Measurement of the Optical Properties of Tissues by a Minimally-Invasive Probe

Bevilacqua F., Piguet D., Marquet P., Depeursinge Ch.

Institut d'Optique Appliquée, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland.

ABSTRACT

A small probe (Ø = 2 mm) was designed to measure locally the optical properties of biological tissues. The sensitivity of the measured signal was assessed by experiments on microsphere suspensions and Monte Carlo simulations. Relative measurements of scattering and absorption coefficients should give local metabolic and tissue structure informations.

INTRODUCTION

Measuring the optical properties of biological tissues is a useful task for several medical applications. For example accurate optical coefficients are necessary for near infrared imaging or for dosimetry in photodynamic therapy. Moreover, the optical properties could also help, in particular cases, to differentiate directly normal and malignant tissues [1]. In such cases, probing locally the optical properties is a promising tool for mini-invasive surgery.

Photon migration in tissues is governed by scattering and absorption. Therefore the important optical parameters of tissues are the absorption coefficient μ_a, the scattering coefficient μ_s and the phase function $p(\cos\theta)$. The phase function is the density probability function for the scattering angle θ. The first moment of $p(\cos\theta)$, denoted g, is the mean cosine of θ. Generally, g varies in tissues between 0.7 to 0.99, which means that light is mainly scattered in the forward direction. It is also useful to define the reduced scattering coefficient $\mu_s' = \mu_s(1-g)$, as explained later.

The scattering properties depend on the tissue structure: cell density and size, organelles density and size, etc. Therefore different types of tissues can be characterized by their scattering properties (μ_s', $p(\cos\theta)$).

The absorption coefficient in tissues is related to the concentration of chromophores such as haemoglobin or cytochrom. Since the absorption spectra of haemoglobin changes with its oxygenation state, measurements of μ_a at different wavelengths allow the determination of the tissue blood content and haemoglobin oxygen saturation, which are important metabolic indicators.

The probe described here allows local measurements of the optical properties in vivo. The method is based on spatially resolved measurements of the reflectance. Similar methods have been reported previously [2], but using measurement of the reflectance over large distances (typically >1 cm) compared to the transport mean free path $mfp' = (\mu_s' + \mu_a)^{-1}$. In our case we measure the reflectance close to the light source (< 2mm) in order to use a relatively small diameter probe (2.2 mm) and to perform local measurements.

MATERIAL AND METHOD

The probe, sketched in Fig. 1, is a a linear array of optical fibres (core diameter of 200 μm, N.A.=0.37). Two fibres, coupled to laser diodes emitting at 670 nm and 820 nm, can be alternatively used to illuminate the tissue. Six other fibres are used to collect the scattered light, and are imaged on a linear Charge-Coupled-Device (CCD). The illuminating are slid in small stainless tubes in order to avoid direct coupling with the collecting fibres. The bundle is set in a stainless tube of 2 mm diameter and 20 cm long. The probe is rigid, which allows an easier handling by the physician. However a flexible probe is also feasible for endoscopic application. The whole probe can be sterilized.
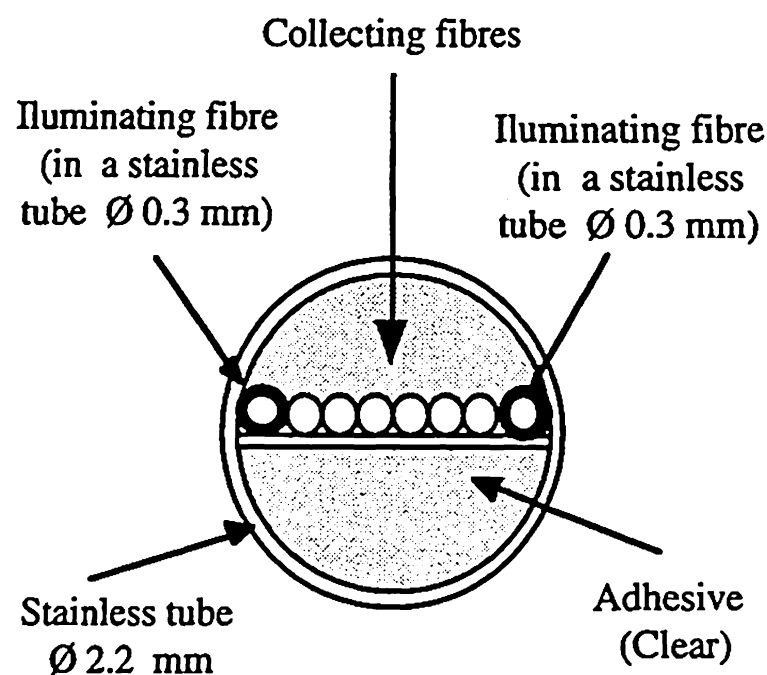

Fig. 1. Measuring probe

THEORY

A model of photon migration in tissues is necessary to explicit the relationship between the measured reflectance and the optical properties. We performed Monte Carlo simulations [3], which give indirectly exact solutions of the transport theory. Analytical solutions from the diffusion equation are not appropriate in our case because we are interested in the reflectance close to the source, at distance comparable to the transport mean free path mfp'.

