The effect of overlying tissue on NIR light propagation in neonatal brain

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1. INTRODUCTION

Near infrared spectroscopy (NIRS) is now widely used for cerebral oxygenation monitoring in both the adult [1,2] and neonate [3,4]. However inhomogeneity of the head causes great problems in quantifying the NIRS data and estimating the spatial sensitivity profiles [5] which indicate the volume of tissue interrogated. In order to solve these problems, it is essential to investigate the effect of the overlying surface tissues of head on the light propagation in the brain. We initially investigated light propagation in an adult head using layered slab models and demonstrated that the layered structure, and especially the clear cerebrospinal fluid (CSF) layer affect the spatial sensitivity profiles [6].

Since the diameter and optical properties of a neonatal head are obviously different from those of the adult head, we need a different model incorporating the curvature of the head in order to investigate the light propagation in a neonatal head. In this study the effect of the presence of the surface tissue and its geometry on light propagation in the neonatal head has been investigated using cylindrical models which consist of multiple layers with different optical properties.

2. MODEL AND METHOD

Two different neonatal head models have been designed consisting of either four or five separate homogeneous media as shown in Figure 1. The model is a concentric cylinder of 80 mm in diameter. The four layered model (a) contains a scalp layer of 1.5 mm thickness, a skull layer of 1.5 mm thickness, a grey matter layer of 2.5 mm thickness and a central white matter layer. The more sophisticated head model (b) contains an added CSF layer of 1 mm between the skull layer

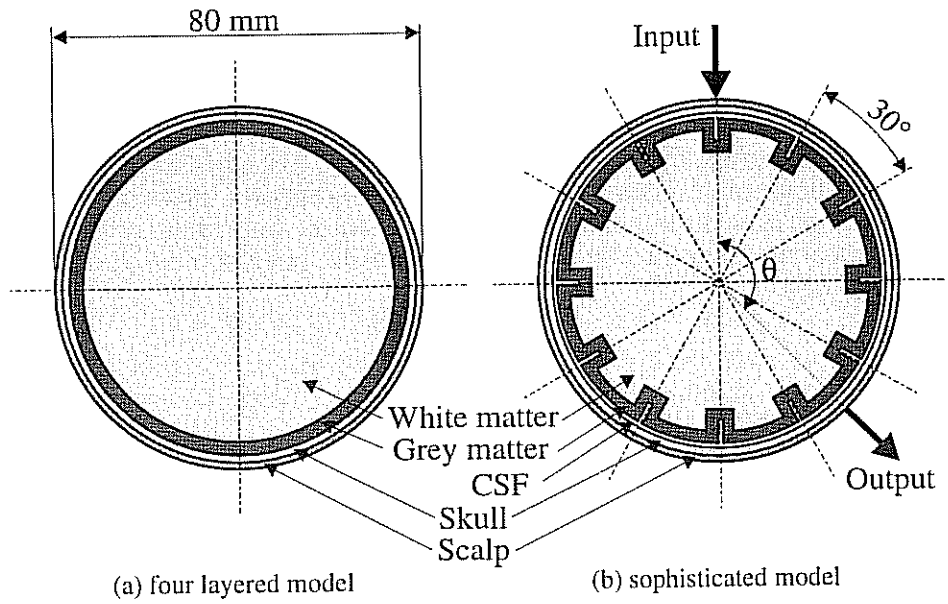


Fig. 1 Model design.

and grey matter layer, the thickness of the other layers being the same as for the four layered model. In addition, slots of 1 mm in width and 5 mm in depth imitating the sulci in the CSF layer are added every 30 degree and hence the boundary between the grey and white matter is uneven at these positions. The thickness of each layer and the overall geometry of the sulci and grey matter have been chosen on the basis of data from an MRI image of a neonatal head. The optical properties for the layers were chosen on basis of the reported data on the optical properties of tissue [7-9]. The optical properties for the scalp are $\mu_s' = 2.5$ mm^{-1}, $\mu_a = 0.25$ mm^{-1}; for the skull $\mu_s' = 2.0$ mm^{-1}, $\mu_a = 0.015$ mm^{-1}; for the CSF $\mu_s' = 0.01$ mm^{-1}, $\mu_a = 0.001$ mm^{-1}; for the grey matter $\mu_s' = 0.5$ mm^{-1}, $\mu_a = 0.025$ mm^{-1}; and for the white matter $\mu_s' = 1.0$ mm^{-1}, $\mu_a = 0.015$ mm^{-1}.

