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Digital modeling of a heterogeneous and dynamic brain phantom: Application to the choice of an RGB camera for intraoperative functional brain mapping studies

Charly Caredda^a, Laurent Mahieu-Williams^a, Raphaël Sablong^a, Michaël Sdika^a, Fabien C. Schneider^b, Thiébaud Picart^c, Jacques Guyotat^c, and Bruno Montcel^a

^aUniv Lyon, INSA-Lyon, Université Claude Bernard Lyon 1, UJM-Saint Etienne, CNRS, Inserm, CREATIS UMR 5220, U1294, F69100, Lyon, France

^bService de Radiologie, Centre Hospitalier Universitaire de Saint Etienne, TAPE EA7423, Université de Lyon, UJM Saint Etienne, F42023 France

^cService de Neurochirurgie D, Hospices Civils de Lyon, Bron, France

ABSTRACT

RGB imaging is a non-invasive technique that is able to monitor hemodynamic brain responses following neuronal activation during neurosurgery. These cameras are often present in operating rooms, but a robust quantification is complicated to perform during neurosurgery. Liquid blood have been proposed, but it is not possible to model hemodynamic responses similar to those that occur in the brain. To overcome this issue, we propose a 3D brain model, including activated, non-activated grey matter and temporal hemodynamic fluctuations using Monte Carlo simulations. Several setups were modeled to evaluate their impact for identifying activated brain areas using statistical parametric mapping.

Keywords: Numerical brain phantom; Statistical parametric brain mapping; Optical imaging; RGB imaging

1. INTRODUCTION

Optical imaging is a non-invasive technique especially adapted for intraoperative functional brain mapping applications. RGB cameras combined with a white light illumination allow the analysis of the light absorption to monitor the brain activity with quantification of the concentration changes in oxy- and deoxygenated hemoglobin (HbO₂ and Hb, respectively) in brain cortex.^{1,2} A robust quantification of these biomarkers is complicated to perform during neurosurgery due to the critical context of the operating room, which makes the calibration of optical devices more complex. To overcome this issue, tissue-simulating objects are required for the development of medical imaging systems. These so-called "phantoms" may be used to evaluate, optimize, compare or control imaging systems.³ Some phantom recipes based on intralipid and blood have emerged to reach that goal.⁴ However, using these liquid phantoms, it is not possible to model hemodynamic responses similar to those that occur in the brain. For this reason, numerical brain phantoms may be especially adapted.⁵

In this work, we propose a 3D brain model, including activated, non-activated grey matter and temporal hemodynamic and metabolic fluctuations using Monte Carlo simulations. Hemodynamic fluctuations were related to brain activity, heartbeat, respiratory and resting state events. Several acquisition setups were modeled (6 RGB cameras and 3 light sources) to evaluate their impact on hemodynamic quantification as well as the performance of the identification of the activated brain area using statistical parametric mapping (SPM) and the random field theory.^{6,7}

Further author information: (Send correspondence to C.C and B.M)

C.C.: E-mail: charly.caredda@creatis.insa-lyon.fr, B.M.: E-mail: bruno.montcel@creatis.insa-lyon.fr

2. MATERIAL AND METHODS

2.1 Numerical brain phantom

We modeled a numerical brain phantom with the simulation of the acquisition of the diffuse reflection spectra of a patient exposed cortex illuminated with a continuous wave white light source during cerebral activity. The patient exposed cortex was modeled by a volume of $60 \times 60 \times 60$ mm of grey matter. Two compartments were created: activated and non activated grey matter. Activated grey matter was represented as a parallelepiped of $6 \times 6 \times 3$ mm located at the surface of the grey matter volume. For both compartments, several physiological events were modeled: the hemodynamic fluctuations due to resting state, heartbeat and respiratory. In activated grey matter compartment, we modeled the absorption and scattering changes due to functional activity, see Fig. 1. For both compartments, we also modeled intensity drift due to tissue desiccation.

