Theoretical and Experimental Investigation of the Influence of Frontal Sinus on the Sensitivity of the NIRS Signal in the Adult Head

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Abstract The sensitivity of the near-infrared spectroscopy signal to the brain activation depends on the thickness and structure of the superficial tissues. The influence of the frontal sinus, which is void region in the skull, on the sensitivity to the brain activation is investigated by the time-resolved experiments and the theoretical modelling of the light propagation in the head. In the time-resolved experiments, the mean-time of flight for the forehead scarcely depends upon the existence of the frontal sinus when probe spacing was shorter than 30 mm. The partial optical path length in the brain, which indicates the sensitivity of the near-infrared spectroscopy signal to the brain activation, in a simplified head model is predicted by Monte Carlo simulation. The influence of the frontal sinus on the sensitivity of the signal depends on the thickness of the skull and the depth of the frontal sinus.

1 Introduction

In near infrared spectroscopy (NIRS) and imaging of brain activation, the source and detection probes are attached onto the scalp, requiring the light to pass through the superficial layers such as scalp, skull, and subarachnoid space filled with cerebrospinal fluid (CSF) both before and after passing through the brain tissue. The heterogeneity of the tissue in the head, especially the low-scattering subarachnoid space has been previously shown to have a strong effect on light propagation in the brain i.e. the sensitivity of the NIRS signal [1]. The frontal sinus in the skull is a non-absorption and non-scattering (void) region. The existence of the frontal sinus is likely to affect the light propagation in the brain. In this study, the mean optical path length in the head and the partial optical path length in the brain are obtained by the time-resolved experiment

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and Monte Carlo simulation to investigate the influence of the frontal sinus on the sensitivity of the NIRS signal to the brain activity.

2 Methods

2.1 Time-Resolved Experiments

The temporal point spread functions (TPSFs) of the forehead of two volunteers were measured by the time-resolved experiment system (TRS-20, Hamamatsu). Figure 1 shows the probe positions of the time-resolved experiments for a volunteer. Each number in the figure indicates the midpoint of the source and detector probes. The probes were attached on the scalp with and without the frontal sinus below. The probe spacing was varied from 22.5 to 37.5 mm. The mean optical path length in the head was calculated from the TPSF.

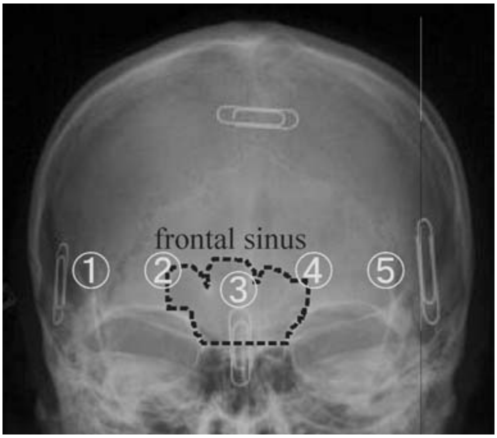

Fig. 1 Probe positions for the time-resolved experiment. The numbers indicate the midpoints of the source and detector probes. The broken line indicates the frontal sinus

2.2 Modelling of the Light Propagation in the Head Model

The light propagation in the simplified head model was calculated to analyse the influence of the frontal sinus on the mean optical path length in the head and on the partial optical path length in the brain. The mean optical path length in the head can be obtained from the TPSF measured by the time-resolved experiment whereas the partial optical path length in the brain cannot be directly obtained from the experimental results. The cross-section of the head model is shown in Fig. 2. The head model consisted of the scalp, skull, subarachnoid space, grey matter and white matter. The optical properties (transport scattering coefficient m_s' and absorption coefficient m_a) of each layer for 780-nm wavelength shown in Table 1 were chosen from the reported data [2–5].

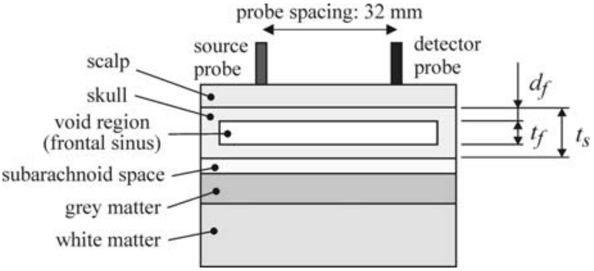

Fig. 2 An adult head model with a void region mimicking the frontal sinus for the estimation of mean optical path length in the head and partial optical path length in the brain

Table 1 The thickness and the optical properties of the head models

Tissue type	Thickness [mm]	μ_s' [mm^{-1}]	μ_a [mm^{-1}]
Scalp	3	1.0	0.02
Skull	7 ~ 21	0.8	0.016
Subarachnoid space	2	0.319	0.0044
Grey matter	4	2.26	0.036
White matter	20	9.25	0.016

The void rectangular region was placed in the skull to mimic the frontal sinus. The depth of the void region d_f, thickness of the skull t_s and void region t_f were varied to evaluate the influence of the frontal sinus on the light propagation in the brain. Reflection and refraction caused by the refractive index mismatch was considered only at the boundary between the scalp and the air. The light propagation in the head model was predicted by Monte Carlo simulation to obtain the mean optical path length in the head and the partial optical path length in the brain for the probe spacing of 32 mm.

3 Results and Discussion

The measured TPSFs of a volunteer for the probe spacing of 37.5 mm at positions 3 and 5 are shown in Fig. 1 and the input pulses are shown in Fig. 3(a). The wavelength of the pulsed laser was 760 nm. The mean time of flight for the forehead with the frontal sinus below (position 3) is shorter than that without the frontal sinus (position 5). The mean optical path length calculated from the TPSFs as a function of probe spacing at each position is shown in Fig. 3(b). The mean-time of flight scarcely depends upon the existence of the frontal sinus when probe spacing was shorter than 30 mm. The mean optical path length for the forehead with the frontal sinus (position 2 and 3) was shorter than that without the frontal sinus when probe spacing was 37.5 mm. The influence of the frontal sinus on the TPSFs of other volunteer was not significant. The influence of the frontal sinus on the light propagation in the head differs among individuals.

