Monte Carlo simulation of the source-detector distance effect on near infrared spectroscopic measurements of subcutaneous adipose tissue in pig carcasses

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Introduction

There is a growing interest in moving from at-line near infrared (NIR) spectroscopic applications (laboratory analysis) to online, in situ and in-field applications. Measurements taken through the skin of animals are an ideal implementation of NIR spectroscopic analysis in the livestock industry due to the ease and speed of data collection. Pérez-Marín et al.[1] evaluated the performance of models developed with spectra taken through the skin of Iberian pig carcasses at the slaughter house and found that models were slightly less accurate than those obtained at-line with free-skin intact adipose tissue measurements. Source-detector distance can significantly affect the sampling region and light penetration path.[2] The optimal source-detector distance can maximise the sensitivity of the spectra measurements to the target layer (subcutaneous adipose tissue), although to measure subcutaneous adipose tissue through skin NIR light has to travel through epidermis and dermis. Understanding the light-tissue interaction is, therefore, relevant for fine-tuning existing commercial instruments, developing new instruments, and for obtaining better measurements. This study reports the relationship between the light penetration depth and source-detector distance on the NIR spectroscopic measurements of subcutaneous adipose tissue through pig skin by numerical simulation.

Materials and Methods

A Monte Carlo method was used for simulating the dependence of light penetration depth on the source-detector distance. This method has been widely used in strongly scattering media such as human skin tissue.[3] Different input parameters have to be known: refractive index, optical properties and thickness of the different layers. Refractive indices (n) of porcine epidermis were reported by Ding et al.[4] for single wavelengths between 325 nm and 1557 nm; in the case of the dermis and subcutaneous adipose tissue it was fixed at 1.36. Pig skin optical properties have been studied by Du et al.[5] for dermis in the 900–1500 nm range and by Cain et al.[6] in the 1000–1600 nm range for epidermis and dermis (thus providing the absorption coefficient (μ_a), the scattering coefficient (μ_s) and the anisotropy parameter (g)). In the case of the subcutaneous adipose tissue, the data reported by Bashkatov et al.[7] for rats was used as pig data were unavailable. The thicknesses used in the simulation for each layer were reported by Renaudeau et al.[8] The wavelength range studied was 1000–1600 nm. The optical arrangement for the Monte Carlo simulations assumed that source and detector were arranged concentrically, with the source in the core and detector at the annulus (Figure 1). The simulation was designed such that only the photons whose incidence angles were lower than 11.5° were detected, corresponding to the optical fibre's numerical aperture of 0.2. As Monte Carlo simulation is a statistical method, a large number of photons is desired to obtain reliable results. In our case, 1,000,000 photons were launched. Different diameters of the optical fibre were evaluated (175 μm, 300 μm or 400 μm) and the source-detector distance was varied from 0.5 mm to 5.5 mm.

Results and Discussion

One of the difficulties encountered in NIR analysis of intact products or biological tissues is that the penetration depth is not well established. A band at 1200 nm has been shown by several authors to be informative about fat and fatty acids absorptions.[9] In this study, the simulated configuration was optimised to get information from the hypodermis layer at 1200 nm band, and then the optimised instrument configuration was studied for each other wavelengths. Different combinations of fibre optic diameters and source-detector distances were evaluated. A fibre optic of 175 μm presented a maximum of photons captured from the hypodermis at a source-detector distance of 3.5 mm (not shown). However, the percentage of photons captured from the adipose tissue compared to the total number of captured photons from all three tissue

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layers (including epidermis and dermis) indicated that the absorption was mainly from the epidermis and dermis. Diameters around 300 and 400 μm obtained more suitable results (data not shown).

A source-detector distance around 4.5 mm for a fibre optic with a diameter of 400 μm showed high sensitivity for measuring absorption at 1200 nm from the hypodermis. Figure 2 shows the simulation of captured photons absorbed by adipose tissue at 1200 nm for source to detector distances ranging from 4 mm to 5 mm at 0.1 mm intervals. Although some variations were present, the maximum number of captured photons absorbed by the target layer was observed at a source-detector distance of 4.8 mm. In this case, the average simulated depth was 2.04 mm, which indicates the relevance of the dermis layer. Studying the distribution of photons captured from different layers, it was observed that only the first millimetre of hypodermis may contribute to the captured light. The signal from the hypodermis may be weak (i.e. only ~1000 photons captured) at the selected configuration. However, that configuration showed the best simulation results for measuring the adipose tissue through pig skin.

