calculate the potential contrast to noise ratio (CNR) due to these T_1 changes for typical sequence parameters and bandwidth values, for a range of repetition times (TR) and flip angles for SPGR and a range of inversion times (TI) for IR-HASTE, so the abilities of the two sequences could be directly compared. **Simulation Results:** Plots showing the calculated variation in CNR in renal tissue for the range of parameters for both sequences are shown in Figure 1. Optimal sequence parameters were then chosen which maximised CNR, whilst still allowing imaging with sufficient temporal resolution to permit analysis of the dynamic signal curve. In the case of the SPGR technique, a TR of 5 ms would allow a temporal resolution of 5.4 s. A flip angle of 11° was then chosen as the simulations predicted this to provide the greatest CNR value for this particular TR, CNR = 1. For the IR-HASTE technique, TI = 900 ms was used as this was predicted to produce CNR = 1.6, a CNR value close to maximum whilst being far enough away from the null point to avoid ambiguous signal changes. Temporal resolution in this case would be defined by the TR, 5900 ms, chosen in order to allow full recovery of the longitudinal magnetisation between inversions.

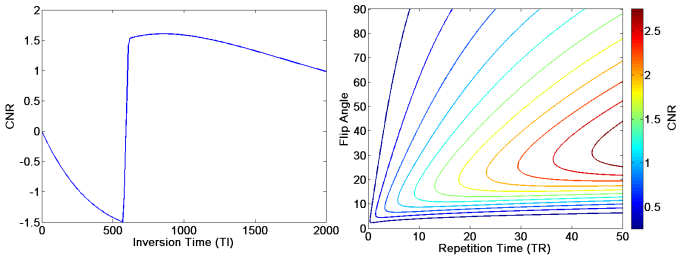

Figure 1: Plots showing CNR for IR-HASTE (left) and SPGR (right)

Head-to-Head Study: A head-to-head imaging session was then carried out in a single healthy volunteer at 1.5 T to compare the signal change produced by each imaging sequence after optimisation. Prior to the dynamic series, T_1 measurements were taken using both acquisition methods. For SPGR T_1 measurement, flip angles of 3°, 11° and 15° were used with a TR/TE of 5/0.96 ms, with T_1 derived using the variable flip angle method [6]. A range of inversion times (TI) from 100 to 5000 ms was used for an IR-HASTE single slice acquisition, with TR/TE = 5000+TI/3.4 ms. Both sequences were acquired coronally, centred on the kidneys, with a slice thickness of 6 mm. During gas switch-over T_1-weighted images were repeatedly taken to capture the gas uptake signal curve using optimised parameters described above. **Head-to-Head Results:** ROI analysis of the dynamic images was carried out to investigate the difference in CNR between the two sequences in the kidney. Mean baseline and peak values for both signal and noise were calculated in order to derive CNR values. These were CNR = 1.1 for SPGR and CNR = 2.6 for IR-HASTE. These results demonstrate that a much greater contrast was produced using the IR-HASTE technique, in agreement with the expectations from the simulation studies, so this acquisition method was further studied. The two dynamic curves for the whole kidney are shown in Figure 2, with mean baseline and peak values for the two sequences shown with dotted lines. **Further In Vivo Study:** Five further healthy volunteers were then scanned using the IR-HASTE protocol described previously. Subjects breathed medical air whilst a T_1 measurement was taken. Dynamic scanning then began and the breathing gas was switched to O_2 after 20 dynamic images. A total of 80 dynamic images were taken before a second T_1 measurement was made whilst the subject continued to breathe O_2. Time series images were registered using the weighted 2D rigid body algorithm in FLIRT [7]. T_1 maps were calculated for both air and O_2; signal was then converted to ΔPO_2 using a published relaxivity constant [8]. Dynamic plots were used to initialise a sigmoid curve fitting algorithm which calculated ΔPO_2 and wash-in time for the dynamic series on a voxelwise basis. **Results:** A map of signal change (left – scale 0 to 16000), ΔPO_2 (centre - scale: 0 to 10^3 mmHg) and wash-in time (right – scale: 0 to 480 s) for one of the subjects is shown in Figure 3. Mean ΔPO_2 in the whole kidney was 53 ± 18 mmHg and in the renal cortex was 300 ± 200 mmHg across all subjects. **Discussion:** Although SPGR sequences have the potential for much greater CNR, when we include consideration of the temporal resolution requirements of a dynamic study we find that using IR-HASTE sequences leads to a much greater CNR. However, our IR-HASTE acquisition was only single slice, and CNR or temporal resolution sacrifices may have to be made if full volume coverage is required. Analysis of dynamic signal changes has previously been demonstrated with OE-MRI in the lungs, aorta and spleen [9, 10]. This study was able to show that through the parameterisation of the dynamic signal curve obtained during gas switch-over, it is possible to create maps which distinguish between regions in the kidney with differing oxygen delivery. It would be interesting to apply this technique in a study involving the use of diuretics, which are known to affect regional oxygenation levels and blood flow within the kidney [11]. The use of OE-MRI as an indicator of plasma-dissolved oxygen delivery to the kidneys may also be considered as a practical alternative to the use of gadolinium-based contrast media for assessment of renal health.

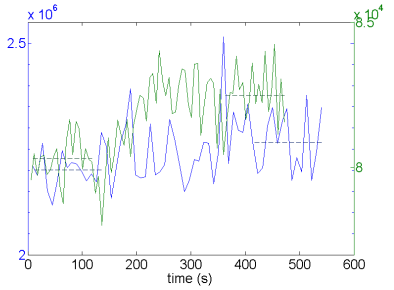

Figure 2: Plot showing dynamic signal upon gas switch-over for SPGR (blue) and IR-HASTE (green).Mean baseline and peak values are indicated using dotted lines.

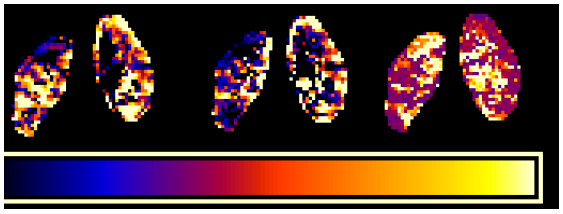

Figure 3: Maps showing signal change (left), ΔPO_2 (centre) and wash-in time (right) for the dynamic signal during gas switchover in the kidneys of a healthy volunteer

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References: [1] Young et al.(1981) *J Comput Tomogr* **5**: 543-547, [2] O'Connor (2008) *Proc 16th Annual Meeting of ISMRM, Toronto*, [3] O'Connor (2007) *MRM* **58**: 490-6, [4] Epstein (1997*) Kidney International* **51**: 381—385, [5] Jones (2002) *MRM* **47**: 728-35, [6] Wang (1987) *MRM* **5**: 399-416, [7] Jenkinson et al. (2002) *NeuroImage*, **17**(2):825-84, [8] Zaharchuk (2006) *Acad Radiol* **13**:1016-1024, [9] Dietrich (2009)*Proc 17th Annual Meeting of ISMRM, Honolulu,* [10] Kershaw (2009) *Proc 17th Annual Meeting of ISMRM, Honolulu,* [11] Brezis (1994) *Am J Physiol Renal Physiol* **267**: 1059–1062.