Design and Realization of NIR Optical Spectroscopy Systems

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ABSTRACT: Microwave photonics techniques have become established for telecommunication and radar systems in the last 20 years; however, the benefits of RF and microwave photonic technology in biomedical applications have not been fully explored. This chapter has presented application of microwave photonics to medical imaging. Microwave photonics techniques are applied to the eventual development of a broadband NIR spectroscopy system to achieve real-time imaging of biological tissues with a millimeter scale spatial resolution. In NIR spectroscopy the main aim is to extract the optical properties (absorption and scattering) of the living tissue. The absorption, μa, and reduced scattering, μs, parameters of tissue can provide information on a variety of physiological processes. Absorption information is used to characterize the concentration of biological chromophores, such as hemoglobin, which in turn indicates the physiological changes in blood. Scattering information quantifies the composition, density and organization of tissue structures, such as cells and sub cellular organelles. The development of specialized optical system with modulation capability of up to 3 GHz is also demonstrated and spectroscopic measurements are conducted for both solid and liquid phantoms.

Keywords: Spectroscopy, imaging, NIR, continuous-wave method.

1 Introduction to Optical Spectroscopy using NIR

Shadow images created as light passes through the body were first proposed by Cutler in 1929 for medical imaging [35]; however, he found the low resolution of the images limited its clinical application due to high scattering and absorption. In the past 20 years, significant advancements in laser and detector technologies in the near-infrared (NIR) electromagnetic spectrum have been driven by the long haul telecommunication industry; combined with a better understanding of light propagation in tissue this has now led to renewed interest in optical imaging of the human body as well as acquiring information about tissue optical and dynamic properties noninvasively.

Near infrared (NIR) spectroscopy is a new, noninvasive technique to analyse living tissue in terms of absorption and reduced scattering coefficients, which could provide information about disease related functional and structural changes [1,2].

2 NIR Techniques

NIR techniques could ultimately provide information about disease-related functional and structural changes in tissue. Currently, three main categories of diffuse optical measurements have been developed: (i) continuous wave (CW), (ii) time domain and (iii) frequency domain measurements. Frequency-domain method has attracted interest from biomedical research field for decades due to its low component cost, ease in separating absorption and scattering parameters, and potential for real-time

imaging. In frequency-domain photon migration (FDPM) methods, diffuse photon density waves (PDW) are generated when light is modulated by radio frequency signals, which propagates with a wavelength of several millimeters to centimeters depending on the modulation frequency. Amplitude and phase information of the diffuse photon density waves are used to map the optical absorption and scattering properties of the medium. These optical properties in turn are used to obtain hemoglobin concentration, blood volume and 'absolute' oxygen saturation .

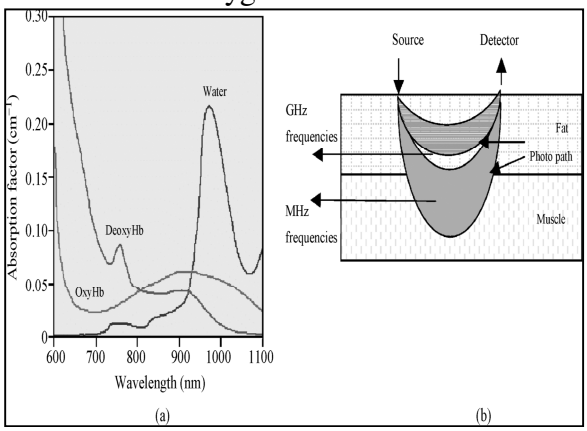


Figure (1.2a) Concept of diffused photon near infrared spectroscopy in biological tissue depicting:(a) optical absorption coefficient of oxygenated and de oxygenated haemoglobin (Oxy Hb and Deoxy Hb)and water in near infrared region; (b) impact of modulation frequency on tissue penetration depth and structure of banana shaped photon scattering in tissue

There are several advantages to multi-frequency instruments compared with single-frequency
instruments. Since most tissues have a layered structure and because photon penetration depth is less at a higher frequency due to a higher loss (Figure 1.2a), by sweeping the modulation frequency one can have information for all layers in a single measurement. This approach is very important in clinical measurements, where it is preferable to make a single measurement and obtain as much information as possible, due to the calibration challenges. The development of specialized optical systems with modulation capability of up to 3 GHz has also been demonstrated and spectroscopic information is conducted for both solid and liquid phantoms.

