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Study on the measurement method of a dynamic spectrum

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Abstract. Continuous non-invasive blood component sensing and regulation is necessary for patients with metabolism disorders. Utilizing Near-infrared Spectroscopy for non-invasively sensing blood component concentration has been a focus topic in biomedical optics applications. It has been shown to be versatile, speedy and sensitive to several kinds of samples. However, there is no report about any successful non-invasive blood component (except the artery blood oxygen saturation) concentration detection techniques that can meet the requirements of clinic application. One of the key difficulties is the influence of individual discrepancies. Dynamic spectrum is a new non-invasive measure method for sensing blood component concentration presented recently. It can theoretically eliminate the individual discrepancies of the tissues except the pulsatile component of the artery blood. This indicates a brand new way to measure the blood component concentration and the potential to provide absolute quantitation of hemodynamic variables. In this paper, the measurement methodology to acquire the DS from PhotoPlethysmoGraphy (PPG) is studied. A dynamic spectrometer to acquire the DS is described.

1. Introduction

The various chemical components present in human body carry important information on health status, and serve as important indicators to a number of clinical diagnostics and therapeutic effects. In many situations, timely even continuously sensing of these chemical concentrations has special meaning for modern health care. A non-invasive measurement method has been desired for a long time. Utilizing Near-infrared Spectroscopy for non-invasive blood component concentration sensing has been a focus topic in biomedical optics applications [1-3]. It has been shown to be versatile, speedy and sensitive to several kinds of samples.

Diffuse optical methods are made possible by an “optical window” in tissue that spans the near-infrared region (approximately 650–950 nm) of the electromagnetic spectrum [4-5]. In this region, the components to be detected are absorbers, and their concentrations are sufficiently low to allow light to pass through several centimeters of tissue and still be detected. The promise of diffuse optical methods lies in their potential to provide absolute quantitation of hemodynamic variables. To accurately quantify the component concentration, the relative contributions of these absorbers must be separated from the raw optical signals. To do so, measurements at several wavelengths are simultaneously acquired, and a model is applied to convert the wavelength data to chromophore concentrations. The standard model used to perform this conversion is based on the modified Beer–Lambert law [6]. Lots
of researchers have devoted to this area for decades. However, there is no report about any successful non-invasive blood component (except the artery blood oxygen saturation [7]) concentration detection techniques that can meet the requirements of clinic application. One of the key difficulties is the influence of individual discrepancies. There are many individual discrepancies that affect the measurement accuracy, including hair, epidermal, dermis, subcutaneous-tissue, muscle, bone, water, color, temperature, etc. Each of these factors is different, and exerts a considerable influence to the measurement result [8-9].

In previous reports [10-11], we presented a new non-invasive blood component concentration measurement method: dynamic spectrum (DS) measurement method. It can theoretically eliminate the individual discrepancies of the tissues except for the pulsatile component of the artery blood (PCAB). This indicates a brand new way to improve the measurement accuracy of the blood component concentration and potential to provide absolute quantitation of hemodynamic variables. In this article, we elaborate on our previous findings by studying the measurement methodology of DS. DS is defined by the optical density (OD) of the PCAB, and is extracted from the photoelectric pulse wave. The photo pulse plethysmography (PPG) is used to measure the raw data and the modified Beer–Lambert law is applied to convert DS to chromophore concentrations. To accurately quantify the component concentration, two key points must be ensured: the wavelength selected and the accuracy of DS measurement. In this paper, the second point is discussed by studying the measure methodology of DS. A simple, facility dynamic spectrometer system is presented in this paper.

2. The measure methodology of the DS

DS is defined as: the spectrum that is constructed by the ODs of PCAB corresponding to each monochromatic light. The photoelectric pulse wave represents the timely-change of absorption of the tissues. OD of the photoelectric pulse wave is mainly contributed to by the absorption and scattering of the blood and other tissues within the detected regions. The modified Beer–Lambert law is typically used to describe the change in light attenuation in scattering media because of absorption changes (which in turn result from changes in chromophore concentrations). When the timely-change in absorption is in the PCAB, then according to the MBLL,

$$OD = -\log \frac{I}{I_0} = 2.303\varepsilon l + G$$

where $I$ and $I_0$ specify the intensity of the incident light and the transmitted light respectively, $\varepsilon$ is the molecular extinction coefficient, $c$ is the concentration of the analyte, $l$ is the mean optical path length and $G$ is OD due to the scattering of the light. In transmission measurement using NIR light, OD is mainly contributed to by the absorption and scattering of the blood and other tissues. Because the scattering in the artery blood is much smaller than the absorption, we can ignore it here. Then $G$ is only contributed to by tissues except the pulsatile component of the artery blood, and remains constant in the measurement.