Figure 3 shows the simulation results of the percentage of absorbed photons captured from the adipose layer for the 1000–1600 nm range (4.8 mm source-detector distance, 400 μm fibre optic). The large decrease of absorbed photons from the adipose layer around 1450 nm is due to the large water absorption by the epidermis and dermis. These results may indicate the complexity of getting information from the adipose tissue at longer wavelengths. The simulated average depth also indicates the decrease in the light path for longer wavelengths, where the main absorption takes place at the dermis layer (Figure 4).

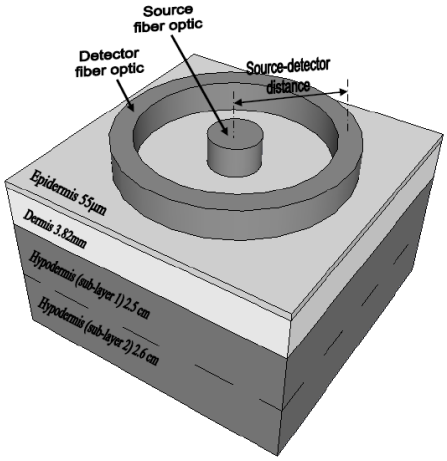

Figure 1. Schematic diagram of the cross section of pig skin tissue and fibre optic configuration.

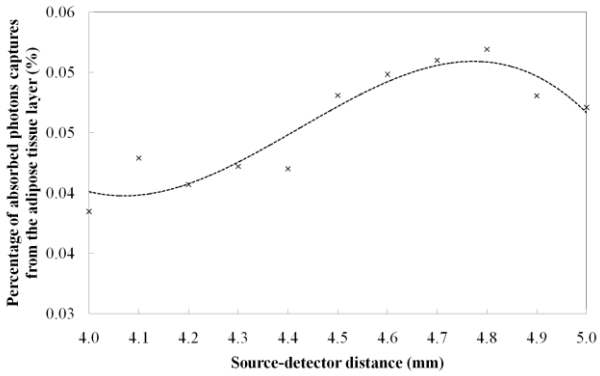

Figure 2. Percentage of absorbed photons captured by the detector with a 400 μm diameter from the adipose tissue layer at 1200 nm.

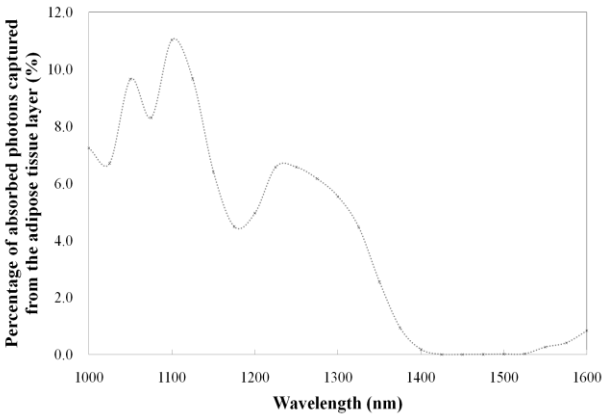

Figure 3. Absorbed photons percentage captured by a fibre optic of 400 μm and a source-detector distance of 4.8 mm from the adipose tissue layer.

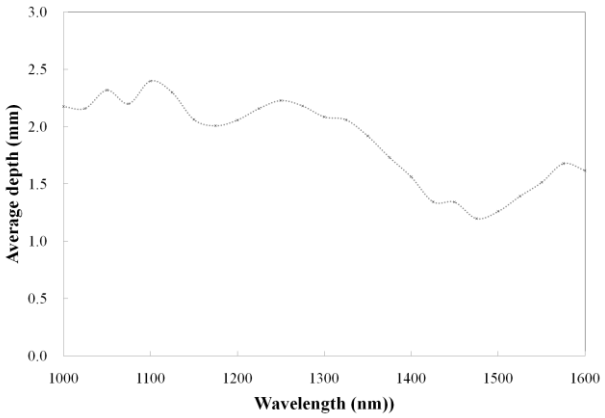

Figure 4. Average depth simulated by Monte Carlo for the range 1000–1600 nm with a fibre optic of 400 μm and a source-detector distance of 4.8 mm.

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Future directions

To verify the simulation results presented in this study, an experiment for measuring fat content through pig skin based on the instrumental performance simulated is in progress. A study of the optical properties of pig epidermis, dermis and subcutaneous adipose tissue from 780 to 2500 nm will be important for improving the optimal distance selection.

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