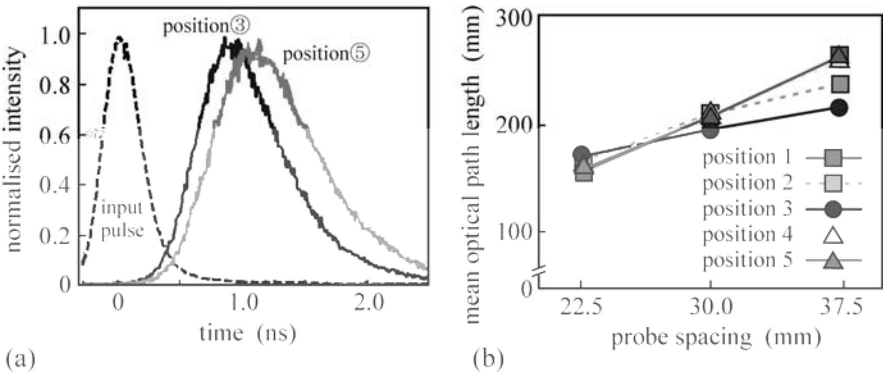

Fig. 3 (a) The TPSFs of human forehead measured by the time-resolved experiments. (b) The mean optical path length calculated from the TPSFs

The mean optical path length and the partial optical path length in the brain for the head models with and without a void region mimicking the frontal sinus as a function of skull thickness are shown in Fig. 4(a). The void region was located at an intermediate depth into the skull and the thickness of the void region was a third of the skull thickness. The mean optical path length in the head with the frontal sinus is shorter than that without the frontal sinus when the thickness of the skull is 7 or 14 mm as shown in Fig. 4(a). The frontal sinus does not affect the mean optical path length in the head model with a 21-mm thick skull. The partial optical path length in the brain, which is the sensitivity of the NIRS signal to the brain activation, decreases with an increase in skull thickness. The partial optical path length is decreased by the influence of the frontal sinus when the skull thickness of the model was 7 mm whereas the partial optical path length is slightly increased when the skull thickness was 14 or 21 mm.

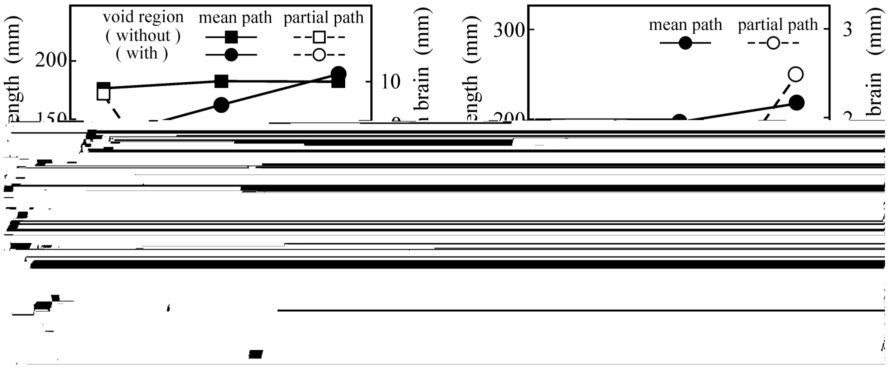

Fig. 4 Effect of skull thickness on the mean optical path length in the head and the partial optical path length in the brain

The influence of the depth of the frontal sinus on the light propagation in the head is shown in Fig. 4(b). The depth of the void region, d_f, was altered but the thickness of the skull and of the void region were held constant at 21 and 9 mm, respectively. In the case where the void region is placed in the shallow region ($d_f = 2$ mm), the light tends to propagate in the shallow region of the skull. Both the mean optical path length in the head and partial optical path length in the brain are decreased by the influence of the frontal sinus. In the case where the void region is placed in the deep region ($d_f = 10$ mm), the light tends to propagate in the deeper region of the skull. The partial path length in the brain is increased by the influence of the frontal sinus whereas the mean optical path length in the head is scarcely changed by the influence of the frontal sinus. The penetration depth, which relates with the sensitivity of the NIRS signal to the brain activation, increases with an increase in the depth of the frontal sinus. The influence of the frontal sinus on the partial optical path length in the brain is more significant than that on the mean optical path length in the head.

4 Conclusions

The mean optical path length of the forehead and the partial optical path length in the brain are obtained by the time-resolved experiments and the modelling of the light propagation in the head to investigate the influence of the frontal sinus on the sensitivity of the NIRS signal to the brain activation. The theoretical analysis reveals that influence of the frontal sinus on the light propagation in the head depends on the thickness of the skull and the depth of the frontal sinus. In the practical brain-function measurements, the amplitude of the NIRS signal reflects the influence of the frontal sinus. The influence of the frontal sinus on the partial optical path length in the brain, i.e. the sensitivity of the NIRS signal to the brain activation, is more significant than that on the mean optical path length in the head. The change in partial optical path length caused by the influence of the frontal sinus cannot be directly deduced from the mean optical path length in the head obtained from the time-resolved experiments. In the experimental analysis, the influence of the frontal sinus on the mean optical path length varies between individuals. Although the difference might be caused by the depth of the frontal sinus, the TPSF measurements in this study were made in two volunteers. It is difficult to draw any conclusions about the influence of the frontal sinus on the TPSF from the experimental results and further TPSF measurements are needed for systematic discussion.

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