RTBioT: a real-time healthcare monitoring Bio-IoT device employing spatially resolved near infrared (NIR) spectroscopy

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ABSTRACT

This paper describes RTBioT, one of the first Internet of Things (IoT) healthcare platforms based on spatially resolved near infrared (NIR) spectroscopy to support non-invasively quantify chromophores in biological tissue. Bluetooth Low Energy (BLE) is used as the primary communication protocol, an IR-enhanced Si PIN photodiode is for a light-receiving element, and a compact fiber-stub type beam combiner is employed as a multiple wavelengths light-emitting source. Most of all, a lock-in amplifier is to retrieve the low noise signal from photodiode which enables accurate measurement of small modulated signals in the presence of noise interference orders of magnitude greater than the signal amplitude by using phase-sensitive detection technique (PSD). The sampling rate of the RTBioT is up to 33Hz, so that it can directly measure mayer wave oscillation, respiration, and cardiac cycle from the raw data. However, it is necessary to approach to the statistical analysis to quantify the concentration of tissue chromophores. First, we determine the optical absorption and scattering properties in the tissue from the locked-in received signal by using the algorithm composed of least square method and diffusion equation. Then, inverse-matrix equation with absorption, reduced scattering and extinction coefficients is solved by the algorithm with respect to chromophores. We conducted an experiment through phantoms simulating human tissue and human subjects to demonstrate its feasibility for the IoT healthcare platform. The experimental results show that it is possible to monitor the biological signals and the concentrations of chromophores in a human subject in near real time fashion.

Keywords: Spatially resolved spectroscopy, real-time, Internet of Things, healthcare

1. INTRODUCTION

With the advent of the smart healthcare, the medical paradigm is shifting from “patient to technology” to “technology to patient.” Previously, people visit hospitals only when they are sick but, now it is changing to constantly monitor the human health conditions by using the Internet of Things (IoT) devices. Recently, IoT devices capable of medical-level healthcare have been attracting attention such as near infrared spectroscopy (NIRS) technologies, which quantify chromophores in tissue, specifically analyze diffuse light propagation [1].

In this paper, we have developed a real-time Bio-IoT device (RTBioT) to provide medical-level healthcare information by noninvasively measuring the absorption coefficient and the reduced scattering coefficient of light in a biological tissue. The developed RTBioT adopted the continuous-wave (CW)-based spatially resolved near infrared spectroscopy to provide physiological information such as oxyhemoglobin, deoxyhemoglobin, water, and lipids.

In fact, there are four types of methods to measure the absorption coefficient and the reduced scattering coefficient in biological tissue: continuous-wave, spatially-resolved, time-resolved, and the frequency-domain methods [2]. Among

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them, the CW method in spatially-resolved domain is advantageous in designing wearable IoT devices in terms of simple circuitry, low power, cost effectiveness, and small form factor [2,3].

The RTBioT was designed by considering three critical design parameters: low power consumption, high-fidelity data acquisition, and system-level optimization for the implementation of wearable size, even it has equipped with six lasers diodes. In more detail, to make our device more compact than any other medical IoT devices, we also have built a beam combiner which is almost quarter coin size and equipped with six different near infrared (NIR) wavelength laser diodes (LDs). Moreover, the beam combiner was fabricated with high coupling efficiency suitable as a battery-operated IoT device. In addition, Bluetooth Low Energy (BLE) is suitable for the data communication interface of the low-power RTBioT.

Optical properties such as absorption and reduced scattering coefficients are the factors to derive concentrations of major chromophores in a biological tissue [4]. In order to separate absorption from reduced scattering in CW domain, it is necessary to use multi-distance configuration, called spatially-resolved method. In our system, three IR-enhanced photodiodes are located in different distances and the light propagation information through turbid medium (i.e., living tissue) is analyzed depending on three different distances.

The received signals from different locations are processed by a lock-in amplifier. In this multi-distance model, thanks to lock-in technique, we can not only avoid ambient light perturbation, but also effectively attain a variable from an algorithm based on diffuse reflectance theory [5]. Furthermore, auto-gain control scheme at receiving part of the RTBioT plays a pivotal role in acquiring secure received signal regardless of various skin tones. With these advanced data processing schemes of the RTBioT, it can guarantee the high-fidelity data acquisition at the system level. The measured data by the RTBioT are converted into optical properties in tissue on the basis of reflectance of spatially resolved light theory, then separated absorption coefficient is turned into physiological information, using molar extinction coefficient for each chromophore so that the quantities of major chromophores are retrieved [6].

