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Temperature Sensitivity of CW-PA-based Sensor dedicated to Noninvasive Monitoring of Physiological Parameters

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1. Introduction

Measurement of body temperature at one location has been used as an indicator of health for a very long time. However, the relevant parameter is the internal temperature of the human body, which can be measured using endoscopes, while the routinely used protocol provides measurements at the skin surface exclusively. The two temperatures differ by about 3 to 5 ºC depending on various parameters such as the measurement site and local environment. The sensor then requires a complex post-processing algorithm in order to estimate the internal temperature from the one measured at the skin surface. Variations from one individual to another also strongly impact the sensor 's accuracy so that only limited information may be used from those sensors. Recent advances in biological and medical diagnosis [1] have shown that a disease such as breast cancer could be detected early from temperature profile abnormalities. However, the actual techniques are limited to tumors located near the skin. To extend the use of diagnosis based on temperature profile measurements, we propose noninvasive techniques based on the continuous-wave photoacoustic (CW-PA) method (Fig. 1) and have already developed two protocols: (i) the frequency-shift (FS) method, which relies on the measurement of resonance frequency shift induced by any change of sample characteristics; and (ii) the optical-power-balance-shift (OPBS) protocol, which utilizes excitation at two optical wavelengths to perform measurements after correcting the frequency shift mentioned above. The two methods were first developed to noninvasively monitor the blood glucose levels; however, both protocols exhibit non-negligible sensitivity to temperature, which can also lead to valuable information about patient health.

Here, we discuss the temperature dependence of the two methods, which relies on two different mechanisms.

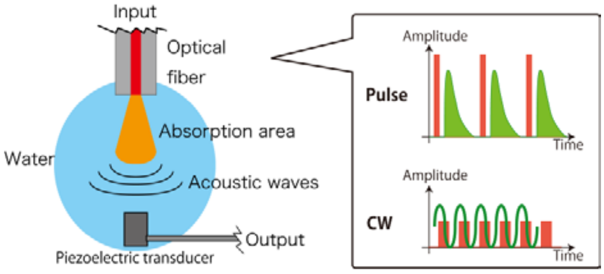

Fig. 1 Schematic view of CW-PA basic concept (left) with the two main excitation sequence: pulse and CW (right).

2. FS Method

Concept validation with glucose

CW-PA uses an optical excitation amplitude-modulated with a square-wave function. This sequence generates standing waves and resonance at specific frequencies that depend on boundary geometry and sample characteristics. When adding glucose to the sample solution, the frequencies at which resonance occurs are gradually shifted. Plotting the relative frequency shift ($\Delta f/f$) versus glucose concentration yields a linear relationship that remains identical whatever the cavity size, acoustic mode, and wavelength [2]. Theoretically, this measurement protocol is equivalent to an acoustic velocity measurement, which can then explain the stable results despite changes in the cavity size and optical wavelength. Moreover, the response slope of the glucose dependence of 0.19 %/g/dL is consistent with reported acoustic velocity measurements from the literature.

Origin of Temperature Dependence

However, the acoustic velocity is a scalar parameter that also depends on several parameters other than glucose concentration, including temperature. From experimental data, we measured a temperature dependence of about 0.16 %/ºC, consistent as well with the literature. But, this dependence on temperature is a physical parameter that cannot be altered nor optimized.

3. OPBS Method

Concept validation with glucose

The OPBS protocol uses excitation at two optical wavelengths amplitude-modulated with two square-waves operating at the same frequency, but in the opposite phase [3]. The acoustic waves then generated in the medium are proportional to the quantity ($\alpha_1 P_1 - \alpha_2 P_2$), with α the optical absorption coefficient and P the optical power; subscripts 1 and 2 refer to wavelengths 1 and 2. It is then possible to adjust the pair of optical powers [through the laser diodes driving voltages (DVs)] in order to minimize the generation of acoustic waves. This precise condition corresponds to the minimum on the amplitude signal, and the inflexion point on the phase. When the glucose concentration of the sample solution is changed, the two optical absorption coefficients are changed so that the set (P_1,P_2) that lead to minimum acoustic wave generation is shifted (Fig. 3). Plotting the quantity (DV_1-DV_2) versus the glucose concentration reveals a linear relationship with a slope that is consistent with relative absorption coefficient-based measurements.