2.1 Approaches to NIR Imaging

In NIR spectroscopy the main aim is to extract the optical properties (absorption and scattering) of the living tissue. The absorption, μa, and reduced scattering, μs, parameters of tissue can provide information on a variety of physiological processes. Absorption information is used to characterize the concentration of biological chromophores, such as haemoglobin, which in turn indicates the physiological changes in blood [3]. Scattering information quantifies the composition, density and organization of tissue structures, such as cells and sub cellular organelles [3, 4]. In continuous wave (CW) systems, light sources emit light continuously at constant amplitude (or are modulated at frequencies not higher than a few tens of kHz to reject ambient light using synchronous detection schemes). CW systems measure only the amplitude decay of the incident light. Time-domain, or time-resolved, systems introduce extremely short (picoseconds) incident pulses of light into tissue, which are broadened and attenuated by the various tissue layers (e.g. shin, skull, cerebrospinal fluid and brain). A time-domain system detects the temporal distribution of photons as they leave the tissue, and the shape of this distribution provides information about tissue absorption and scattering. In frequency-domain systems, the light source shines continuously but is amplitude-modulated at frequencies at least on the order of tens of MHz Information about the absorption and scattering properties of tissue are obtained by recording the amplitude

decay and phase shift (delay) of the detected signal with respect to the incident signal.

2.2.1 Continuous-wave (CW) Method

The absorption spectrum of tissue is wavelength dependent, which is mainly the contribution of
Hb (hemoglobin), HbO and water, as depicted in Figure 2.2, where the absorption coefficient
is provided for blood concentration of 5% in whole tissue and 100% water. Measuring the concentration of an absorbing species in a sample is accomplished by applying the Beer Lambert law [5], where the absorption of a sample at a given wavelength is directly proportional to the concentration of the absorbing material, its extinction coefficient and the path length of light through it. The Beer Lambert law assumes that the medium is homogeneous, the incident light is collimated and reflection and scattering do not contribute to the loss of the transmitted light. The Beer Lambert law analytically expresses optical density (i.e. absorbance) as

$\ln (I/I_0) = \sigma \int \rho = \mu_a d$

where I0 is the incident intensity, I is the transmitted light intensity, sigma is the absorption cross
section, ρ is the number density of the absorbing molecules.
The Beer Lambert relation holds true when specular reflection or scattering does not contribute to the loss of transmitted light. This is clearly not the case in tissue. When the scattering length is shorter than, or comparable to, the absorption length, the optical properties cannot be accurately determined using the Beer Lambert law. The first attempts at diagnostic imaging using optical radiation revealed that multiple scattering occurs when visible to near-infrared light propagates through tissue and blurs features below the surface. As a consequence, any measurement of the transmitted intensity through more than a few millimeters of tissue is dominated by scattered light. The scattering characteristic of tissues is commonly expressed in terms of the transport (or reduced) scattering coefficient (corresponding to isotropic scattering),

$\mu_{s'} = \mu_s (1\text{-}g)$

The quantity of oxygen in blood is often expressed as the haemoglobin oxygen saturation (S),
which is defined as

$S = \frac{HBO}{HBO+[Hb]} * 100\% = \frac{HBO}{HBO+[HbT]} * 100\%$

This expresses the percentage of the total oxygenated haemoglobin.

2.3 Working Principle

A typical CW imager is shown in Figure 2.3, where light sources are driven by the drive circuitry and emit near-infrared light into tissue. The diffused and attenuated light is collected and converted to an analogue electrical signal by the photodetector. Finally, the amplified signal goes through the A/D converter so that a computer can be used to process and display the data. As shown in Figure 2.3, the light source is at the second stage of the open loop, so that the quality of the light source is vital to the whole system. Generally, there are three choices for light sources in CW imagers: white light (such as tungsten light bulbs), lasers and light-emitting diodes (LED). Light spectrum purity and light intensity output are two important parameters. White light has been extensively used with interference filters at 760 nm and 850 nm to detect blood volume and deoxygenation changes [6]. Lasers are ideal light sources for many applications due to their excellent spectral purity and collimation. The linewidth of the isolated wavelength is less than 1 nm. A laser beam focuses all the light energy into a very small area and over a

very small wavelength bandwidth, with potential for tissue damage even though its power is much less than that of a white light source. This is why its power is limited to less than 0.1mWby the Food and Drug Administration's (FDA.s) law (type I) when laser light is applied to humans. Thus, it will be difficult to satisfy the light intensity requirement of a CW imager.

