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Optimal positioning of optodes on the scalp for personalized functional near-infrared spectroscopy investigations

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ABSTRACT

Background: Application of functional Near InfraRed Spectroscopy (fNIRS) in neurology is still limited as a good optical coupling and optimized optode coverage of specific brain regions remains challenging, notably for prolonged monitoring.
Methods: We propose to evaluate a new procedure allowing accurate investigation of specific brain regions. The procedure consists in: (i) A priori maximization of spatial sensitivity of fNIRS measurements targeting specific brain regions, while reducing the number of applied optodes in order to decrease installation time and improve subject comfort. (ii) Utilization of a 3D neuronavigation device and usage of collodion to glue optodes on the scalp, ensuring good optical contact for prolonged investigations. (iii) Local reconstruction of the hemodynamic activity along the cortical surface using inverse modelling.
Results: Using realistic simulations, we demonstrated that maps derived from optimal montage acquisitions showed, after reconstruction, spatial resolution only slightly lower to that of ultra high density montages while significantly reducing the number of optodes. The optimal montages provided overall good quantitative accuracy especially at the peak of the spatially reconstructed map. We also evaluated real motor responses in two healthy subjects and obtained reproducible motor responses over different sessions.
Comparison with existing methods: We are among the first to propose a mathematical optimization strategy, allowing high sensitivity measurements.
Conclusions: Our results support that using personalized optimal montages should allow to conduct accurate fNIRS studies in clinical settings and realistic lifestyle conditions.

1. Introduction

Continuous wave functional Near InfraRed Spectroscopy (fNIRS) is a non-invasive methodology that measures hemodynamic changes associated with brain activity (Scholkmann et al., 2014; Jobsis, 1977). In fNIRS, a spatially distributed set of sources and detectors, resulting in a so-called optode montage, are placed on the scalp emitting and detecting near infrared light. In the near infrared spectrum, the two main optical absorbers in cerebral tissue are oxygenated (HbO) and deoxygenated (HbR) hemoglobin. Consequently, changes in Optical Density (ΔOD) measured at two or more wavelengths (690 and 830 nm in this study) can be converted to local changes in hemoglobin concentration ($\Delta[HbO]$ and $\Delta[HbR]$). The modified Beer Lambert Law, which makes assumptions of a homogeneous medium and concentration changes inside the illuminated volume, is commonly used to obtain estimates of $\Delta[HbO]$ and $\Delta[HbR]$ for each source-detector pair (Delpy et al., 1988; Kocsis et al., 2006).

fNIRS has potential clinical applications to investigate functional processes associated with brain disorders. Its non-invasiveness, portability and absence of strong motion constraints remain very attractive

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from a clinical perspective, allowing prolonged acquisitions at bedside. Despite its known advantages, clinical use has been so far very limited (Irani et al., 2007; Obrig, 2014). Important limitations derive from: (i) the difficulty to position and sustain long lasting good optical coupling of the optodes (Orihuela-Espina et al., 2010; Yücel et al., 2014); (ii) the lack of quantitative accuracy due to unknown partial volume effects in the modified Beer Lambert Law (Boas et al., 2001; Strangman et al., 2003); (iii) the uncertainty in controlling the cortical volume illuminated by a given optode montage, as the depth sensitivity of fNIRS measurements strongly depends on source-detector distances and on the thickness of superficial tissues (Strangman et al., 2013; Haeussinger et al., 2011; Mansouri et al., 2010).

In order to control the cortical volume illuminated, we proposed in Machado et al. (2014) an original method for computing the 'optimal' set of optodes positions on an ElectroEncephaloGraphic(EEG)-fNIRS cap. The so-called optimal montage methodology was developed to provide the best sensitivity to some target cortical Volumes Of Interest (VOIs) as clinical investigations with fNIRS might be targeted to patient-specific areas of interest (e.g., an epileptic focus, an ischemic area, structural lesions, tumors). Using light sensitivity profiles estimated from the patient's anatomical head model, the optimization problem of optode positioning was formulated as a mixed linear integer programming problem under functional constraints. We observed that optimal montages yielded improved spatial density of fNIRS measurements over the targeted regions together with an increase in signal-to-noise ratio.

Improved quality of measured optical signals and reduction of motion artifacts can be achieved by using a water-resistant adhesive (e.g., collodion) to glue the optodes on the scalp (Yücel et al., 2014). Such an approach is particularly useful when prolonged acquisitions of several hours are required for clinical purposes. Attaching electrodes using collodion is a common technique in clinical EEG prolonged recordings. Originally proposed by Yücel et al. (2014), the use of collodion in fNIRS is not yet very common, more likely because it requires a proper ventilated room to dissipate the fumes emitted by collodion during the installation. Based on our own experience, using collodion, one can maintain optical signals of excellent quality for at least 6 h, and likely even more (Pellegrino et al., 2016). An additional important advantage associated to the use of collodion, is that it becomes feasible to investigate in fNIRS almost any subject, independently of their hair color, since hair can be removed from the tip of the optode during the gluing procedure.