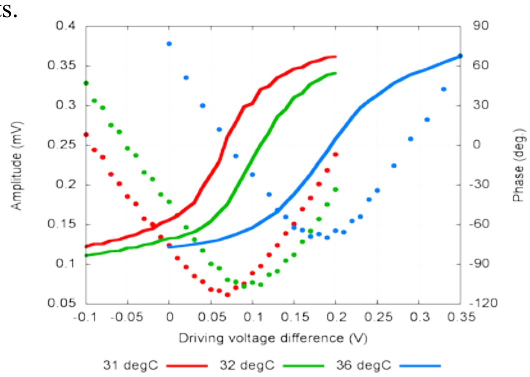

Fig. 2 OPBS-based amplitude (dots) and phase (lines) signals for water solution at three temperatures.

Origin of Temperature Dependence

The compound concentration dependence of OPBS is intuitive, since every compound exhibits a fractional absorption with highs and lows that depend on its respective chemical structure. However, experimental data also showed that OPBS is sensitive to temperature (Fig. 2). This characteristic comes from the fact that water provides the main contribution in term of absorption of NIR optical energy, which enables in turn efficient generation of acoustic waves. Furthermore, it has been shown that the water absorption spectrum shifts toward the low wavelengths as temperature increases [4]. It is then possible to compute an equivalent fractional absorption coefficient for temperature, similar in shape to the first derivative of the spectrum at one reference temperature (Fig. 3).

From spectroscopic data, we then measured this temperature coefficient and compared it with the OPBS-based measurement performed at a (1382, 1610) pair of wavelengths. With very similar coefficients for glucose concentration and temperature, the results are in/show good agreement/consistency. Furthermore, we could also compare our results to absorptiometry measurements [5] (purely optical) performed according to the same optical excitation and similar wavelengths, which reveals a consistent tendency (Table I).

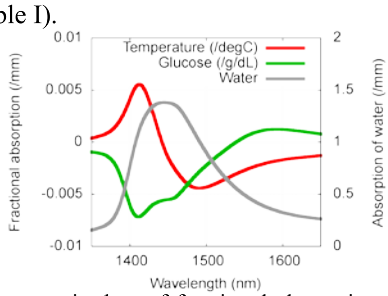

Fig. 3 Spectroscopic data of fractional absorption coefficients of glucose and temperature, and comparison with water absorption.

4. Comparison of the two methods

The two methods proposed here are based on the same CW-PA technique, but look specifically at two different parts of the process. While the FS method focuses on the mechanical part, the OPBS one yields an optical-based measurements. Furthermore, FS leads to measurement of acoustic velocity over the full cavity length, which consists of a sample medium between the acoustic sensor and the optical fiber tip facing each other [2]. The final result then provides a measurement consistent with an average of the temperature.

Nevertheless, OPBS depends on the optical wavelengths used, and more precisely on the optical absorption of water at these wavelengths. With a high coefficient, most of the optical energy is absorbed within the first few hundred micrometers, whatever the cavity size is. The measurements performed are then sensitive to the temperature change occurring within this penetration layer exclusively. Changing the pair of wavelengths then allows tuning of the penetration depth. OPBS then potentially allows depth profiling of the temperature based on the choice of optical wavelengths.

Table I Comparison of absolute value of glucose-concentration and temperature dependence of various protocols.

Method	Glucose dependence	Temperature dependence	Ratio
Spect. meas. (1382,1610)	1.03 $(g/dL)^{-1}$	0.93 $(°C)^{-1}$	1.11 g/dL/ºC
OPBS (1382,1610)	27 mV/g/dL	26 mV/ºC	1.04 g/dL/ºC
Absorptiometry (1304,1554) [5]	3.3 mV/g/dL	2.01 mV/ºC	1.64 g/dL/ºC

5. Conclusions

The two protocols based on CW-PA technique can provide noninvasive measurements of temperature. However, the two protocols enable different measurements. FS provides sensitive measurements of an average temperature over the total thickness, while OPBS provides information over a depth (thin layer from the exposed surface) that depends on the optical wavelengths used. OPBS can be tuned according to the targeted area of interest.

Furthermore, the robustness of CW-PA technique (insensitive to scattering of the sample) makes these methods particularly suitable for in vivo monitoring of physiological temperature.

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