LED spectral purity is about 30 nm and it is good for a CW imager. More light intensity can be utilized since LEDs illuminate the tissue more diffusely than a laser but more like a point light source than white light, and with less heat. Stability of light intensity is another important requirement of a CW imager. Both white light and LEDs have a drift of light power and thus require 2 3 minutes for warming up, but the laser diode operates more stably.

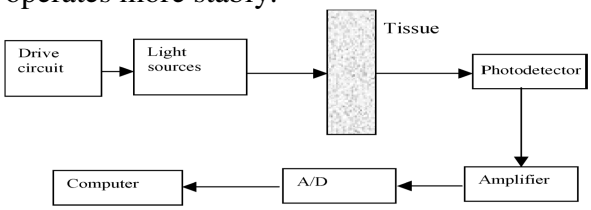
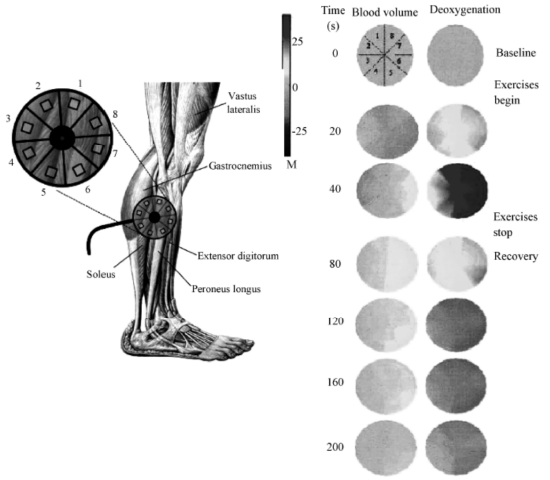


Figure (2.3) Typical block diagram of a single channel CW imager

2.4 Experimental Result of NIR imaging

A typical experimental result by an LED imager is shown in Figure 2.4. The probe was placed on the lateral side of the lower right-hand side of the leg. Seated baseline measurements were made for 1 minute. Seated exercise began by the subject doing 60 repetitions of toe extension (pointing the toe as far as possible)[7]. This seated exercise recruited the extensor muscles to a greater extent than the flexors which are more activated during plantar flexion or walking.



Figure(2.4) : Blood volume and deoxygenation changes during cycling exercise are presented during physical exercise and rest periods .Agrey scale coding (black for increase, light grey color is for moderate decrease, and dark grey for significant decrease) is employed to provide approximate changes in blood volume and deoxyngenation levels (in unit aM) compared to the initial condition represented in grey colour.

2.5 Experimental Results and Discussions: The development of specialized optical system with modulation capability of up to 3 GHz is also demonstrated and spectroscopic measurements are conducted for both solid and liquid phantoms. Moreover, accuracy of broadband extraction process is compared to the single-frequency extraction for phantom resemebling breast tissue, where the results of this extraction are extended to future clinical imaging. Comparison of amplitude and phase response of three intra-lipid samples at 144MHz(single frequency I/Q receiver) and 1GHz (a microwave photonics solution) is depicted in Fig. 2, which proves that higher frequency measurement has higher sensitivity to detect absorption change in a turbid medium.[4] Broadband frequency domain system has also added benefit over I/Q single frequency measurement system, where an average error of 35.2% for μ_a and 23.6% for μ_s, for the single-frequency extraction in phantom

as compared to 8% and 3% respectively in broadband (100-1000MHz) measurement system.[6] These techniques are to be applied to clinical environments for further evaluations.