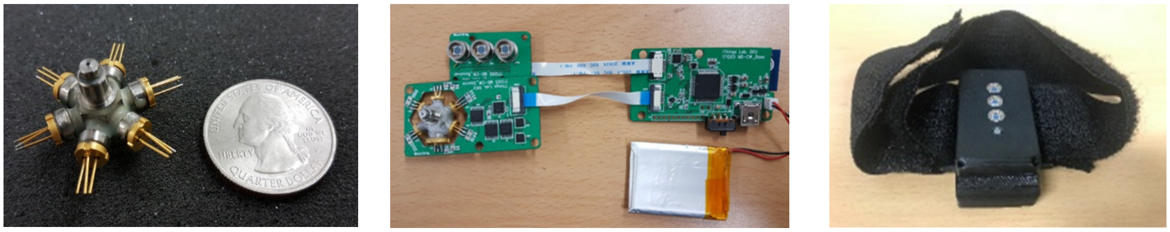
2. MATERIALS AND METHODS

2.1 RTBioT for wearable healthcare device

A Bio-Internet of Things (IoT) device, RTBioT was developed based on continuous-wave (CW) spatially resolved near infrared spectroscopy to support non-invasively quantify chromophores in living tissue. The developed RTBioT in Fig. 1 is composed of three units which are as follow:

Light Transmitter: a fiber-stub type beam combiner is a dominant component that couples the output of six wavelengths (685, 785, 830, 852, 920, and 980nm) through a single 400-μm-diameter fiber stub for wearable Internet of Things (IoT) devices [7]. The major feature for the beam combiner is high optical coupling efficiency. This is the because the wearable IoT devices for medical-level healthcare should be operated by a battery; therefore, the essential factor in low-power RTBioT of a wearable type is optical coupling efficiency to minimize the power to drive the light sources. Basically, the optical coupling e□ciency of a beam combiner is expressed as the ratio of the input power to the output power. RTBioT has achieved the average coupling e□ciencies > 80% for each of the 6 laser diodes. The driving circuit supports an auto power control (APC) function for constant optical output power.

Light Detection: RTBioT has three IR-enhanced photodiodes (S11499) with multi-distances by each 10mm as a light-receiving component. The IR-enhanced photodiode detects the reflected diffusion signal on the surface of the tissue and converts it into an electric signal with a gain from amplifier. Above all, the primary function in the light receiving part is auto-gain control scheme. Optical properties in tissue is dependant on skin colors [8]. As a result, the auto-gain control scheme was designed to broaden the dynamic range in receiving subsystem of the RTBioT to cover varying optical properties due to skin colors.



(a) Beam Combiner (b) PCB Assembly (c) RTBioT

Figure 1. Photos of RTBioT for wearable healthcare device

Data interface for communication and signal processing: For wireless communication with laptop or smartphone, the RTBioT is equipped with a Bluetooth Low Energy (nRF51822, Nordic Semiconductor). Due to its low power consumption and communication advantage, the operation time of the RTBioT lasts up to six hours after fully charged since the capacity of battery is 650mAh and the device's standby current and operating current are 32μA and 85mA each. The prominent feature of the RTBioT is a lock-in amplification scheme. As the light propagation distance goes further, the reflectance is decreased exponentially thus the farthest detector will receive less signal than the closest one and possibly could be interrupted by noises. To increase signal to noise ratio (SNR) for multi-distance photodiodes, a lock-in amplifier would be helpful to retrieve signals with specific phase [9].

2.2 Data Processing Algorithm of RTBioT

Pipeline design for real-time measurement: Even though we improved the performance of the RTBioT by optimizing circuitry of the RTBioT, the real-time measurement still poses on a challenge to realize. Since LDs are switched respectively to retrieve reflectance with respect to six wavelengths, they need a short moment to be stabilized which is so called chirping time. Adding delay time to compensate chirping time was the first approach to deal with it but this way was a bottleneck to reach over 19Hz sampling rate. To increase sampling time up to 30Hz, we modified the firmware design by applying pipelining scheme. The pipelining scheme for RTBioT is shown in Fig. 2(a) [10]. Thanks to the pipeline scheme, RTBioT now has 33Hz sampling rate and works in real-time fashion.

Derivation of optical properties from spatially resolved steady state reflectance: Empirically reflectance in spatially resolved steady state is usually multiplied by a system parameter α changing the magnitude of the measured reflectance.

