Pixel-wise and real-time estimation of optical mean path length using deep learning: application for intraoperative functional brain mapping

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ABSTRACT

Optical imaging is a non-invasive technique that is able to monitor hemodynamic and metabolic brain response following neuronal activation during neurosurgery. However, it still lacks robustness to be used as a clinical standard. In particular, the quantification of the biomarkers of brain functionality needs to be improved. The quantification relies on the modified Beer Lambert law, which needs a correct estimation of the optical mean path length of traveled photons. Monte Carlo simulations are used for estimating the optical path length, but it is time-consuming, especially when modeling a patient's brain cortex. In this study, we developed a neural network based on the UNET architecture for a pixel-wise and real-time estimation of optical mean path length. The neural network was trained with segmentation of brain cortex as input and mean path length data as target. This deep learning approach allows a real time estimation of the optical mean path length. 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: Monte Carlo simulations, mean path length, Deep-learning, Digital instrument simular, optical imaging

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. The quantification of the biomarker of brain functionality relies on the modified Beer Lambert law which needs a correct estimation of the optical mean path length of traveled photons. With intraoperative imaging, it is not possible to measure this optical path length, so it is common to use Monte Carlo simulations to estimate it. With this technique, a heterogeneous brain tissue can be modeled with high resolution which allows a pixel-wise estimation of the optical mean path length. However, these simulations are time-consuming, a complete mean path length calculation is obtained in several hours, so these simulations cannot be performed in real-time during neurosurgery.

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In this study, we developed a deep learning pipeline for a pixel-wise and real-time estimation of the optical mean path length during intraoperative functional imaging. The neural network was trained with segmentation of brain cortex as input images and mean path length data as target.

The results can be beneficial and useful within the frame-work of our recently started, EU-funded HyperProbe consortium and project[3,4] which aims at transforming neuronavigation during glioma resection using novel hyperspectral imaging technology.

2. MATERIAL AND METHODS

We used a neural network based on the UNET architecture (with resnet34 as the encoder) for a pixel-wise estimation of optical mean path length. The encoder weights are pre-trained on the imagenet dataset. A mean square error loss was used combined with the Adam optimizer. The neural network was trained with segmentation of brain cortex as input images and mean path length data as target.

The input images were obtained by segmenting an RGB image of a patient's exposed cortex into three classes (grey matter, capillaries and large blood vessels). The segmentation approach was performed with adaptive thresholding and morphological operations. The segmentation maps were then converted into binary maps using the one hot encoding of size $(64, 64, 3)$, see Fig. 1.

The target data are images of mean path length of size $(64, 64, \lambda)$, λ denoting the number of wavelengths (601 wavelengths, between 400 and 1000 nm). These target images were obtained with Monte Carlo simulations (for more information, see the companion abstract: "A digital instrument simulator to optimize the development of hyperspectral systems for intraoperative brain mapping"). 144 data were split in an 80%-20% ratio for model training and validation.

3. RESULTS AND DISCUSSION

The training was performed with 700 epochs reaching by the end of training the loss of 0.085 for the training dataset and 0.127 for the validation dataset, see Fig. 2.

The training process can be improved by using another loss function that takes into account the high frequencies related with the wavelength dependency of the mean path length. In Fig. 3, we represented the estimated pathlengths and the targets for different tissue location.

4. CONCLUSION

We presented the methodology for the pixel-wise and real-time estimation of optical mean path for intraoperative functional imaging studies. This approach can be used to reduce the partial volume effect and to obtain a precise quantification of the biomarker of brain functionality.

