A digital instrument simulator to optimize the development of hyperspectral systems for intraoperative brain mapping

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ABSTRACT

Optical imaging is a marker-free, contactless, and non-invasive technique that is able to monitor hemodynamic and metabolic brain response following neuronal activation during neurosurgery. However, a robust quantification is complicated to perform during neurosurgery due to the critical context of the operating room, which makes the calibration and adjustment of optical devices more complex. To overcome this issue, tissue-simulating objects that mimic the properties of biological tissues are required for the development of detection or diagnostic imaging systems. In this study, we developed a digital instrument simulator to optimize the development of a novel hyperspectral system for application in brain/cortex imaging. This digital phantom is based on white Monte Carlo simulations of the light propagation in tissues. The output of the Monte Carlo simulations are integrated with the key instrument parameters in order to produce realistic images. The results can be beneficial and useful within the framework of our EU-funded HyperProbe project, which aims at transforming neuronavigation during glioma resection using novel hyperspectral imaging technology.

Keywords: Digital instrument simular, hyperspectral imaging, functional brain mapping, Monte Carlo simulations

1. INTRODUCTION

Optical imaging is a non-invasive technique especially adapted for intraoperative functional brain mapping applications. Hyperspectral 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, deoxygenated hemoglobin (HbO2 and Hb) and the oxidative state of cytochrome-c-oxidase (oxCCO) 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]

In this study, we developed a realistic digital instrument simulator for optimizing the development of hyperspectral systems for intraoperative brain mapping. We modeled the light propagation in a realistic tissue with Monte Carlo simulations. The tissue was modeled from an image of exposed brain acquired during neurosurgery. We incorporated physiologic changes in modeled tissues related to cerebral activity, breathing or cardiac beating.

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The Monte Carlo outputs were integrated with the hyperspectral device parameters to model realistic images.

The results can be beneficial and useful within the frame-work of our recently started, EU-funded HyperProbe consortium and project[4,5] which aims at transforming neuronavigation during glioma resection using novel hyperspectral imaging technology.

2. MATERIAL AND METHODS

The numeric phantom models a realistic exposed brain. We used an RGB image of an exposed brain acquired during neurosurgery to model a heterogeneous tissue defined with three compartments: grey matter, large blood vessels and capillaries. Each compartment included different optical properties, which allowed us to model physiological changes in the brain.

A white Monte Carlo approach was implemented: the absorption coefficient of the tissue was set to 0 cm-1 and the considered outputs were the exit position and direction of each detected photon, and their partial pathlength (PPL) i.e. the length that each photon has spent in each classes of the domain. The advantage of this approach is that the absorption can then be considered a posteriori, by using the Beer-Lambert law. Thus, when changing the absorption parameters in the tissue, the simulation does not need to run again.

Using this approach, we modelled a region of activated grey matter having temporal hemodynamic and metabolic variations related to cerebral activity (increase of C_{HbO_2}: 5 μM, decrease of Hb: -3.75 μM and increase of $oxCCO$: 0.5 μM).

We simulated the acquisition of the reflection spectra with an optical device composed of a lens, a hyperspectral or an RGB camera. We calculated the position of each photon exiting the tissue onto the camera sensor by taking the initial exit photon position and direction and applying a transfer matrix.

We incorporated the spectral sensitivities of the light source and of the camera sensor, as well as the noise of the acquisition chain to model realistic images. After image reconstruction, diffuse reflectance and optical mean path length could be estimated for each camera pixel.

We implemented an optimization routine based on the genetic algorithm to perform a heuristic search for wavelength combinations that can provide accurate measurements of hemodynamic and metabolic changes. The algorithm relies on the differential evolution method from Python Scipy library[6] to find the minimum of a cost function defined by the mean square error calculated between modelled concentration changes and those measured with the modified Beer-Lambert law.