Finally, fNIRS quantitative accuracy can be further improved using Diffuse Optical Tomography (DOT) (Boas et al., 2001, 2004b) that reconstructs $\Delta[HbO]$ and $\Delta[HbR]$ in the brain volume by solving an ill-posed inverse problem (Arridge, 1999; Durduran et al., 2010). Achieving accurate DOT reconstruction with good spatial resolution usually requires the use of dense array of optodes allowing overlapping measurements and uniform spatial coverage (Boas et al., 2004a; Zhao et al., 2006; Joseph et al., 2006; Tian et al., 2009; White and Culver, 2010; Zhan et al., 2012). However, due the extra time required to install a large number of optodes, DOT is usually experimentally difficult, especially for clinical applications.

In this study, we evaluate within a realistic simulation environment and on real data a new procedure allowing rapid installations of fNIRS personalized montages and accurate investigation of specific brain target areas using inverse modelling. This procedure was designed to conduct fNIRS studies in clinical settings and realistic lifestyle conditions such as walking, driving, sleeping. Our proposed methodology consists in three steps: (i) Personalized fNIRS montage: a priori maximization of spatial sensitivity of fNIRS measurements in target brain regions identified a priori, while reducing the number of applied optodes in order to decrease installation time and improve subject comfort. To do so, we improved significantly the optimal montage methodology originally proposed in Machado et al. (2014) introducing new functional constraints on the optimal set of optodes positions, allowing to take into consideration any position along the scalp surface, as opposed to fixed discrete positions along an EEG cap. (ii) Utilization of a 3D neuronavigation device and usage of collodion to glue optodes on the scalp, ensuring good optical contact for prolonged investigations. (iii) Local reconstruction of the hemodynamic activity along the cortical surface using inverse modelling in order to improve the quantification of $\Delta[HbO]$ and $\Delta[HbR]$. We hypothesize that personalized optimal montages with few optodes aimed at specific target regions using overlapping measurements are, despite their limited spatial extent, adequate to perform accurate local reconstructions.

2. Material and methods

2.1. Optimal montage methodology

2.1.1. Defining a set of possible optode positions on the scalp

The first step of the optimal montage methodology requires to define the set of possible optode positions over the subject's scalp considering all the vertices of a high density mesh. This increases flexibility of the installation when compared to a set of possible discrete positions defined on an EEG cap as proposed originally in Machado et al. (2014). Scalp meshes were segmented from anatomical T1-MRIs using *Brainvisa*[1] software package (Mangin et al., 1995) with a mean edge length of 5 mm which was adequate to obtain an accurate scalp representation (Fig. 1A). Vertices around the face, neck and ears regions were removed resulting in scalp meshes with approximately 4000 vertices.

2.1.2. fNIRS forward model

The second step of the methodology requires computing the subject-specific light sensitivity profiles (Fig. 1C) for all pairs of vertices (i.e., representing possible source-detector pairs) on the scalp mesh. To reduce the number of possible combinations, only pairs within a specific separation range were taken into account (e.g., 15–35 mm).

For each vertex, Monte Carlo simulations (using 10^8 photons) at each wavelength were used to determine the photon fluence rate distribution ($W\,m^{-2}$) within the specific head model of the participant, using a 3D grid of $1 \times 1 \times 1$ mm (Boas et al., 2002; Fang and Boas, 2009). The scalp vertices corresponding to voxel segmented as belonging to air in the 3D grid head model (due to small registration or segmentation errors) were projected back to the closest skin tissue voxel according to the normal of the mesh face it belonged to.

The sensitivity profiles were computed using the adjoint formulation and were normalized with the Rytov approximation (Arridge, 1999). In order to define the optical properties required for Monte Carlo simulations, the T1-MRI voxels were classified into five tissue types (Collins et al., 1995)[2]: skin, skull, cerebrospinal fluid, gray matter and white matter (Fig. 1B).

Based on estimates available from the literature (Strangman et al., 2003), absorption and scattering coefficients values at 830 nm and 690 nm associated to each tissue type of our anatomical head model are reported in Table 1. The anisotropy coefficient of tissues was set to 0.92 and the refractive indices of air and tissue were assumed to be 1.0 and 1.37, respectively.

Sensitivity coefficients $a_{ij}^{\lambda}(v)$ (in mm) represent how local variations in absorption properties of a specific voxel v impact the measured ΔOD^{λ} between a source i and a detector j. For a given montage, considering all measurements together, the fNIRS forward model can then be described by the following linear model:

$$\boldsymbol{\Delta OD}^{\lambda} = \boldsymbol{A}^{\lambda}\boldsymbol{\Delta\mu}_{\boldsymbol{a}}^{\lambda} \tag{2.1}$$

where matrix $\boldsymbol{\Delta OD}^{\lambda}$ is the change in optical density (number of measurements × number of time samples); $\boldsymbol{A}^{\lambda}$ (number of measurements ×

[1] Brainvisa software package available at http://brainvisa.info

[2] Segmentation tools available at http://www.bic.mni.mcgill.ca/ServicesSoftwareAdvancedImageProcessingTools/HomePage