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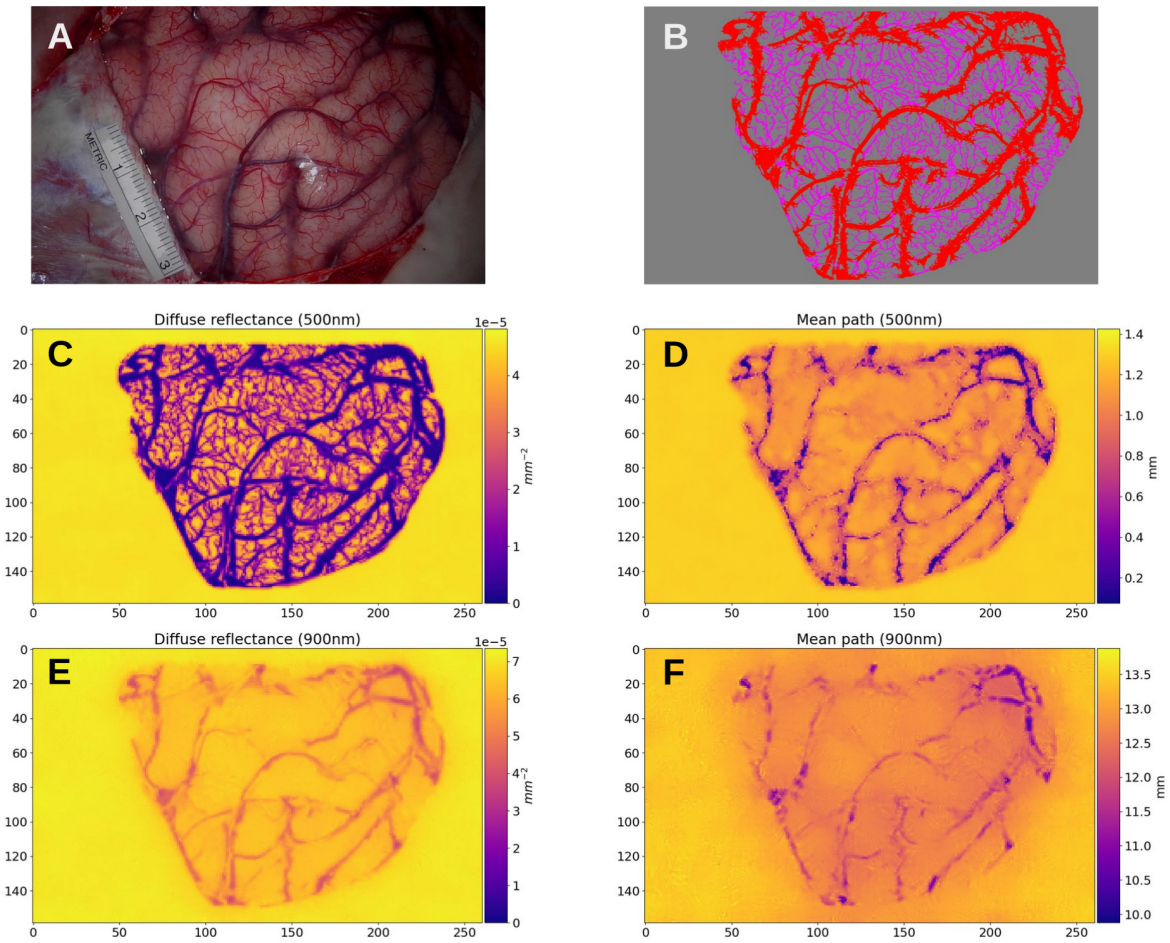

Figure 1. Images obtained with the digital instrument simulator. (A) Input image used to define the classes of the Monte Carlo model (B). (C) Image of intensity at 500 nm. (D) Image of mean path length at 500 nm. (E) Image of intensity at 900 nm. (F) Image of mean path length at 900 nm.