For hemodynamic monitoring, we compared the quantification errors obtained with optimized configurations for 2 and 4 wavelengths with those presented in the literature:

- Bouchard et al.:[7] 470 and 530 nm
- White et al.:[8] 470, 530, 590, 625 nm

For hemodynamic and metabolic monitoring, we compared the quantification errors obtained with the optimized configuration for 4 wavelengths with those presented in the literature:

- Arifler et al.:[9] 785, 809, 849 and 889 nm
- Bale et al.:[10] a broadband spectrum from 780 to 900 nm

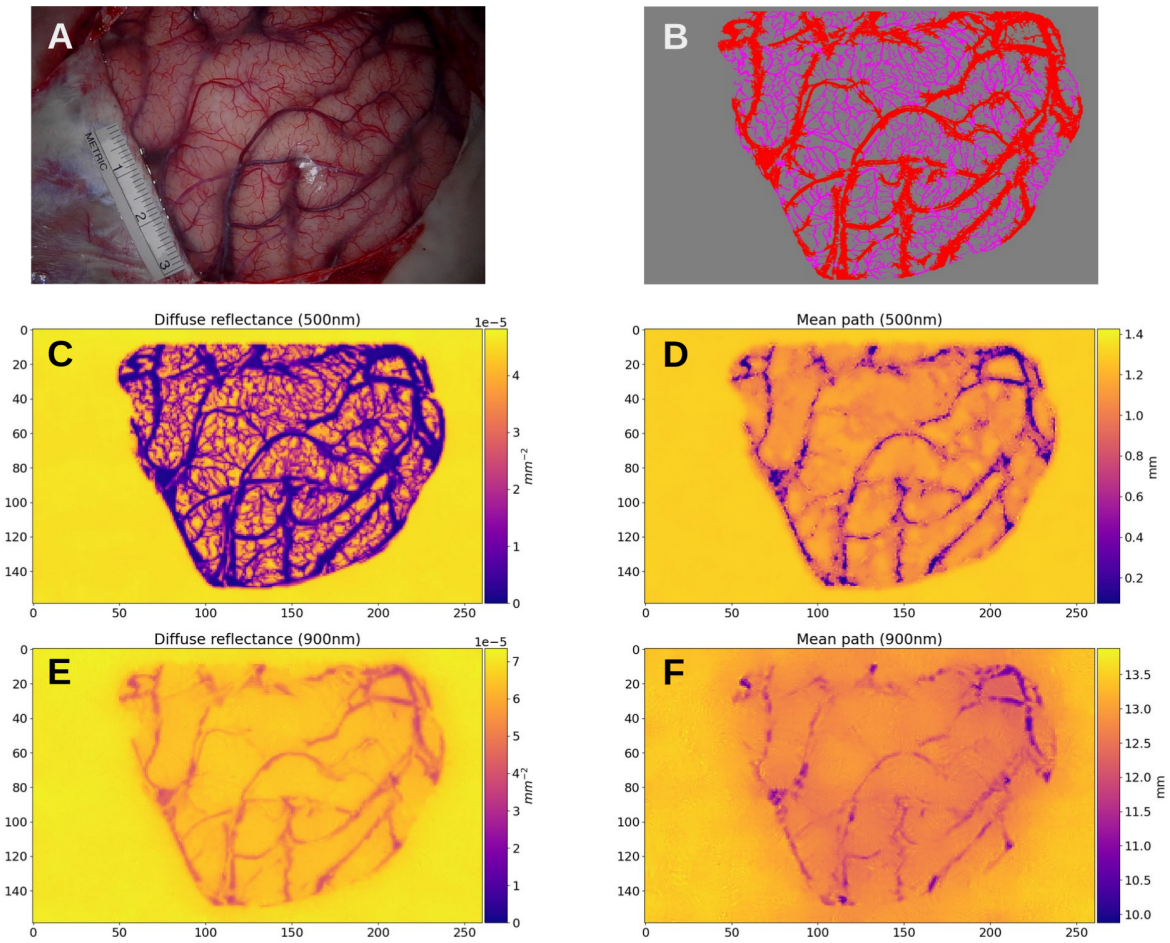

Figure 1. Images obtained with the digital instrument simulator. (A) Input image used to define the classes of the Monte Carlo model (B). (C) Image of intensity at 500 nm. (D) Image of mean path length at 500 nm. (E) Image of intensity at 900 nm. (F) Image of mean path length at 900 nm.

3. RESULTS AND DISCUSSION

In Fig. 1, we represented the simulated image obtained with the digital instrument simulator at 500 nm (C) and 900 nm (E), as well as the image of mean path length at 500 nm (D) and 900 nm (F). Image (A) is the RGB input image used to define the classes of the Monte Carlo model (B).

