Potential tracking of oxygen consumption using arterial spin labeling susceptibility imaging

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Deoxygenation in venous vessels, the basis of the BOLD effect in functional imaging, plays a huge role in current neuroscience research. Arterial Spin Labeling (ASL) offers the possibility to probe the physiological transport mechanisms in the brain. However, many physiological parameters, such as water transfer between capillaries and the brain as well as flow effects, influence ASL measurements and complicate interpretation of the data. In this work, efficient ASL measurements of the human brain are presented that potentially provide oxygen saturation, based on simultaneous gradient and spin echo acquisition combined with a 3D-SPIRAL-GRASE readout and via signal change over inflow time TI.

Theory: The readout based on a 3D-GRASE-like acquisition scheme [1]. The contrast mechanism is shown in Fig. 1 and yields R2'-R2. In [2], a description for the R2' dependency in a tissue voxel perfused by a capillary bed has been developed. It depends on the oxygen saturation Y and the partial venous blood compartment V_v, both variables subject to change with brain activation. For 3T, the formula can be evaluated to approximate

$$R2' = V_v \cdot (1 - Y) \cdot 270 \, [1/s]$$

Although this formula only gives a rough estimate, it shows the basic relationship of Y and V_v with R2'. With the simplification of constant R2=20 1/s, the dynamic changes of R2' with blood inflow can be mapped. R2' increases with increasing V_v and with decreasing Y. General linear regression can be used to derive from variations in R2' the coefficients of V_v and Y.

Methods: Measurements have been done on a Trio Siemens MR scanner (3T) with a 32 channel head coil. The acquisition protocol contained the ASL and a T1 weighted imaging sequence. The ASL sequence is basically described in [3]. Readout module was a double echo spiral GRASE [1]. The blood bolus length was 1200 ms, repetition time 3300 ms, total measurement time 22 min. The double spiral readout had six segments, three averages and 20 slices. The segmentation reduced the spin echo time TE to 16.26 ms, ΔTE was 5.35 ms. Eleven time steps from 250 ms to 2750 ms have been acquired with a step size of 250 ms. Resolution was 3.4 x 3.4 x 4 mm³. Four healthy volunteers of age 24 to 40 have been recruited, consent has been given.

Datasets have been smoothed with a Gaussian filter (sigma:1.4 voxel) in all spatial and the TI direction. An ASL fit has been done over TI for all voxel. The obtained bolus arrival time (BAT) map was used to exclude data points of times before the blood arrival. R2' maps have been obtained and the R2' development fitted over TI.
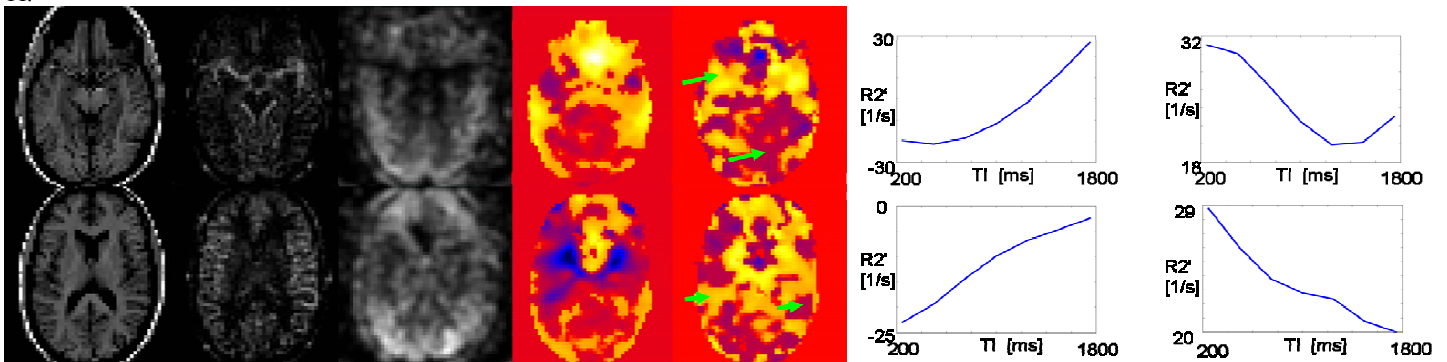

Fig. 1: Schematic sequence diagram and contrast mechanism; the signal is sampled at two time points, a gradient echo at TE-ΔTE and a spin echo at TE.

