Measurement of placental depth during time domain NIRS using deep learning

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ABSTRACT

MAESTROS is a state-of-the-art in-house developed multi-wavelength time-domain NIRS system. Using NIRS to measure in-vivo placenta oxygenation non-invasively at the bedside could potentially provide valuable insights into the health status of the pregnancy. However, the variable depth of the placenta in the abdomen results in reliability issues for monitoring with NIR. Here, a deep learning model is presented to estimate the placental depth using the Distribution of Time of Flight (DTOF) measurements from the MAESTROS system. The model trained with 108 cases predicted the placental depth in 20 test cases with a mean error of 0.42 cm and a strong statistical correlation between predicted values and the measurements from the ultrasound scans. The model was 100% accurate when identifying the 20% of cases where the placenta is deeper than 3 cm, where the depth is great enough to undermine NIRS. The model could be used to alert TD-NIRS operators early in the acquisition about placental depth or could assist with data cleaning in study analysis. Furthermore, a technique for explainable Artificial Intelligence was applied to provide insight into the features of the DTOF data used by the model to predict placental depth, which were consistent with expectations based on the physics and anatomy of this application.

Keywords: TD-NIRS, Time Domain, Placenta, Depth Sensitivity, Machine Learning, XAI

1. INTRODUCTION

MAESTROS (Metabolism and hAemoglobin Evaluation via a Spectroscopic Time Resolved Optical System) is a state-of-the-art in-house developed multi-wavelength time-domain NIRS system [1] with multiple source to detector distances, capable of monitoring absorption and scattering in multilayer tissue structures. The placenta is an organ of interest because of the relationship placental oxygenation measured by NIRS during pregnancy has with pregnancy and birth outcomes [2]. However, the variable depth of the placenta in the abdomen results in reliability issues for monitoring with NIR. Here, a deep learning model is presented to estimate the placental depth using the distribution of time of flight (DTOF) measurements from the MAESTROS system positioned on the surface of the abdomen.

2. METHODOLOGY

The MAESTROS system [1] uses 4 source-to-detector distances (2,3,4,5 cm). The laser source uses a supercontinuum laser (Fianium/NKT) coupled to an Acousto-Optical Filter (AOTF). Each detector (H-PMT, PMA Hybrid-50P Picoquant) is connected to a multichannel event timer and Time-Correlated Single Photon Counting (TCSPC) device (MultiHarp 150, picoQuant) and measures four different distribution of arrival time of photons (DTOF) from each of the four H-PMTs at 16 NIR wavelengths (equally spaced from 780 to 870 nm). Therefore, the raw DTOF data consists of 64 data channels. For 128 scanned participants, a placental depth label (skin to upper surface of the placenta) was obtained using ultrasound scans segmented for skin, adipose tissue, muscle and placenta (see Figure 1).