In a previous report [11], we demonstrated that when using the DS, the MBLL is written as

$$\Delta OD_i = 2.303(\sum_{j=1}^m c_j \varepsilon_{ij}) L$$

where $\Delta OD$ is the change in OD measured at a given wavelength according to the pulsatile artery blood, $c$ is the concentration of blood composition $j$, $\varepsilon_{ij}$ is the molecular extinction coefficient of blood composition $j$ at the single wavelength $i$, $L$ is the difference of the max mean optical path length and the min mean optical path length of the artery.

$\Delta OD$, which is simply contributed by the PCAB, reveals the absorption of the PCAB. In nature, it is equivalent to getting rid of the other tissues and only leaving the PCAB to conduct the measurement. According to the definition of DS, the spectrum constructed by $\Delta OD$ corresponding to each monochromatic light in one period of the photoelectric pulse wave is regarded as the DS. The DS, therefore, will not be influenced by the interference of the individual discrepancy.
DS is sensitive to several kinds of samples. It can obtain several kinds of component concentrations simultaneously. To accurately quantify several component concentrations at the same time, the relative contributions of the absorbers must be separated from the raw optical signals. To do so, measurements at several wavelengths are simultaneously acquired. According to the equation (2), the concentration of the blood compositions $c_1, c_2, \ldots, c_n$ can be obtained by establishing the system of equations with the unknowns $c_i$ and $L$. Thus, DS should be measured according to at least $n+1$ wavelengths. In considering the utilizing of analysis methods, more photoelectric pulse waves corresponding to each monochromatic light are usually measured as data redundancy.

3. The monitoring method of DS

The photoelectric pulse wave represents the change of absorption of the tissues. The transmitted light is mainly influenced by the absorption and scattering of the blood and other tissues within the detected regions. The sketch diagram of the photoelectric pulse wave constitution is shown in figure 1.

The $I_0$ is the incident light of the tissues. The photo-electronic signal acquired by the PPG is a DC pulsatile wave with the wave top ($I_{\text{max}}$) and the bottom ($I_{\text{min}}$), the $I_{\text{max}}$ and $I_{\text{min}}$ as the transmitted light is relative to the maxim artery blood volume and the minimum artery blood volume.

Then, the difference of the max OD ($OD_{\text{max}}$) and the min OD ($OD_{\text{min}}$) in one period of the photoelectric pulse wave can be expressed as:

$$\Delta OD = OD_1 - OD_2 = \lg(I_0/I_{\text{min}}) - \lg(I_0/I_{\text{max}}) = \lg\left(\frac{I_{\text{max}}}{I_{\text{min}}}\right)$$

The $I_{\text{max}}$ is the maximal value detected by photo-electronic sensor when an artery contracts minimally and we regard it as the incident light of the PCAB, and the $I_{\text{min}}$ is the minimal light when the artery expands maximally and we regard it as the minimum transmitted light of the PCAB. Therefore, the incident light and the transmitted light of the PCAB can be extracted from the photo-electronic pulse wave, and the OD of PCAB is $\ln(I_{\text{max}}/I_{\text{min}})$.

There are many difficulties to get high accuracy DS: Firstly, the absorbency of pulsatile part of artery is very weak since the scaling that relates the $I_{\text{max}}$ to the $I_{\text{min}}$ is smaller than 3% of $I_{\text{max}}$ when the photo-electronic signal is detected from the finger. It is difficult to identify the $I_{\text{max}}$ and $I_{\text{min}}$ from the photoelectric pulse wave. The next, fast sample rate is needed to get $I_{\text{max}}$ and $I_{\text{min}}$. It is hardly possible to achieve DS in high accuracy by use of a normal spectrum instrument or method since they always use long-time integration to improve the measurement accuracy. It is impossible to calculate $\ln(I_{\text{max}}/I_{\text{min}})$ accurately with an analog circuit.

$$\Delta OD = \ln\left(\frac{I_{\text{max}}}{I_{\text{min}}}\right) = \ln\left[1 + \left(\frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{min}}}\right)\right]$$

According to the equation (4), the value of $\Delta OD$ is only relative to the $(I_{\text{max}} - I_{\text{min}})/I_{\text{max}}$. The accuracy of the eigenvalue of $(I_{\text{max}} - I_{\text{min}})/I_{\text{max}}$ is more important than the accuracies of $I_{\text{max}}$ and $I_{\text{min}}$. This reduces the requirement of the stability of the system and the light source.

