Calculations of BOLD signals by use of NIRS Photon Migration Hitting Density Functions

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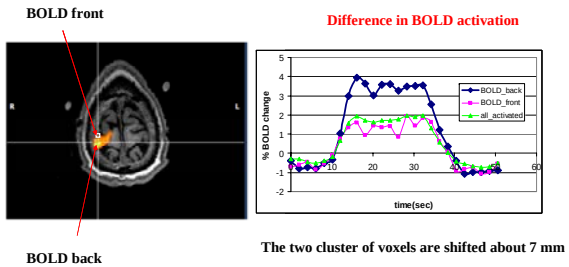
Motivation of the study

The main motivation of this study was to better understand the different comparison between BOLD signal and the changes in oxy and deoxy-hemoglobin that had been presented in the literature. Usually the BOLD signal is obtained as a simple average from all the activated voxels. However if we take a closer look to the signals calculated by selecting different clusters of voxels, we found that usually they don't match, the difference being either in the amplitude or sometimes in the shape, or both. The main point that we are making is that there is not a unique BOLD signal, therefore we should question about the correct way to compare fMRI and NIRS. For this reason we propose a new method for the calculation of blood oxygen level dependent (BOLD) signal which is more meaningful for comparison with near infrared spectroscopy (NIRS) data. We presented a case study of functional activation during a finger tapping test where we used the new method for the calculation of BOLD signal. For every optical source-detector pair we calculated a weighted BOLD signal by using a photon hitting-density function, and by using a simple backprojection algorithm we were able to generate BOLD 2D maps. We found that the weighted BOLD signals calculated from different source-detector pairs, scale in a similar way to the corresponding oxy and deoxy-hemeoglobin concentration changes calculated from NIRS data, for most of the time range of the task. Therefore the BOLD 2D maps were quantitatively similar to the optical maps calculated at different times during the protocol.



The two cluster of voxels are shifted about 7 mm

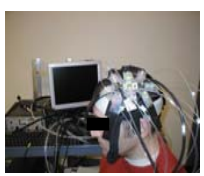
Experimental protocol & data analysis for concerrent fMRI-NIRS

Functional magnetic resonance imaging (fMRI) is performed on a 3 Tesla Siemens Trio whole body magnetic resonance scanner (Siemens Medical Systems, Erlangen, Germany). A quadrature birdcage probe, open at both ends and with a removable top section, is used to allow the optical fibers to be placed on the subject's head without significant bending. After localization and shimming, a series of fMRI images are acquired. Image parameters are as follows: gradient echo EPI, TE/TR=30/2020ms, 64x64 image matrix, full k-space acquisition, FOV 220x220, 30 interleaved coronal slices (R/L readout), 3mm thick, 0mm gap, with the slice stack centered on the motor strip. 120 time points are acquired after 12 dummy shots. Images are saved in DICOM format and processed using Brain Voyager QX (Brain Innovations B.V., Maastricht, The Netherlands). The update rate of fMRI data is 0.5 Hz.

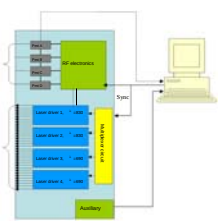
The optical experimental setup is a frequency-domain tissue imager (Imagent, ISS, Inc.,Champaigne, IL) comprising sixteen laser sources at 690 nm and sixteen laser sources at 830 nm (average power about 1 mW) and four optical detectors (photomultipliers tubes, Hamamatsu Photonics R928). The laser diodes are modulated at a frequency f =110 MHz, and are coupled to optical fibers 400 µm in core diameter and 10 m long. The subject (30 years old healthy male) lies motionless inside the magnet. One minute of baseline optical and fMRI data are acquired. Afterwards six cycles of 20 sec right hand tapping and 20 sec of rest are carried out by the subject while simultaneous NIRS and fMRI data are acquired The optical data are filtered to cut off the lower (< .0125 Hz) and higher frequencies (>.1 Hz) , averaged over the six cycles (folding average) and then analyzed by using modified Lambert-Beer law for the change of oxy and deoxy hemoglobin. Temporal trends and spatial mapping are obtained for both NIRS and fMRI.