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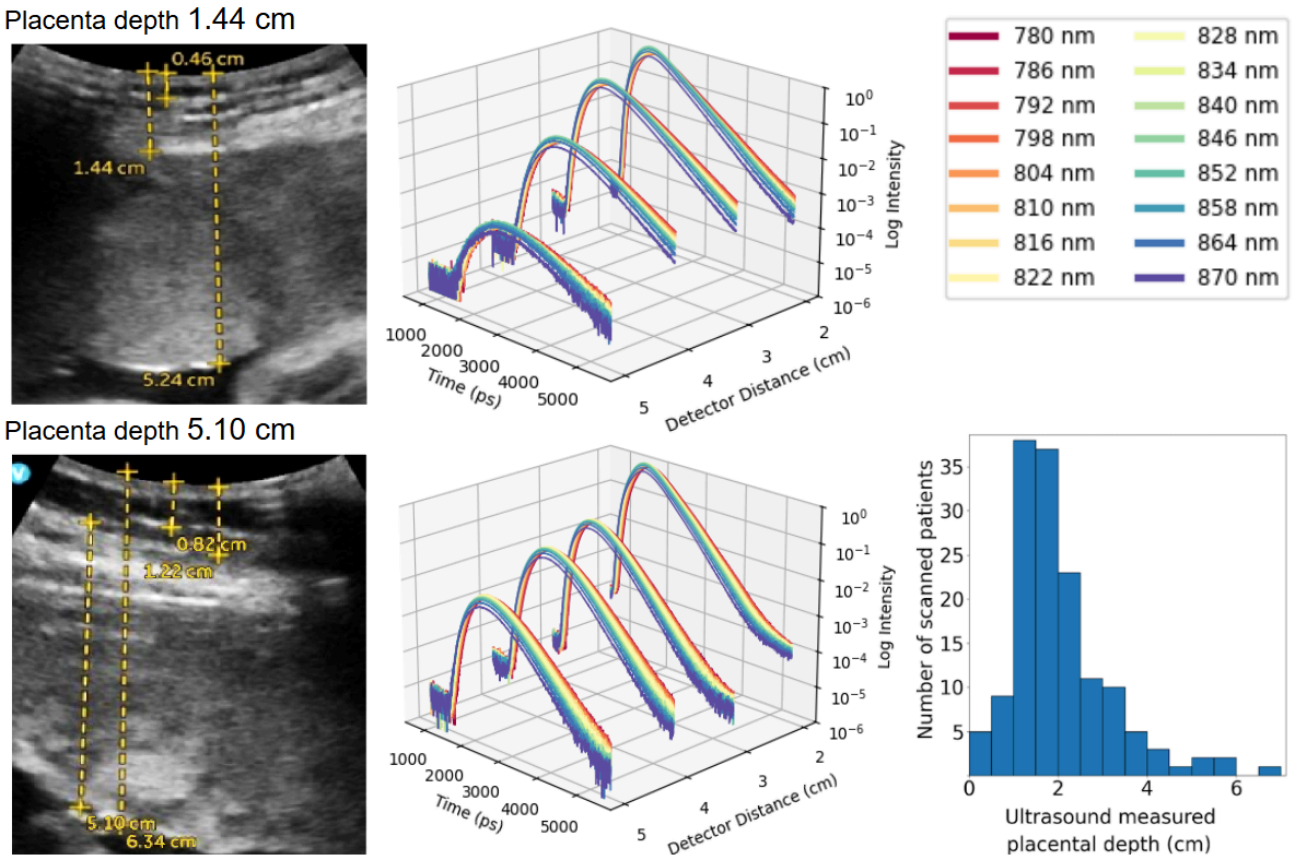

Figure 1: ***Left:*** **The average DTOF measured during a TD-NIRS scan, with 16 wavelengths (color) and 4 source detector distances, next to ultrasound images demonstrating the placental depth in those cases.** ***Bottom Right:*** **The distribution of placental depths according to the ultrasound scans among the 128 participants.**

A 500 MB neural network with two convolutional layers and two fully connected layers was constructed using PyTorch and trained to predict placental depth from the 64 data channels (see Figure 2). The input data was the average of a group of 30 consecutive DTOF time windows (1 to 5 ns), acquired in 60 seconds. Training data augmentation involved adding gaussian noise (s.d. 1% max intensity), random phase shifts in the time domain (s.d. 0.5 ns), and random dropout of 25% of the channels. The cost function was the mean square error between the placental depth measured from the ultrasound scans and the predicted value.

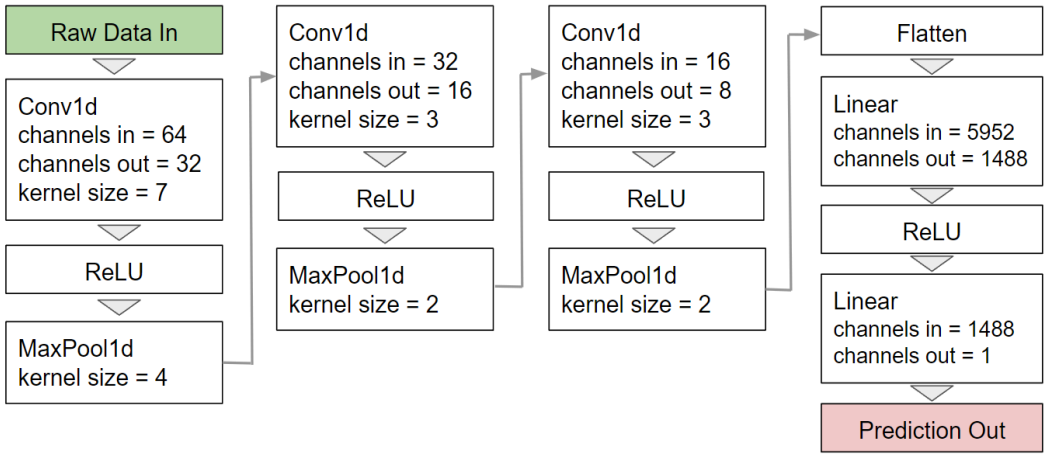

Figure 2: The architecture of the convolutional neural network for regression of placental depth built using PyTorch.