In Fig. 2, we represented with vertical lines the literature and the optimal spectral configurations for the quantification of hemodynamic and metabolic changes. We also represented the quantification errors obtained with these spectral configurations.

For hemodynamic monitoring, the optimal combination of 2 wavelengths (476 and 522 nm) allows to reduce the quantification errors in ΔC_{HbO_2} and ΔC_{Hb} of 75% compared to the configuration proposed by Bouchard et al.[7] The optimal combination of 4 wavelengths (474, 523, 550 and 568) allows to reduce the quantification errors in ΔC_{HbO_2} and ΔC_{Hb} of 81% compared to the configuration proposed by White et al.[8]

For hemodynamic and metabolic monitoring, the optimal combination of 4 wavelengths (534, 562, 640 and 659) allows to reduce the quantification errors in ΔC_{HbO_2}, ΔC_{Hb} and ΔC_{oxCCO} of 99% compared to the configuration proposed by Bale et al.[10] and Arifler et al.[9]

This digital instrument simulator can be used to validate the measurements of ΔC_{HbO_2}, ΔC_{Hb} and ΔC_{oxCCO} using hyperspectral imaging. It also provides an excellent means for defining the optimal wavelength used for measuring hemodynamic and metabolic changes.

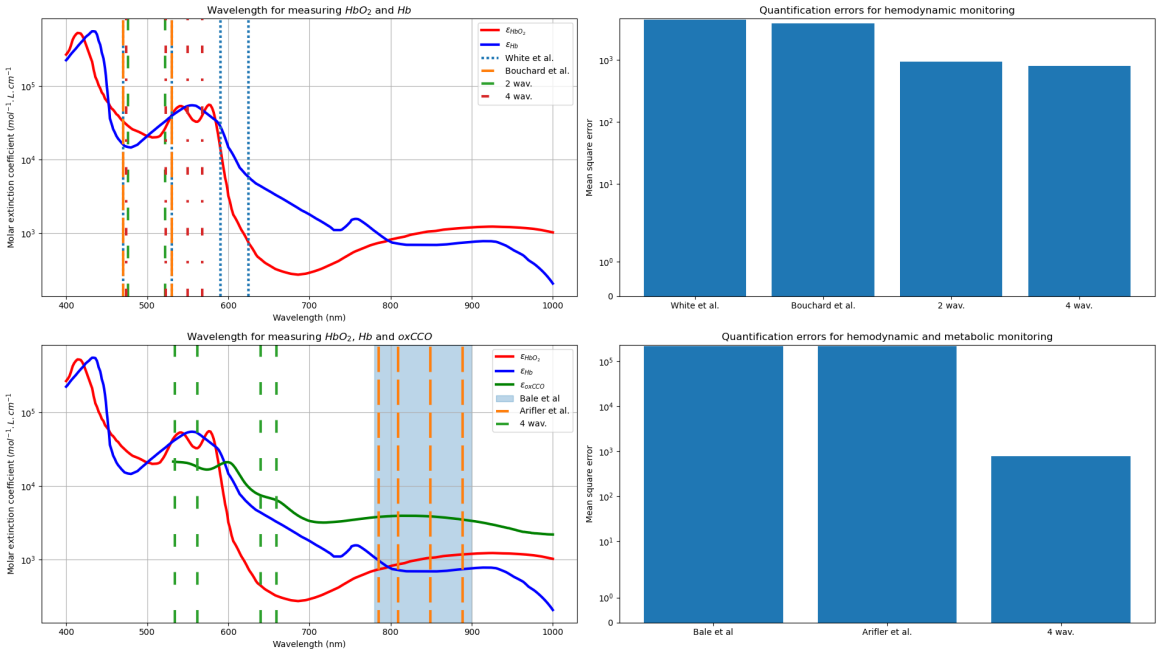

Figure 2. Optimized wavelength for the quantification of hemodynamic and metabolic changes and quantification errors in respect with literature spectral configurations.

4. CONCLUSION

We presented the methodology to design a digital instrument simulator to optimize the development of hyperspectral systems for intraoperative brain mapping studies. This instrument simulator mimicked a realistic brain tissue and modeled the acquisition of retro-diffused light. This simulator can be used to evaluate the robustness and the quantification performance of experimental setups.

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