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Pixel-wise modified Beer-Lambert model for intraoperative functional brain mapping

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ABSTRACT

A RGB camera and a continuous wave white light illumination is a suitable approach to intraoperatively localize the sensory and motor areas of the patient brain. The analysis of the reflectance spectra through the modified Beer-Lambert law enables us to measure the concentration changes of oxygenated and deoxygenated hemoglobin during the video acquisition. However these concentration changes depend on the wavelength dependent optical mean path length. A manual image segmentation and Monte-Carlo simulations allow us to precisely choose the mean path length in a pixel-wise manner.

Keywords: functional brain mapping, Monte-Carlo simulations, intraoperative imaging, RGB camera

1. INTRODUCTION

Non-invasive functional brain mapping is an imaging technique used to localize the functional areas of the patient brain. This technique is used before brain tumor resection surgery to indicate to the neurosurgeon the cortical tissues which should not be removed without cognitive impairment. MRI-f is widely used to localize patient sensory or motor areas. However, after patient craniotomy, a brain shift invalidates the relevance of neuro-navigation to intraoperatively localize the functional areas of the patient brain. For this reason, the localization of cortical motor or sensory areas is currently achieved through electrical stimulation but this technique suffers from limitations.

Chance et al. have demonstrated that optical imaging can be used to monitor brain activity with the determination of concentration changes of oxygenated hemoglobin $\Delta[HbO_2]$, deoxygenated hemoglobin $\Delta[Hb]$, blood volume $\Delta[Hb] + \Delta[HbO_2]$ and oxygenated cytochrome-oxidase.¹ It also has been demonstrated that a device consisting of a continuous wave white light illumination and a RGB² or hyperspectral camera³ is a suitable approach.

The motivation for this work is derived from the necessity to precisely assess $\Delta[HbO_2]$ and $\Delta[Hb]$ for each camera pixel. This requires a precise determination of the optical mean path length for the computation of the modified Beer-Lambert law.⁴ We propose to estimate a wavelength dependent optical mean path length for each camera pixel with a manual image segmentation and Monte-Carlo simulations.

2. MATERIAL AND METHODS

2.1 Experimental setup

The instrumentation consisted of a digital RGB CMOS camera (BASLER acA2000- 165uc), a continuous wave white light source (OSRAM Classic 116W 230V Light bulb) and a laptop (processor: Intel Core *i5* – 7200U, 2.50GHz \times 4, ram: 15.3GiB). The RGB camera was used with an Edmund Optics camera lens ($f = 16mm$ $f\# = 1 : 1 : 4$) and data were directly acquired by the laptop via an USB link. The sensor provided 8 bits RGB images every 33 ms.

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2.2 Patient inclusion and experimental paradigm

The video acquisition was realized before a brain tumor resection surgery. The patient was awakened and functional tests have been realized. Stimulation of the motor cortex was achieved through successive fist clenching and relaxing. The paradigm consisted of 3 steps: 30s of rest, followed by 30s of stimulation and 30s of rest. The neurosurgeon realized electrical brain stimulation to localize patient brain motor and sensory areas.

2.3 Data pre-processing

The first image of the video sequence was segmented with a semi automated procedure into three classes: grey matter, surface blood vessel and buried blood vessel. Pixels were clustered into four clusters using the K-Means algorithm from the C++ library OpenCV (*v3.2.0*).⁵ Then these clusters were manually sorted and attributed to the three classes. Non selected clusters corresponded to saturated areas (specular reflection) were discarded. The algorithm developed by *Sdika et al.*^{6,7} was implemented to ensure that each camera pixel corresponds to the same cortical area all along data acquisition. As the brain repetitive motion is compensated, the segmentation of the first image is valid during the whole video sequence. The RGB intensities of the acquired image are then independently filtered with a low-pass IIR Bessel temporal filter.¹ The slow drift of the collected intensity due to cortical tissue desiccation during the video acquisition⁸ was corrected through a linear regression subtracted to the original data.

2.4 Model

The assessment of Hb and HbO_2 concentration changes was realized through the modified Beer-Lambert law.⁴ These measurements depend on the determination of the wavelength dependent mean path length of the detected photons. The mean path length values were computed with Monte-Carlo simulations.⁹ In Fig. 1-A and B, two cortical tissues were modeled under a homogeneous white light illumination. Each voxel of the modeled tissues included the values of optical parameters (absorption, reduced scattering, anisotropy coefficients and refractive index).