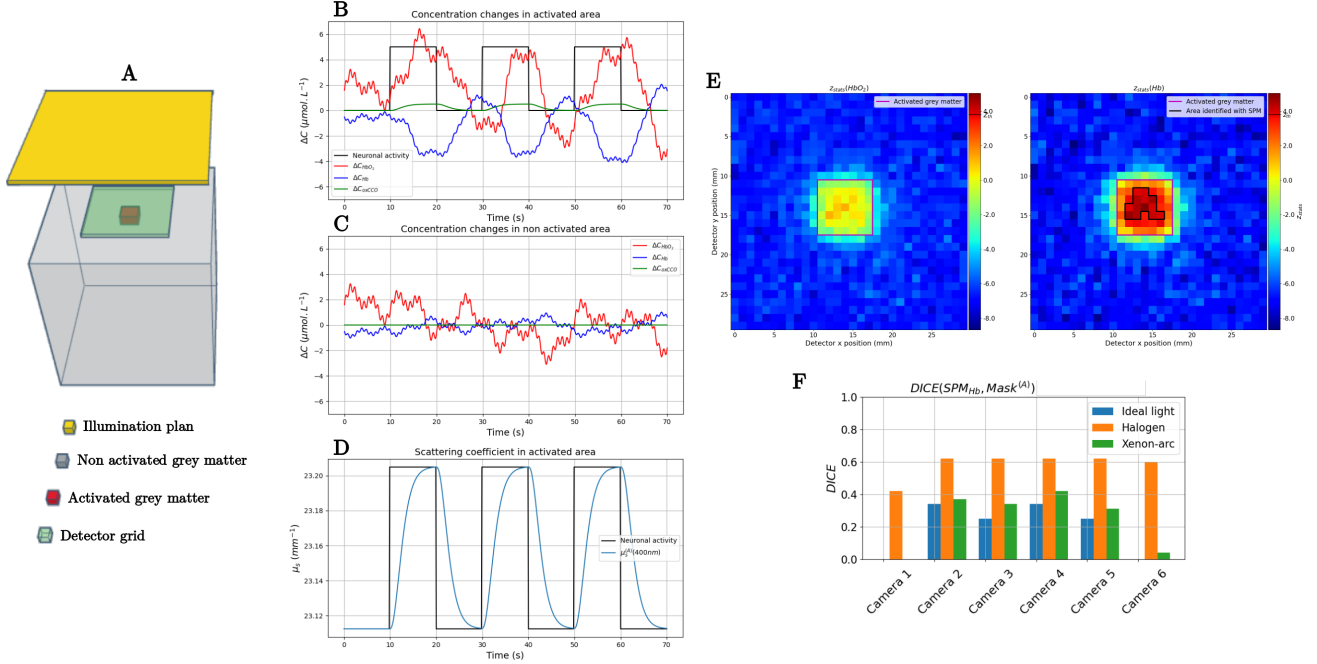


Figure 1. A - Schematic of the brain numerical phantom. Non activated grey matter is represented in grey, activated grey matter in red, the illumination plan in yellow, and the detector grid in green. B - Hemodynamic and metabolic concentration changes in activated grey matter. C - Hemodynamic and metabolic concentration changes in non activated grey matter. D - Scattering coefficient changes at 400 nm in activated grey matter. E - Z statistics matrix obtained with HbO₂ and Hb data modeled for camera 1 and illumination source 2. Boundary of activated grey matter is indicated by magenta contour, and functional brain area identified by SPM is represented with black contour. F - DICE coefficients computed between functional brain area identified by SPM and the modeled activated grey matter (Mask(A)).

This dynamic brain model was simulated by Monte Carlo simulations using MCX software.⁸ Each voxel of the modelled tissue included the information of optical parameters (absorption μ_a , scattering μ_s , anisotropy g coefficients and refractive index n). A white light illumination has been simulated by scanning the optical parameters along the entire illumination spectrum (from 400nm to 1000nm in steps of 1nm). Details regarding the optical properties can be found in Ref.⁵ 10^8 packet of photons were homogeneously illuminating the modeled surface. Several simulations were computed to model the dynamic aspect of the numerical brain phantom. Physiological changes were modeled by changing the values of the optical properties. Optical mean path length and the diffuse reflection spectra were measured at the detectors position (grid of 30×30 detectors placed at the center of the top face of the volume) during 70s at 10 frames per second, with the integration time set to 33ms.