$$s_{SE} = m \cdot e^{-R2 \cdot TE}$$

$$s_{GE} = m \cdot e^{-R2 \cdot (TE - \Delta TE)} \cdot e^{-R2' \cdot \Delta TE}$$

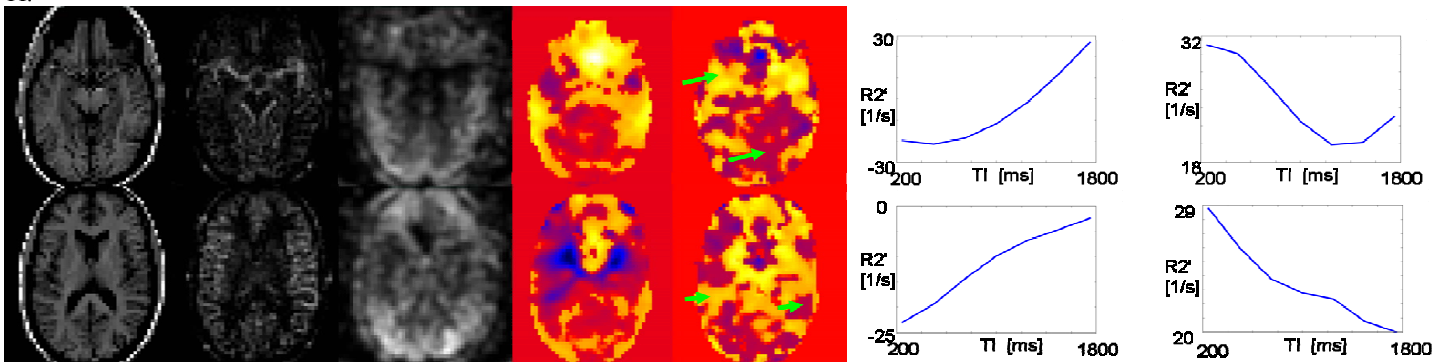$$R2^+ \equiv R2' - R2 = -\frac{1}{\delta TE} \cdot \ln \frac{s_{GE}}{s_{SE}}$$

Fig. 2: Left to right: T1 weighted image, ASL perfusion map, ASL blood bolus arrival time (BAT) map, R2' map (yellow: R2'>R2; blue: R2'<R2), R2' linear dependency with the inflow time TI (yellow: R2' increase; blue: R2' decrease); The plots on the right show typical curves of R2' development over TI in different regions (green arrows; with assumed R2=20 [1/s]; TI already corrected for BAT).

Results: Trends in R2' variations in tissue with increasing inflow time can be observed. However, there are areas of increasing and decreasing apparent R2'. Comparison with the ASL perfusion image shows that in regions with large arterial component (MCA, PCA) apparent R2' generally increases. This could be explained by flow effects which reduce the spin echo and would lead to a substantially larger apparent R2. The ascending trend curves show negative values of R2' which support this assumption. Flow effects decrease with TI as more water has arrived in the capillary bed / tissue space. The descending curves can be better associated with tissue signal changes. R2' values between 20 and 30 1/s correspond to T2' values from 30 to 50 ms. The decreases in R2' points to either increase of V_v or decrease of Y in the direct area surrounding the labeled spins. This can be explained by a larger venous volume "seen" by the spins at later inflow times as the water molecules fill the voxel.

Discussion: Compared to an earlier approach to map perfusion and cerebral blood volume based on ASL R2 measurements [4], which relied on separate calculations in label and control data (and not the difference data), the here presented method provides a more sensitive and robust method to directly measure these parameters depending on the inflow time in a single shot.

The results show trends in R2' development which can be explained by physiological dynamics. However, the results are difficult to interpret. Decreasing oxygenation in the vicinity of the labeled blood would lead to an increase in R2'. Therefore, the effect of increasing apparent venous compartment size seems to dominate the signal change over TI. Measuring R2 simultaneously could help quantifying oxygenation and separate the effects of Y and V_v. Employment of crusher gradients to reduce the flow effects should improve the measurements and benefit interpretation.

References: [1] Gregori, J., N. Schuff and M. Günther (2009). Proc. 17th Scientific Meeting, ISMRM, Honolulu, p 4469. [2] Yablonskiy, D. A. and E. M. Haacke (1994). MRM 32(6): 749-63. [3] Günther, M., K. Oshio and D. A. Feinberg (2005). MRM **54**(2): 491-8. [4] Thomas, D. L., M. F. Lythgoe, F. Calamante, et al. (2001). MRM 45(5): 853-63