3. RESULTS AND DISCUSSION

In Fig. 1-D, the manual segmentation of the Fig. 1-C aims to associate each pixel of the acquired frame with a specific tissue. In Fig. 1-E, several wavelength dependent mean path lengths measured on the surface of the modeled tissues (see Fig. 1-A and B) are plotted. These mean path lengths are used in the modified Beer-Lambert law to compute different $\Delta[Hb]$ and $\Delta[HbO_2]$ time courses (see Fig. 1-F). The grey matter point localized by a red cross in Fig. 1-C is situated at the surface of the tissue, $1.34mm$ away from a blood vessel. So the most appropriate mean path length is represented by the black curve in the Fig. 1-E and the most appropriate $\Delta[Hb]$ and $\Delta[HbO_2]$ time courses are represented by the black and green curves in Fig. 1-F. The influence of the choice of the mean path length in the modified Beer-Lambert law can be observed in the Fig. 1-F. Our method can be improved with an automatic mean path length estimation by fitting the acquired reflectance spectra with the simulated reflectance spectra. This comparison appears not to be an easy task since only three spectral values are acquired which are integrated over the broad wavelength ranges covered by each detector. An hyperspectral camera seems to be a more appropriate solution to answer this problem. A similar method has been implemented by *Pichette et al.*³ using an hyperspectral camera and a two class image segmentation but this technique does not take account of the distance between cortical tissues and blood vessel.

4. CONCLUSION

A RGB camera and a white light illumination are a suitable approach to intraoperatively monitor the sensory and motor areas of a patient brain. A semi automated segmentation and Monte-Carlo simulations allow us to precisely assess the Hb and HbO_2 concentration changes with a pixel-wise selection of the mean path length.

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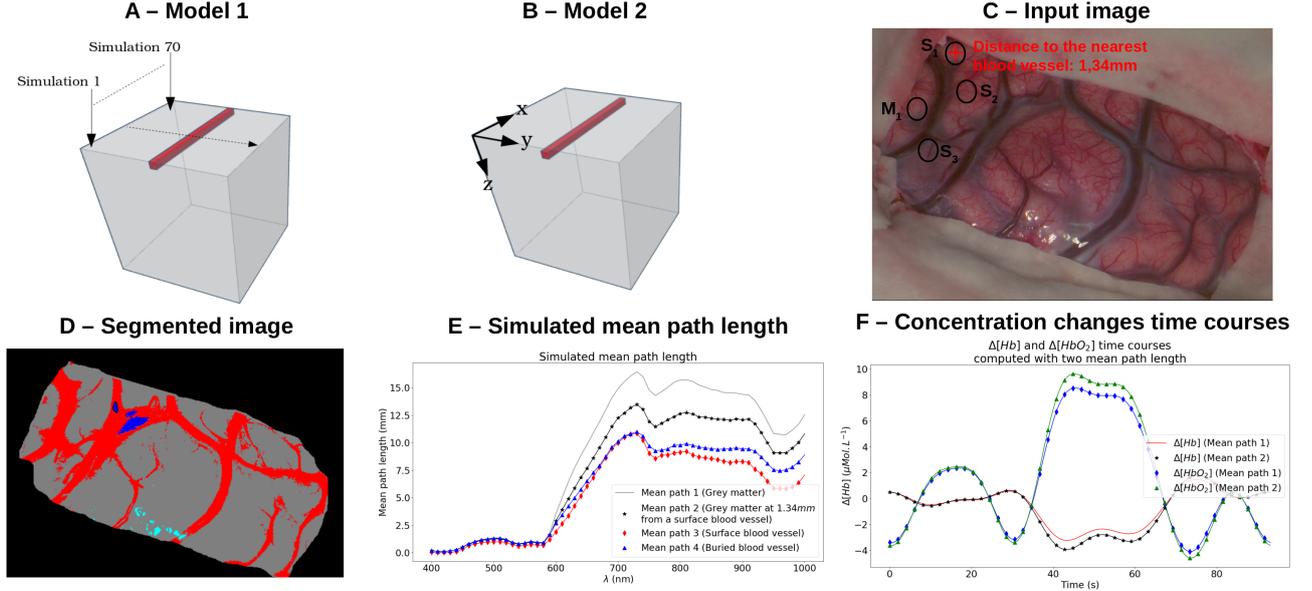


Figure 1. **A and B** - Representation of modeled cortical tissues. Volumes are made up of $70 \times 70 \times 70$ voxels with 1mm^3 resolution. The model 1 represents a 2 mm diameter blood vessel on the surface of the cortical tissue, the model 2, a 2 mm diameter blood vessel buried under 1 mm of grey matter. The red voxels represent the blood vessel and the grey voxels the grey matter. A Black arrow symbolizes a Monte-Carlo simulation for a single position (10^6 packets of photon). **C** - First frame of the patient brain. M_i and S_i designate the patient motor and sensory areas i validated by electrical stimulation. **D** - Manual image segmentation (red : surface blood vessel, blue : buried blood vessel, grey : grey matter and cyan : unprocessed data). **E** - Mean path length of the models represented in Fig. A and B. **F** - $\Delta[Hb]$ and $\Delta[HbO_2]$ time courses of the cortical tissue localized by the red cross in Fig. C.

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