Changes in μ_a related with resting state functional connectivity are due to low frequency fluctuations of the concentrations of Hb and HbO₂ within 0.01–0.08 Hz.⁹ We adapted the formalism proposed by Di and Biswal¹⁰

to model concentration changes in Hb and HbO_2 due to functional connectivity at rest. Concentration changes of Hb and HbO_2 due to heartbeat and respiratory were modeled as sinus functions of frequency 1 Hz and 0.2 Hz respectively. Phase and amplitude of the sinus functions have been retrieved from the literature.^{11,12} Functional activity was modeled as changes in μ_a and μ_s induced by neuronal activity. This last was represented by a periodic square function with three repetitions. One period was defined by 10 s of rest and 10 s of neuronal activity. Changes in μ_a are due to cerebral hemodynamic and metabolic changes (concentration changes in HbO_2 , Hb and in oxidative state of cytochrome-c-oxidase $oxCCO$), see details in Ref.⁵ Changes in μ_s are also called 'event related optical signal' (EROS)¹³ and are no larger than 0.4%.¹⁴ To model its dependency over time, we made the hypothesis that changes in μ_s related to functional activity have the same temporal dynamic than ΔC_{oxCCO} that occurs in the mitochondria.

2.2 Data analysis

We modeled the acquisition of RGB intensities retro-diffused at the surface of numerical brain phantom with different optical setups. We used methodology we proposed in Ref.⁵ Six cameras and three light sources were simulated, see table 1.

Table 1. List of modelled RGB cameras and illumination sources.

Camera ID	Model	Lightning ID	Model
1	<i>BASLER acA2000-165uc</i>	1	Ideal illumination (uniform distribution of emitted wavelength)
2	<i>BASLER acA1920-25uc</i>		
3	<i>Thorlabs CS126CU</i>	2	Halogen lamp <i>OSRAM Classic 230V</i> (spectra was experimentally measured)
4	<i>Thorlabs CS135CU</i>		
5	<i>Thorlabs CS165CU</i>	3	Xenon-arc lamp <i>Thorlabs SLS401</i>
6	<i>Thorlabs CS235CU</i>		

For each combination of camera and illumination source, processing steps described in Ref¹ were executed to computed concentration changes in Hb and HbO_2 for each detector. We also applied the SPM technique combined with the random field theory^{6,7} for the identification of the activated grey matter surface in the numerical brain phantom. Functional brain images computed with HbO_2 and Hb were compared to the ground truth using the DICE coefficient. This ground truth was defined as a binary mask of 30×30 pixels representing the surface of numerical brain phantom (0: non activated brain area, 1: activated brain area).

3. RESULTS

Z-statistic maps obtained with SPM and concentration changes in Hb and HbO2 computed with camera 1 and illumination source 2 are represented in Fig. 1 E. The boundary of activated grey matter is indicated by magenta contour, and functional brain area identified by SPM is represented with black contour. For HbO_2 , SPM does not identify the activated grey matter area due to low z-statistic values. For Hb , an area is identified with SPM, which corresponds to the modeled activated grey matter (DICE = 0.42).

In Fig. 1 F, the DICE coefficients computed between functional brain areas identified by SPM with the different optical setups and the ground truth are plotted. For HbO_2 , DICE coefficients are 0 for all optical devices, meaning that no functional brain area were identified with SPM. For Hb, the best DICE coefficients were obtained when the halogen bulb was modeled.

4. DISCUSSION

The results of this study show that RGB imaging is capable of identifying functional brain areas using SPM combined with the quantification of concentration changes in Hb . RGB imaging is more suitable for monitoring Hb than HbO_2 responses in the brain. As we have shown in a previous study, quantification errors in Hb are smaller than those in HbO_2 with RGB imaging.⁵ The presence of more physiological noise in HbO_2 response does not allow, after filtering, to perfectly recover the response induced by neuronal activity. This is concordant

with our experimental results in Ref,¹ in which we observed that correlation coefficients calculated between measured and expected concentration changes time courses were higher for Hb than for HbO_2 . Results indicate that halogen light sources are adapted for functional brain mapping studies bases on RGB imaging.

5. CONCLUSION

In this study, we provide a Monte Carlo framework that provides a two-compartments brain phantom with realistic absorption and scattering fluctuations. Based on our previous studies,^{1,5,7} we incorporated the possibility to simulate the acquisition of reflection spectra with different cameras and light sources illumination. We showed that RGB imaging is capable of identifying functional brain areas using SPM combined with the quantification of concentration changes in Hb . This numerical brain phantom could be used to guide the design of intraoperative setups for functional brain mapping studies. However, several improvements need to be integrated. The noise of the acquisition chain needs to be modeled. A more realistic volume of gray matter must be modeled. To reach this goal, a real RGB image of a patient cortex could be transformed in a 3D volume. Dynamic hemodynamic fluctuations in arterial, capillary and venous compartments must be modeled. For this purpose, we plan to use the dynamic model proposed by Sergio Fantini.¹⁵

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