NIRS

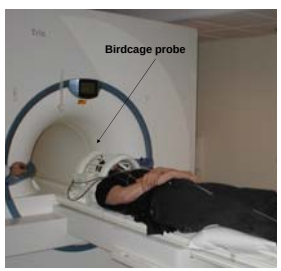
Optical/NIRS helmet



Block diagram of experiment setup

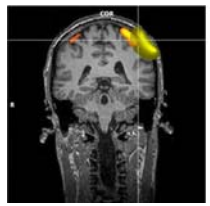


fMRI

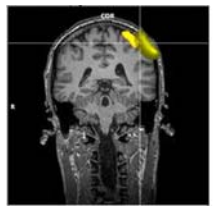


fMRI machine and view of the quadrature birdcage probe

Photon migration probability distribution



k = 2 cm^{-1}



k = 3 cm^{-1}

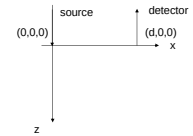
Photon migration occurs with a hitting density expressed by:

$$P(x,y,z)=\frac{z^2\exp(-k\{(x^2+y^2+z^2)^{1/2}+[(d-x)^2+y^2+z^2]^{1/2}\})}{(x^2+y^2+z^2)^{3/2}[(d-x)^2+y^2+z^2]^{3/2}}\times$$
$$[k(x^2+y^2+z^2)^{1/2}+1]\{k[(d-x)^2+y^2+z^2]^{1/2}+1\}$$

$k=\sqrt{3\mu_a\mu_s'}$

μ_a **absorption coefficient**

μ_s' **reduced scattering coefficient**



Definition of BOLD Photon Migration Averaged

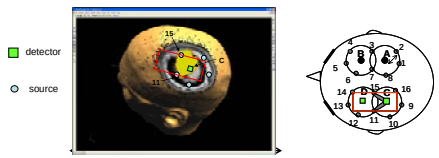
BOLD (PMA)

$$\int\frac{\Delta BOLD(y,z,l)}{BOLD(x,y,z)}P_l(x,y,z)dxdydz$$

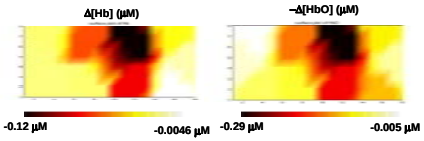
$$\Delta BOLD(y,z,l)=BOLD(x,y,z,l)-BOLD(x,y,z)$$

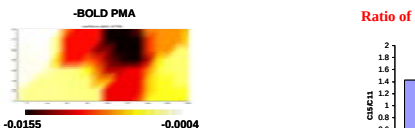
→ Folding Average

Standard BOLD activation map and localization of optical fibers

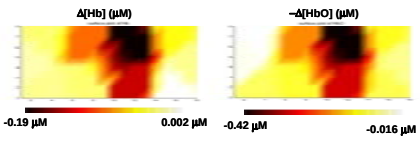


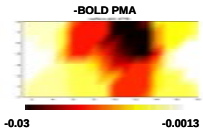
Comparison NIRS data and BOLD PMA; t = 6 s after Onset of activation (k = 2 cm^{-1})



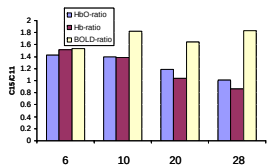


Comparison NIRS data and BOLD PMA; t = 10 s after Onset of activation (k = 2 cm-1)

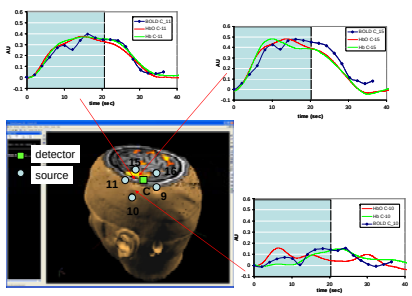




Ratio of signals C15/C11 at t = 6, 10, 20, 28 sec



Comparison of BOLD (PMA) and NIRS temporal trends



CONCLUSIONS

1) Different BOLD signals are calculated in different voxels; this reflects at least different intensities of the activation with respect to the rest condition

2) Since in NIRS the changes that are measured on the surface are the results of the sensitivity of photon migration to the activated area, it is meaningful to define a BOLD signal which has the same sensitivity

3) Comparison of the BOLD PMA with NIRS data shows that the two methodologies are sensitive to the same physical changes

Acknowledgements

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