Input gradient-based saliency [3] was applied to explain which features of the DTOF data the trained model uses to predict placental depth. This technique uses backprojection of the trained neural network to quantify how much the output would be changed by variation in each element of each input case. Saliency was visualised by finding the mean absolute saliency for each timepoint and channel across all validation cases.

3. RESULTS

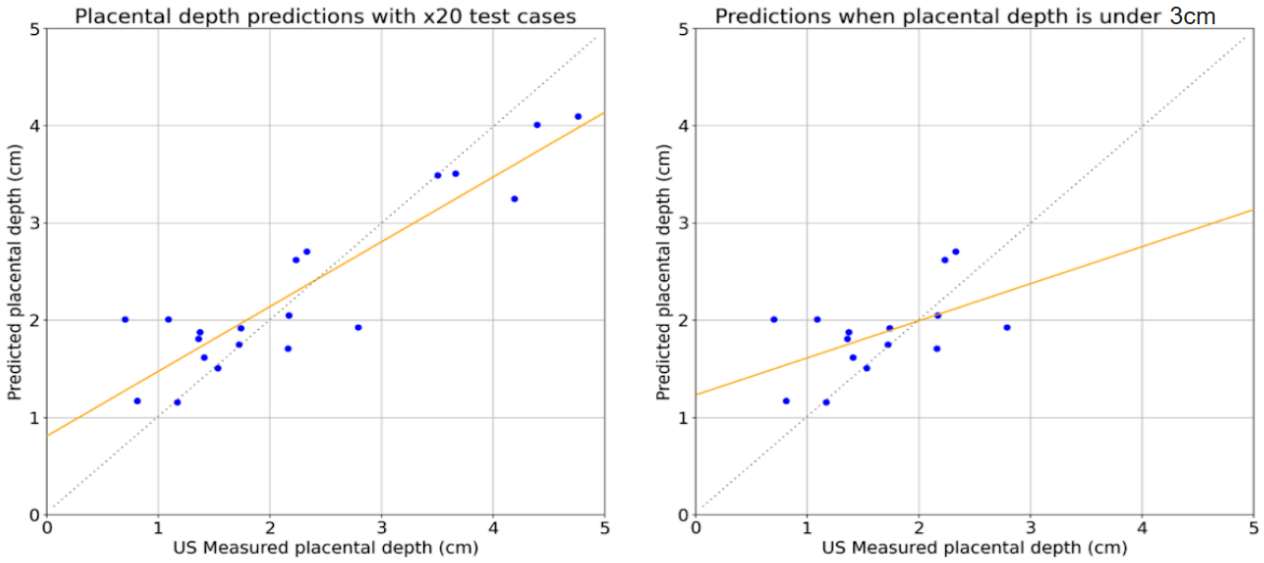

Figure 3: ***Left:*** **The result when the model was applied to unseen test cases data, where the positive correlation between the labeled placental depth and the model prediction shown by the linear fit (orange line) has high significance p<0.0001.** ***Right:*** **The significance of this relationship is weaker at p=0.041 if only cases with placental depth below 3cm are considered.**

The model trained with 108 cases predicted the placental depth in 20 test cases with a mean error of 0.42 cm and a strong statistical correlation between predicted values and the measurements from the ultrasound scans (see Figure 3). However, the correlation becomes much weaker if only the test cases with a placental depth less than 3 cm are considered, where the placenta is close enough to the skin for more reliable NIRS [2][4]. Therefore, the model is likely most useful to identify the minority of cases where the placenta is deeper than 3 cm, which account for 20% of cases in this cohort (see Figure 1). When applied to this classification task, the model is 100% accurate with the test data.

The model explanation analysis (Figure 4) shows that data from the shortest source detector distance (2 cm) has the least salience, which can be expected because the shortest photon diffusion trajectories have the least depth. The last part of the time window (4000-5000 ps) clearly has the strongest salience, representing the late arriving photons which have the deepest diffusion trajectories and so are most likely to interact with the placenta. The longest wavelength channels (840-870 nm) have the strongest saliency, which may be related to the high absorption coefficient of oxygenated hemoglobin in this range and the typically high oxygenation of the placenta compared to other abdominal tissue [5].