Photon propagation in each model was calculated by a Monte Carlo method using the variance reduction technique [10-13]. Photons which have unit weight are injected into the model one-by-one and the individual photon history is traced. In the case of the more sophisticated head model, the photon is injected just over the centre of a slot. The propagation of a photon in each layer is determined by the transport scattering coefficient μ_s' and random numbers. If a photon crosses the boundary between different layer, the distance to the next scattering event is corrected using the transport scattering coefficient in the subsequent layer. Reflection and refraction of light on the surface of the model are taken into account. When the photon is scattered out of the model, the weight of the photon at the detector is calculated from the absorption coefficient μ_a and partial pathlength in each layer. A complete history of the photon propagation is stored when the photon reaches particular detection optodes. The histories of the photon paths are weighted by their output values and are transcribed onto a matrix for calculating the spatial sensitivity profiles. The histories of 5 million photons were traced, then the mean optical pathlength at various detection angle and the spatial sensitivity profiles were calculated.

3. RESULTS AND DISCUSSION

The Monte Carlo predictions for the total mean optical pathlength are shown in Figure 2. The optical pathlengths for both models are almost same when the detection angle is less than 15°. When the detection angle is greater than 15°, the optical pathlength for the sophisticated model with a clear CSF layer is smaller than that in the simpler four layered model. Although the predicted results contain considerable errors caused by poor statistics, the differences in the optical pathlengths between the models at detection angles of over 120° are relatively smaller than for smaller detection angles from 15° to 120°. This result indicates that the clear CSF layer and its geometry considerably affect the optical pathlength when the detection angle is between 15° and 120°.

The spatial sensitivity profiles for both the four layered and the sophisticated models at a detection angle of 75° (i.e. at an optode spacing of 52 mm) are shown in Figures 3 (a) and 3 (b). The difference in the spatial sensitivity profiles between the models is at its most significant at about this detection angle. In the four layered model, the spatial sensitivity profile penetrates deeply into the white matter. However the spatial sensitivity profile of the more sophisticated model is obviously distorted and the light mainly follows the boundary of the clear CSF layer. Little penetration into the white matter can be observed and the sensitive area is confined to the grey matter. These results indicate that the CSF layer obviously works as a conduit for the light, and hence is responsible for the reduction in the mean optical pathlength at this detection angle. At smaller detection angles the spatial sensitivity profiles of both models tend to be confined to the surface layers and grey matter. Conversely, the spatial sensitivity profiles are distributed around the chord joining the source and detection positions at large detection angles of over 120°. In NIRS measurements on neonates the optode spacing is usually set around 50 mm. These results indicate that under these circumstances the change in the NIRS signal will depend mainly on the absorption changes in the grey matter.

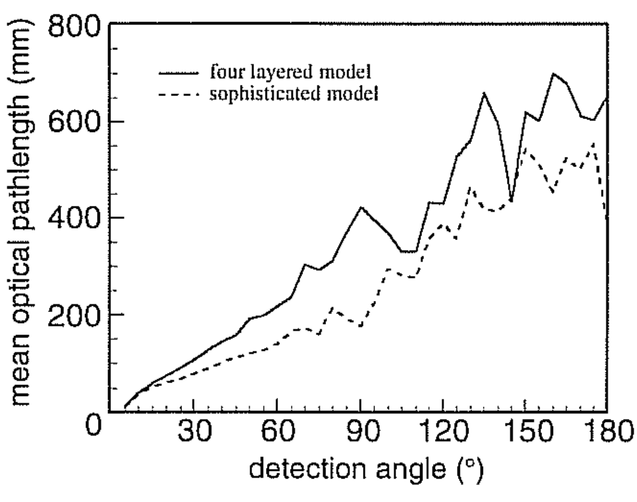
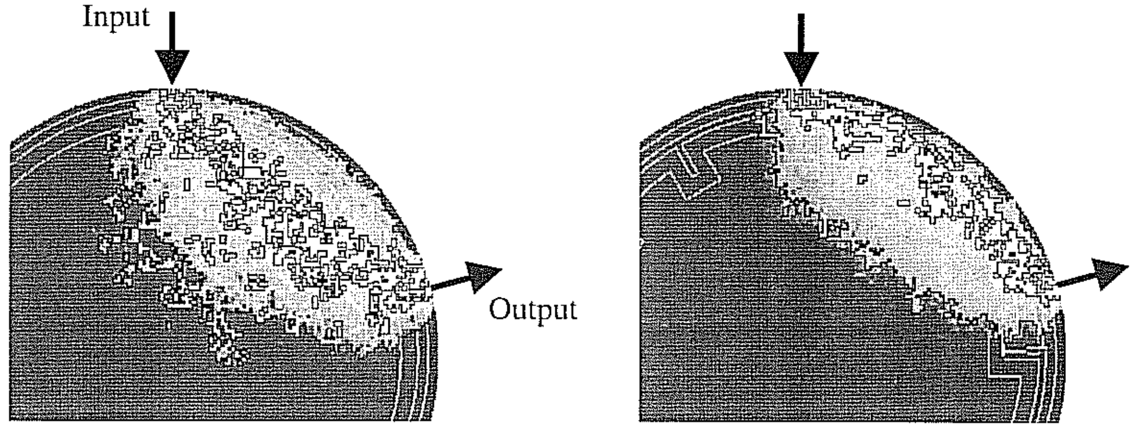