Our simulations take into account the exact diameter of the illuminating and collecting fibres, as well as their numerical apertures.

The reflectance depends on μ_s, μ_a and $p(\cos\theta)$. Far from the source (d>> mfp') only the first moment g of the phase function plays a role, and the reflectance depends only on two parameters: μ_a and μ_s'. These two parameters are usu-
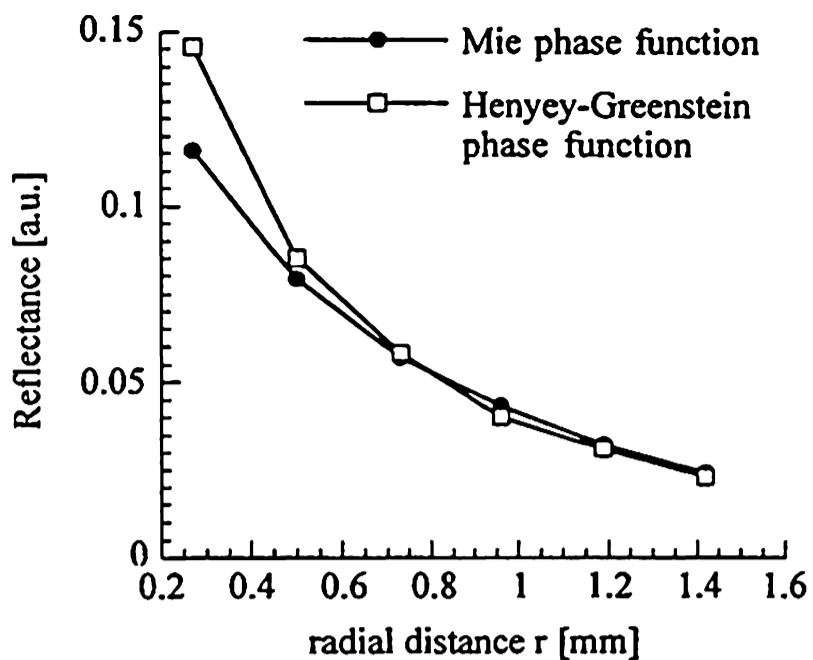
Fig. 2. *Reflectance from simulations. The dots represent the intensity collected by the six fibres. g=0.92, $\mu_a=0.06$ mm^{-1}, $\mu_s'=1$ mm^{-1}*

ally used to characterize a given tissue. Close to the source (d ≈ mfp') higher moments of the phase function also play an important role. This is illustrated in Fig. 2, where a simulation of a probe reflectance measurement is plotted as a function of the radial distance r, using two different phase functions, with the same first moment g=0.92. The first one is the Henyey-Greenstein phase function, very often used in tissue modelling. The second one is the phase function obtained from Mie theory, corresponding to the microspheres used in the experiments described below. The important difference shown in Fig.2 between the two curves for radial distance < 0.5 mm, is explained by the role of the second and higher order moments, different for each phase function.

A complete analysis of light propagation close to the source, taking into account the importance of the phase function is under investigation. It will yield an optimized way to analyse the curve measured, in order to minimize the artefact due to the imprecisely known phase function of the investigated tissue.

PRELIMINARY RESULTS AND DISCUSSION
The sensitivity of the probe has been experimentally tested using polystyrene microsphere suspensions (∅ = 1 μm). Mie theory allows to compute p(cosθ) and μ_s of the suspension. The absorption is assumed to be equal to the water absorption. Absorption can be increased when ink is added. The ink absorption coefficient of the ink has been previously calibrated as a function of the concentration.