Since $|I_{\text{min}}/I_{\text{max}}| < 1$, (4) is decomposed into Taylor series as:
\[ \Delta OD = \ln \left[ 1 + \left( \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{min}}} \right) \right] = \left( \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{min}}} \right) - \frac{1}{2} \left( \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{min}}} \right)^2 + \frac{1}{3} \left( \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{min}}} \right)^3 \]

\[ = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}}} - \frac{1}{2} \left( \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{min}}} \right)^2 + \frac{1}{3} \left( \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{min}}} \right)^3 + \ldots \]

where \( R_3 \) is the third remainder term of Taylor series. Since the \( (I_{\text{max}} - I_{\text{min}})/I_{\text{max}} \) is smaller than 0.03, the relative error is only less than 0.03% when using the first two items of the Taylor series. Therefore, high precision signal can be achieved by a linear analog amplifier and turned into a digital signal. DS is computed by a quadratic equation, which can be computed rapidly with acceptable accuracy. When the OD is extracted by MCU unit, this rapid method is preferable.

4. The dynamic spectrometer

To acquire the DS, the spectrum must be scanned several times in a single period of the photoelectric pulse wave (about 1 second). The spectrometers for DS must have time-resolved regimes. According to equation (4), the dynamic spectrometer must identify the alternating component of the photoelectric pulse wave. This is one of the main differences between the dynamic spectrometer and the normal spectrometers.

Figure 2 is the schematic diagram of the system using spatial domain spectroscopy. A grating is employed in the system. The schematic diagram of the signal conditioning circuit is shown in figure 3.

(1) The signal conditioning circuit consists of the Charge Couple Device (CCD) and its drive circuit. The output of the signal conditioning circuit is the scan signal of the photoelectric pulse wave corresponding to each monochromatic light.

(2) A multi-channel circuit structure is employed in this system to improve the conversion speed. The signal corresponding to each monochromatic light is transmitted into a special channel. Every channel transfers a special photoelectric pulse wave.

(3) The band pass filter is used to acquire and amplify the alternating component of the pulse wave to improve the accuracy of the DS.

(4) Since the goal of the detection system is to obtain the value of \( (I_{\text{max}} - I_{\text{min}})/I_{\text{max}} \), the gain of the AMPs can be adjusted respectively according to the signal amplitude of each pulse wave.

5. Discussion

The modified Beer-Lambert law is used to describe the change in light attenuation in the PCAB because of absorption changes (which in turn result from changes in chromophore concentrations). This model is highly dependent on knowledge about the mean pathlength \( L \) within the light-sampling region. According to our test, the pulsating blood in the finger tip is thinner than 10 \( \mu \text{m} \), and proper wavelength selection can help to minimize this systematic error. Only the light absorption in the PCAB is taken into account, while the scattering of light in the blood is ignored, and \( L \) is a constant
with respect to different wavelength. This has also established a theoretical foundation for picking-up
the information of blood component concentration by an analytic method. We will discuss this point in
another article.

The DS is made up of the OD of the PCAB. \( I_{\text{inc}} \) and \( I_{\text{trans}} \) are the incident light and the transmitted
light of pulsating blood respectively. The amplitude of these two signals is pretty much the same, and
can be converted with the same circuit. This eliminates the additional error from the mismatch of the
lamp source correct circuit and the measure circuit. Since the incident light and the transmitted light
are measure simultaneously by the same circuit, the smoothness to the amplitude of lamp source is not
expected too much.

But DS only correlates with the optical parameter of pulsating artery blood. It only can measure the
component concentration of artery blood and is not sensitive to the components in other tissues. This
limits the application of the DS method.

6. Summary
Noninvasive measurement of blood compositions may be realized without the influence of individual
discrepancies using the dynamic spectroscopy. It will have a great effect on the development of
methodologies for the noninvasive measurement of blood compositions. The DS can be acquired by a
simple system with linear circuit. The promise of the DS method lies in the potential to provide
absolute quantitation of hemodynamic variables.

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