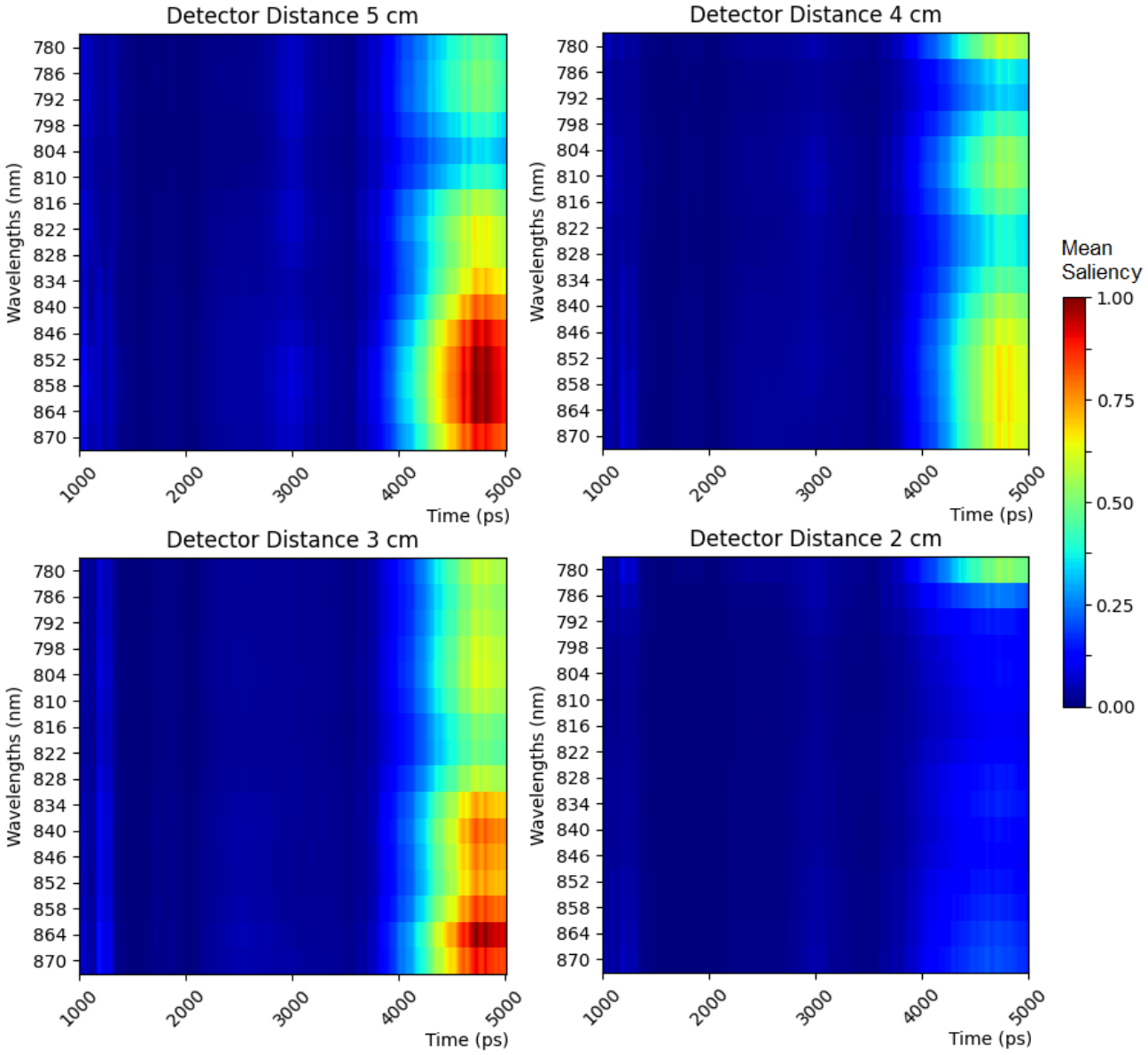

Figure 4: The absolute input gradient-based saliency for the trained model, as the mean across all scans in the validation dataset, normalised from 0 to 1. The quadrants represent the four source-detector distance, each showing the salience of each time point in the input DTOF time window for each wavelength.

4. CONCLUSION

The model could be used to alert TD-NIRS operators early in the acquisition about placental depth. It can reliably classify placenta depth above 3cm. It could be used as a data cleaning tool for study analysis and also provide a sensitivity to placenta metric for data quality checking. In further work, the model is likely to become capable of predicting placental depth more precisely as more training data is acquired. When greater precision is combined with simultaneous prediction of the thickness of the other tissue layers, the requirement for the ultrasound scan preceding TD-NIRS could be removed. The model's architecture may also be part of a classifier for pregnancy complications to be developed in future work, allowing the raw data to be combined with physiological features in the processed data.

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