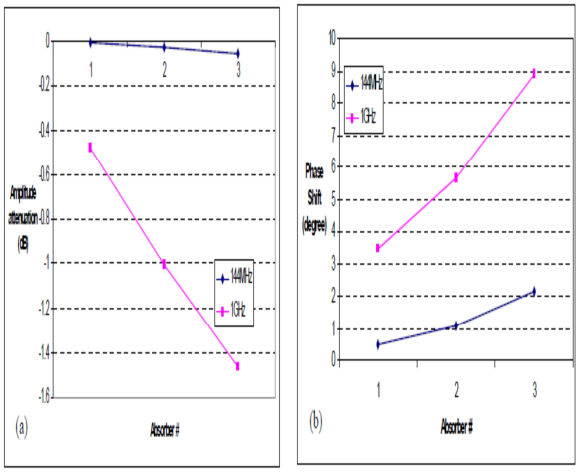


Fig. 2.5 Sensitivity of the measured signal to the absorption parameter of three different intra-lipid absorbers at 144MHz and 1GHz: a) amplitude change; b) phase shift.

Table II: Broadband Extraction and percentage Error Results

		Extracted values (cm^{-1})	Manufacture values (cm^{-1})	Error (cm^{-1})	Error (%)
Frequency range from 100 MHz~ 400MHz	μ_a	0.0488	0.045	0.0038	8.44
	μ_s'	11.0769	10	1.0769	10.77
Frequency range from 400MHz ~ 700MHz	μ_a	0.0487	0.045	0.0037	8.22
	μ_s'	9.0779	10	0.9221	9.22
Frequency range from 700MHz ~ 1GHz	μ_a	0.0436	0.045	0.0014	3.11
	μ_s'	9.4321	10	0.5679	5.68
Frequency range from 100MHz ~ 500MHz	μ_a	0.0499	0.045	0.0049	10.89
	μ_s'	10.2672	10	0.2672	2.67
Frequency range from 500MHz ~ 1GHz	μ_a	0.0479	0.045	0.0024	5.33
	μ_s'	9.4655	10	0.5345	5.35
Frequency range from 100MHz ~ 1GHz	μ_a	0.0488	0.045	0.0038	8.44
	μ_s'	9.6711	10	0.329	3.29

CONCLUSION: Microwave photonics techniques are also applied to the eventual development of a broadband NIR spectroscopy system to achieve real-time imaging of biological tissues with a millimeter scale spatial resolution. The optical system was designed for a flat frequency response up to 3 GHz, where spatial resolution of a few millimeters is predicted. Both broadband extraction and single-frequency extraction have been performed to extract optical parameters ma and ms for a phantom that resembles breast tissue as a turbid media. Results show that the accuracy of broadband extraction is much better than single-frequency extraction and table shows the different values of all parameters at different frequency ranges with error. The development of specialized optical system with modulation capability of up to 3 GHz is also demonstrated and spectroscopic measurements are conducted for both solid and liquid phantoms.

REFERENCES

[1] T. H. Pham, O. Coquoz, J. B. Fishkin, E. Anderson and B. Tromberg, ‘‘Broad Bandwidth Frequency Domain Instrument for Quantitative Tissue Optical Spectroscopy’’, Rev. Sci. Inst., vol. 71, pp. 2500 2513, 2000.

[2] A. Duncan, T. L. Whitlock, M. Cope and D. T. Delpy, ‘‘A Multi wavelength, Wideband, Intensity Modulated Optical Spectrometer for Near Infrared Spectroscopy and Imaging’’, SPIE, vol. 1888, pp. 248 257, 1993.

[3] W. B. Spillman, Jr. and R. L. Gravel, ‘‘Moving fiber optic hydrophone’’, Optics Letters, vol. 5, No. 1 pp. 30 31, January 1980.

[4] P. Morris, A. Hurrell and P. Beard, ‘‘Development of 50 MHz Fabry Perot type fiber optic hydrophone for the characterization of medical ultrasound fields’’, Proceedings of the Institute of Acoutics, vol. 18, pp. 717 725, 2006.

[5] K. Srinivasan,‘‘Noise Cancelled Optical Receivers in Fiber Optic Hydrophone up to 100MHz?’’, M.S. Thesis, Drexel University, USA, 2007.

[6] Y. Lin et al., ‘‘Noninvasive, low noise, fast imaging of blood volume and deoxygenation changes in muscles using

light emitting diode continuous wave imager'', Rev. Sci. Instrum., vol. 73(8), pp. 3065 3074, 2002.