In Fig. 3 and 4, measured signals are shown for suspensions of different microsphere concentrations and ink concentrations. The corresponding μ_s' and μ_a are in the range of standard optical properties of biological tissues. Fig. 3 and 4 clearly show that, as expected, the average measured intensity increases if μ_s' increases or μ_a decreases. The slope of the logarithm of the reflectance increases if μ_s' increases. However the slope is only slightly affected by μ_a. This observation is only valid close to the source. This shows that absolute intensity measurements is then

necessary to extract μ_a from the measured curve. Significant systematic errors could then appear if the role of the phase function is not properly taken into account, as discussed before. Nevertheless a relative measurement of μ_a is still possible. In particular a spectroscopic analysis of the measured signal could give important informations about the metabolism of the investigated tissues.
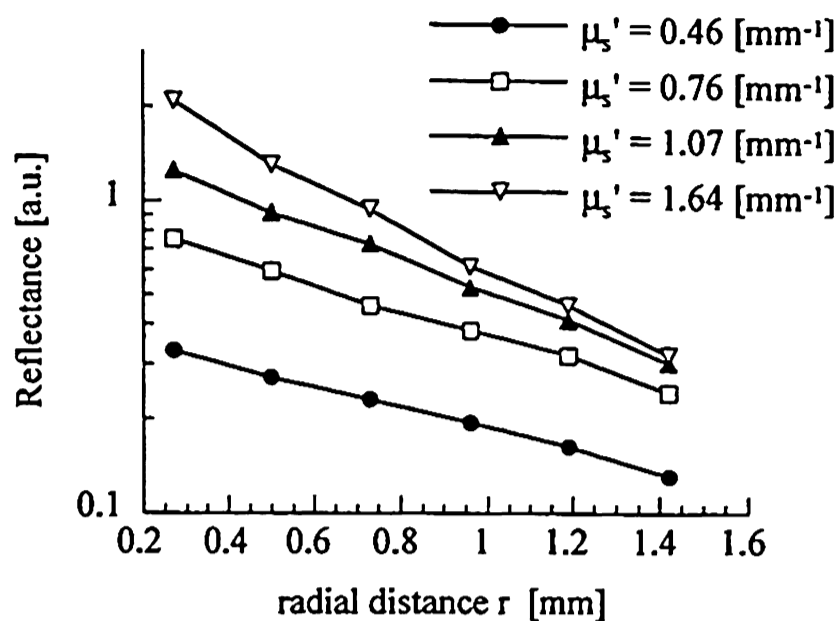

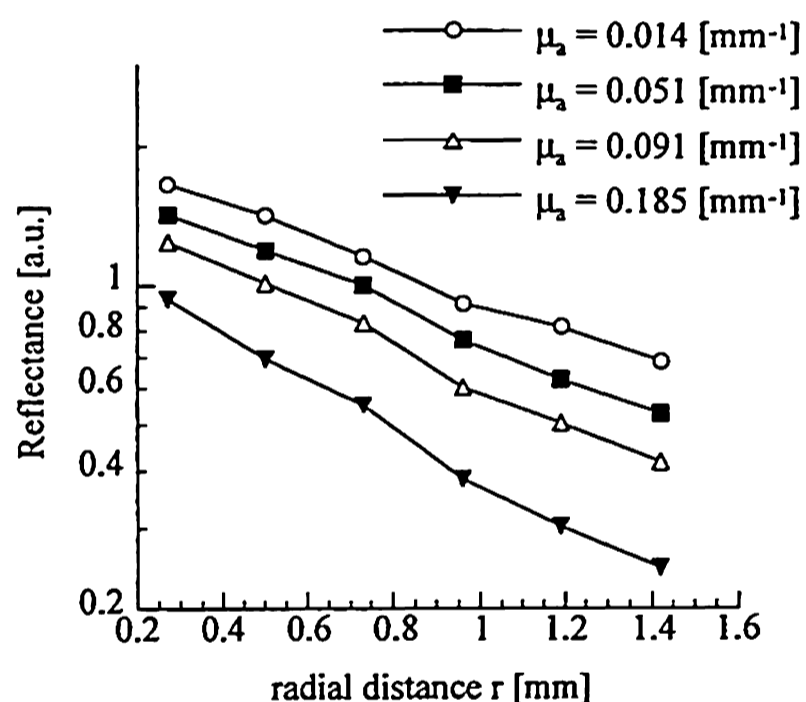Fig.3. *Reflectance measured on microsphere suspensions. g=0.92, $\mu_a=0.0005$ mm^{-1}, $\lambda=670$ nm.*

Fig.4. *Reflectance measured on microsphere suspensions (+ink). g=0.92, $\mu_s'=0.5$ mm^{-1}, $\lambda=670$ nm.*

CONCLUSION
This preliminary study shows that the probe gives important local informations about the scattering and absorption properties of biological tissues. Clinical assessment of the probe is planned.

REFERENCES
[1] J. R. Mourant et al.; Lasers. Surg. Med. 17, 350, (1995).
[2] See T. J. Farrell et al.; Med. Phys. 19, 879 (1992) and the references therein.
[3] P. Marquet et al.; Opt. Eng. 34, 2055, (1995).