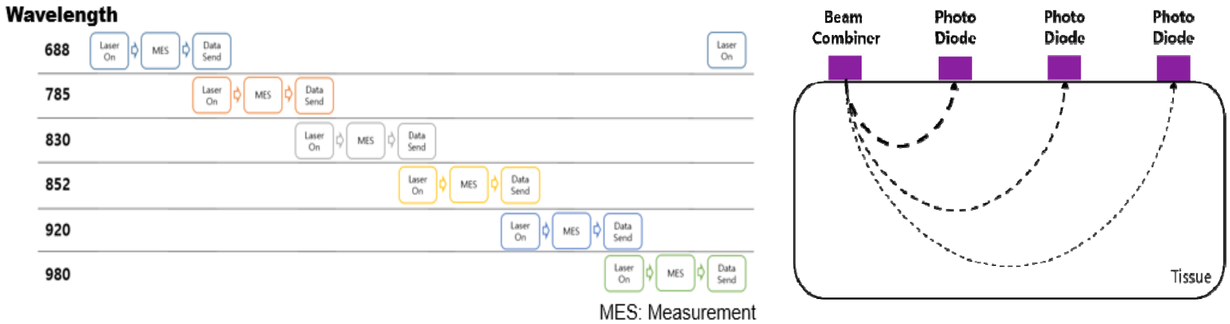
$$\mathrm{R}(\rho) = \alpha R_{exp}(\rho) \quad (1)$$

This relation is stated in Eq. (1), where R is reflectance which is a function made of and absorption coefficient (μ_a) and reduced scattering coefficient (μ_s') respectively, ρ is the source-detector distance, and R_{exp} is measured reflectance [11]. To remove the system parameter, α Nichols et al placed detectors in different distance, and then canceled α out using the relation shown in Eq.(2).

$$\mathrm{R}(\rho_n) = R(\rho_n)_{exp} / R(\rho_1)_{exp} \quad (2)$$

Besides, there was an attempt to derive variables effectively by calibration with a target with known optical properties [12]. The process algorithm to derive optical properties in RTBioT is to calibrate with a silicon phantom simulating human tissue. We conducted experiments with mDOSI device (Beckman Laser Institute and Medical Clinic, Irvine, CA, USA) to compare with optical properties from both devices. The first approach to attain optical properties was to divide reflectance from different detectors by the closest detector and fit these results to the diffusion equation, which is eliminating the system parameter (i.e., α). Another way is to derive the system parameter by phantom calibration instead of removing it.

When it comes to the first approach, the error rate for absorption coefficient was over 30% and the value for reduced scattering coefficient did not change over wavelengths. However, when we applied the second approach, the error rate for both properties is less than 10%. As a result, the process algorithm consists of the phantom calibration and fitting to the diffusion equation by Levenberg-Marquardt non-linear least square fitting algorithm [13].



(a) Pipelining Scheme for real-time (b) CW spatially-resolved method

Figure 2. Data Processing Algorithm of RTBioT

Chromophore fitting algorithm: Optical properties derived is fitted to the Eq. (3) to quantify quantities of chromophores.

$$\epsilon^{\lambda}_{[O2Hb]} \cdot [O2Hb] + \epsilon^{\lambda}_{[HHb]} \cdot [HHb] + \epsilon^{\lambda}_{[water]} \cdot [water] + \epsilon^{\lambda}_{[lipid]} \cdot [lipid] = \mu^{\lambda}_{a} \quad [14] \qquad (3)$$

$\epsilon^{\lambda}_{[Choromphore]}$ is molar extinction coefficient with respect to wavelengths and chromophore. As seen above, chromophores we are calculating are oxyhemoglobin, deoxyhemoglobin, water and lipid. The RTBioT has six wavelengths, while according to Eq. (3), four chromophores is be calculated; therefore, the way to calculate inverse matrix with square matrix could not be matched mathematically. In this reason, the quantification of chromophores is derived by linear least square fitting algorithm, not by the closed-form approaches.

3. RESULTS AND DISCUSSIONS

3.1 Calculation of optical properties on silicon phantoms simulating human tissue.

As we are using the phantom calibration to process and acquire optical properties, we have conducted measurements to attain optical properties, comparing with mDOSI as a reference standard device. The graphs shown in Fig. 3 contain the result of comparisons with RTBioT and mDOSI respect to absorption coefficient and reduced scattering coefficient. We tested on three phantoms with different optical properties and as result shown, the error rate for RTBioT is less than 11% so we proved RTBioT's possibility to calculate optical properties effectively.