Fig. 2 Total optical pathlength as a function of detection angle estimated from Monte Carlo simulation.



(a) four layered model (b) sophisticated model

Fig. 3 Spatial sensitivity profiles at a detection angle of 75° (optode spacing of 53 mm)

4. CONCLUSIONS

In this study the effect of the layered surface tissues on light propagation in the neonatal head has been investigated by Monte Carlo prediction. The clear CSF layer significantly affects the light distribution when the detection angle is between 15° and 120°. The light mainly follows the boundary of the CSF layer and hence the volume of tissue interrogated is largely confined to the grey matter layer.

5. REFERENCES

1. O.Hazeki, A.Seyama and M.Tamura, "Near infrared spectrophotometric monitoring of haemoglobin and cytochrome aa3 in vivo", Adv. Exp. Med. Biol. **215**, pp. 283-289, 1987.
2. M.Ferrari, E.Zanette, I.Giannini, G.Sideri, C.Fieschi and A.Carpi, "Effect of carotid artery compression test on regional cerebral blood volume, haemoglobin oxygen saturation and cytochrome -c- oxidase redox level in cerebrovascular patients", Adv. Exp. Med. Biol. **200**, pp. 213-222, 1986.
3. J.S.Wyatt, D.T.Delpy, M.Cope, S.Wray and E.O.R.Reynolds, "Quantification of cerebral oxygenation and haemodynamics in sick newborn infants by near infrared spectrophotometry", Lancet **2** 1063-1066, 1986
4. A.D.Edwards, G.C.Brown, M.Cope, J.S.Wyatt, D.C.McCormick, S.C.Roth and D.T.Delpy, "Quantification of concentration changes in neonatal human cerebral oxidized cytochrome oxidase", J.Appl.Physiol., **71**, 1907-1913, 1991
5. E.Okada, M.Firbank and D.T.Delpy, "The effect of overlying tissue on the spatial sensitivity profile of near infrared spectroscopy", Phys.Med.Biol., **40**, 1995 [in press]
6. E.Okada, M.Firbank, M.Schweiger, S.R.Arridge, M.Cope and D.T.Delpy, "A theoretical and experimental investigation of the effect of sulci on light propagation in brain tissue", Proc. EOS/SPIE **2626**, 1995 [in press]
7. W.F.Cheong, S.A.Prahl and A.J.Welch, "A review of the optical properties of biological tissues", IEEE J.Quantum Electron., **QE-26**, pp. 2166-2185, 1990.
8. P.van der Zee, M.Essenpreis and D.T.Delpy, "Optical properties of brain tissue," Proc.SPIE **1888**, pp. 454-465 (1993).
9. M.Firbank, M.Hiraoka, M.Essenpreis and D.T.Delpy, "Measurement of the optical properties of the skull in the wavelength range 650-950," Phys.Med.Biol., **38**, pp. 503-510, 1993.
10. M.Hiraoka, M.Firbank, M.Essenpreis, M.Cope, S.R.Arridge, P.van der Zee and D.T.Delpy, "A Monte Carlo investigation of optical pathlength in inhomogeneous tissue and its application to near-infrared spectroscopy", Phys. Med. Biol., **38**, pp. 1859-1876, 1993.
11. B.C.Wilson and G.Adam, "A Monte Carlo model for the absorption and flux distributions of light in tissue", Med. Phys. **10**, pp. 824-830, 1983.
12. P.van der Zee and D.T.Delpy, "Simulation of the point spread function for light in tissue by a Monte Carlo technique", Adv. Exp. Med. & Biol. **215**, pp. 179-191, 1987.
13. M.S.Patterson, B.C.Wilson, D.Wyman,"The propagation of optical radiation in tissue I. Models of radiation transport and their application," Lasers in Med. Sci. **6**, pp. 155-168, 1990.