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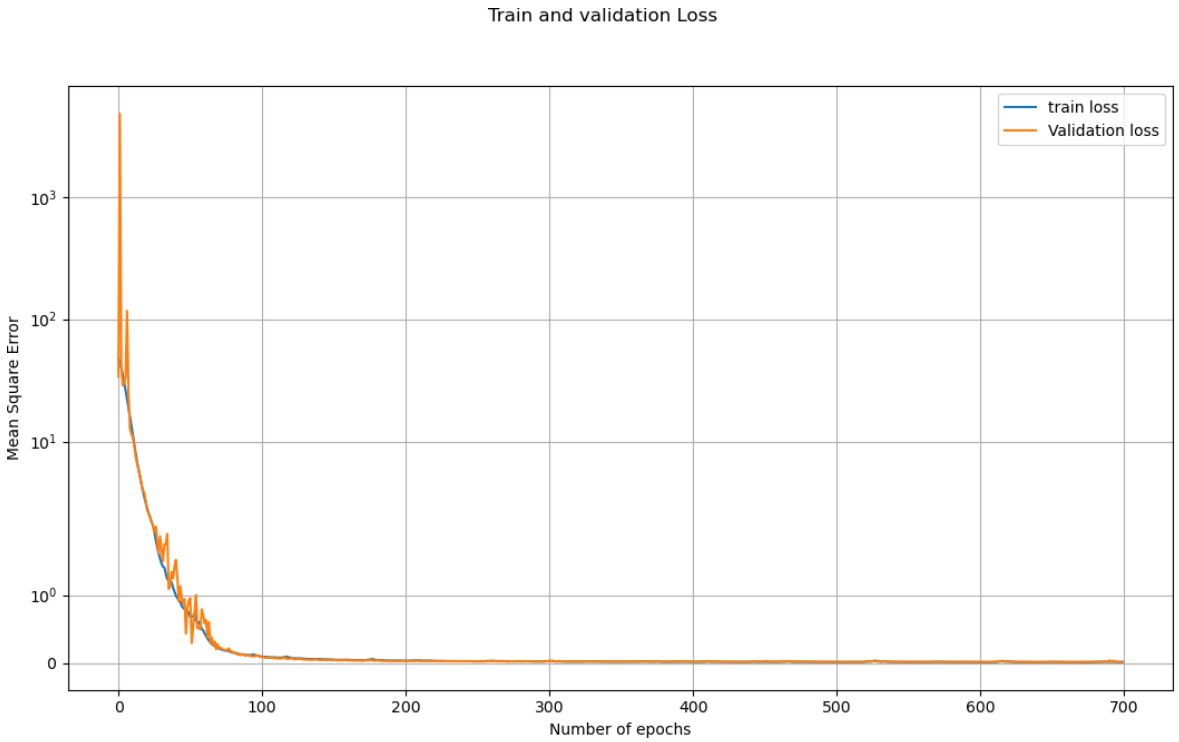

Figure 2. Training and validation loss.

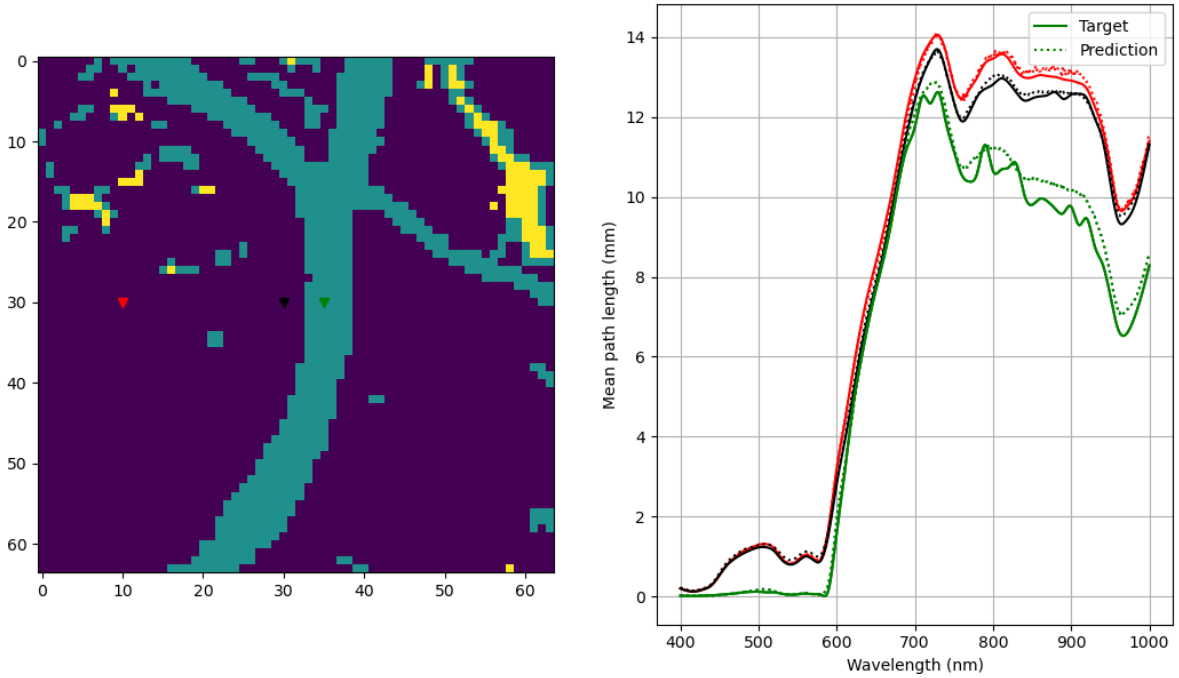

Figure 3. Estimated pathlengths and targets for different tissue location. The indicators in red, black and green indicate grey matter tissue, grey matter close to a large blood vessel and a large blood vessel.