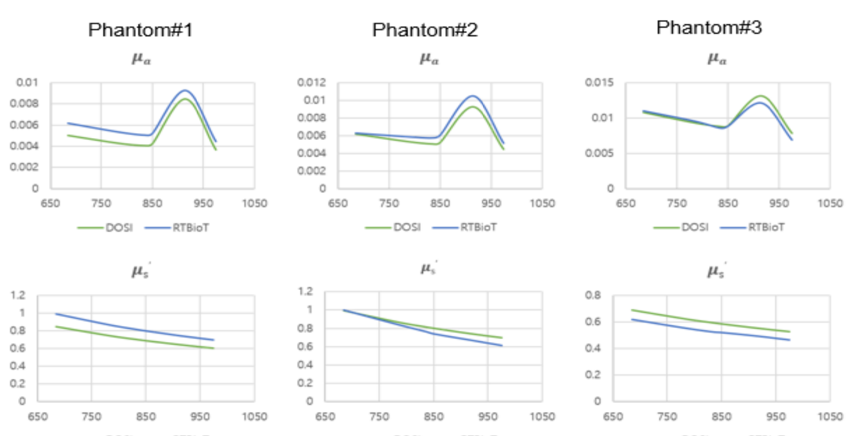
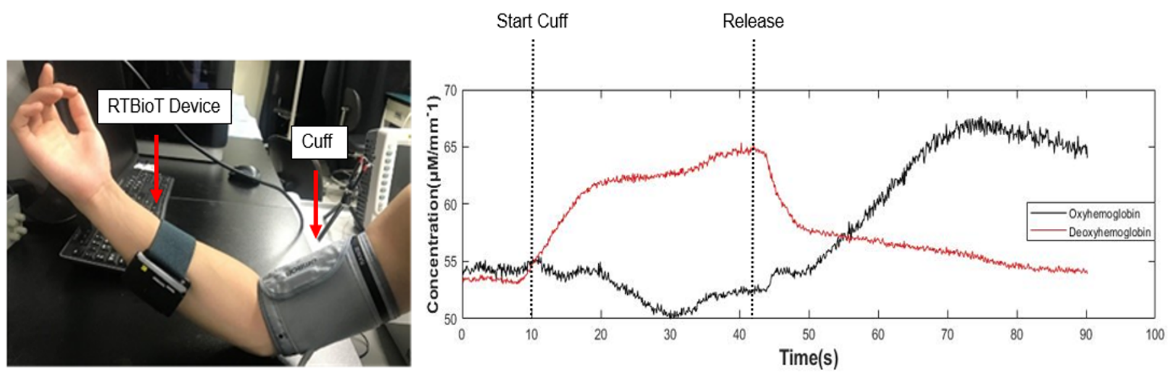


Figure 3. Optical properties comparisons

3.2 Real-time measurement for hemoglobin change

We have conducted an experiment to verify the feasibility of RTBioT's performance of chromophores quantification in real time fashion. The experimental setup is as shown in Fig. 4(a). We placed the RTBioT on lower arm of a subject and cuff machine on the upper arm to see the change of hemoglobin during cuff. First, we have checked the hemoglobin information ten seconds in normal condition. After ten seconds, we started the cuff machine to set up a different condition to the measurement. This condition is kept for thirty seconds and the cuff machine released to be back to the normal condition. The concentration of hemoglobin information was recorded in real- time fashion. As a result, we were able to monitor their change according to before and after cuff. The result is shown in Fig. 4 (b), the concentration of both are steady before cuff. When we started the machine, blood vessel is blocked gradually by the machine. Therefore, the concentration of oxyhemoglobin is decreasing, and the concentration of deoxyhemoglobin is increasing. When the machine is released, an effect of a blockage in blood vessel is getting lower so that the concentration of oxyhemoglobin is increasing, meanwhile the concentration of deoxyhemoglobin is decreased.



(a) Cuff experiment setup (b) Real-time measurement

Figure 4. Real-time measurement of hemoglobin changes by using cuff machine

We have presented a novel fast Bio-IoT device based on spatially resolved near infrared spectroscopy. The performance of accuracy and a real time measurement at RTBoT is proved by both silicon phantom analysis between mDOSI and RTBioT and a real implementation of a cuff device-based blood flow with oxy-hemoglobin and de-oxyhemoglobin concentration algorithm. Experimental results show it promising on real applications. The low power consumption and small form factor of the RTBioT enables implementation on the IoT sensing front end or wearable devices. We also showed that the fast analysis algorithm supported by high sampling rate of RTBioT to be a viable option, in contrast to traditional NIRS or DOS used in previous works. We accelerate the process by taking advantage of the lock-in function, pipelining, and auto gain control schemes. Our experience shows two important implications: 1) The signal processing properties should be thoroughly studied in order to reduce the complexity of RTBioT. 2) The algorithm for the physiological information in tissue should be specific to the target applications.

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