# Wearable Blood Flowmeter Appcessory with Low-Power Laser Doppler Signal Processing for Daily-Life Healthcare Monitoring

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***Abstract*— A new appcessory for monitoring peripheral blood flow in daily life consists of a wearable laser Doppler sensor device and a cooperating smart phone application. Bluetooth Low Energy connects them wirelessly. The sensor device features ultralight weight of 15 g and an intermittent signal processing technique that reduces power consumption to only 7 mW at measurement intervals of 0.1 s. These features enable more than 24-h continuous monitoring of peripheral blood flow in daily life, which can provide valuable vital-sign information for healthcare services.**

## I. Introduction

New healthcare services based on wearable sensor devices that monitor vital sings, such as heart rate [1], the heart's electrical activity [2], and body motions [3], are rapidly spreading. Some of these devices are connected to and cooperate with a smart phone application via Bluetooth Low Energy (BLE) [4] to improve usability. These new types of sensor devices are called appcessories, which is a new word combining application and accessory.

In this paper, we present a new healthcare appcessory that monitors peripheral blood flow in daily life. Blood flow contains a great deal of information about our physical and mental condition. Peripheral blood flow is measured by laser Doppler flowmeters [5], but commercially available devices are desktop size and used in only hospitals and laboratories. Making the devices wearable will enable daily-life monitoring and provide new valuable vital-sign information for healthcare services [6, 7]. Our blood flowmeter is small, lightweight, and wearable. It also features low power consumption, which allows long-term continuous monitoring. The smart phone application provides real-time visualization and storage of measured data and enables Cloud-based healthcare services. The design of the appcessory and some experimental results are described in the next sections.

## II. Design

### *A. System Architecture*

The system architecture of our blood flowmeter appcessory (Fig. 1) comprises a sensor device and a smart phone. The sensor device consists of a main unit, an electrical cable, and a sensor head that includes a laser diode (LD) and a

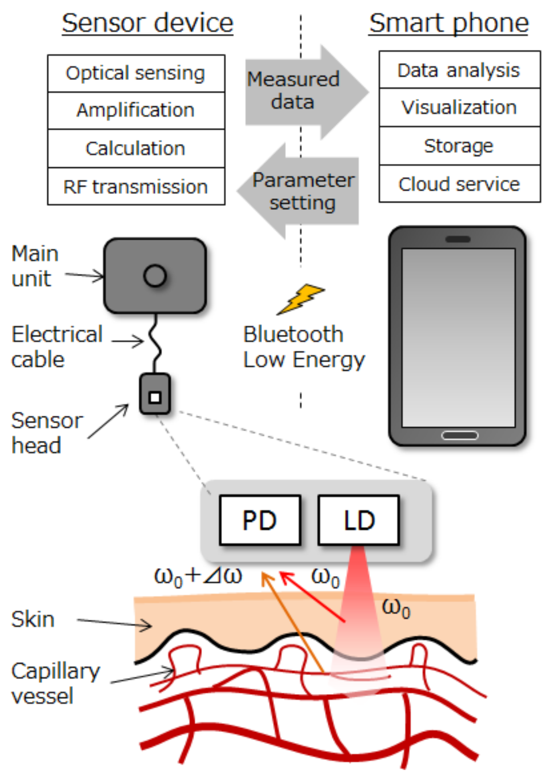


Figure 1. System architecture of the wearable blood flowmeter appcessory.

photodiode (PD). Compared to commercially available blood flowmeters that use an optical fiber, the structure of the sensor head reduces motion artifacts by integrating the optical components and replacing the optical fiber with an electrical cable [6-8].

To reduce the size and power consumption of the sensor device, various processes are shared by the sensor device and the smart phone application. The sensor device performs preprocessing such as optical sensing and basic calculations, and the smart phone application performs postprocessing such as advanced data analysis and visualization. The interface is determined so that the power consumed by the sensor device is minimized. The system operates as follows. First, light emitted by the laser is scattered by tissue and sensed by the PD. Then, blood flow is calculated by the main unit. The data is transmitted to the smartphone via BLE, and they are analyzed, visualized, and stored by the smart phone application.

The cooperation with the smart phone application yields not only size and power reductions but also an improved user

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978-1-4244-7929-0/14/$26.00 ©2014 IEEE

experience. The measured data can be displayed visually in real time, and sophisticated Cloud services such as healthcare advice can be offered by using Long Term Evolution technology.

### B. *Circuit Configuration*

The circuit configurations of the sensor head and the main unit are illustrated in Fig. 2. To reduce the size and power consumption, we construct the circuits with a limited number of components having sleep mode, which reduces power consumption substantially when they are disabled.

The sensor head includes an LD driver circuit and a transimpedance amplifier (TIA). The main unit includes a programmable gain amplifier (PGA), a low pass filter (LPF), and a core module that integrates an ARM coretex-M0 processor and BLE circuits. A current generated by the PD is amplified by the TIA and its DC signal is extracted by the LPF. The output signal of the TIA is further amplified by the PGA. Differential amplification of the TIA's output and the DC signal provides amplified AC signal. The AC and DC signals are converted to digital signals by analog-digital converters (ADC) in the core module. The digital signals are processed by the core module and calculated data are transmitted to the smart phone by the BLE circuits. These circuits are powered by a lithium ion secondary battery having a capacity of 110 mAh.

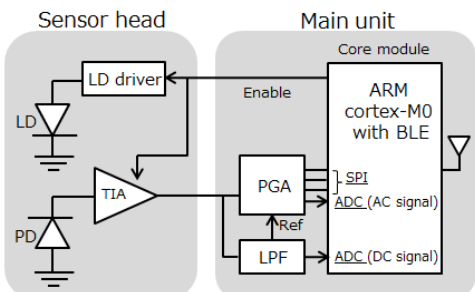


Figure 2. Circuit diagram of the sensor device.

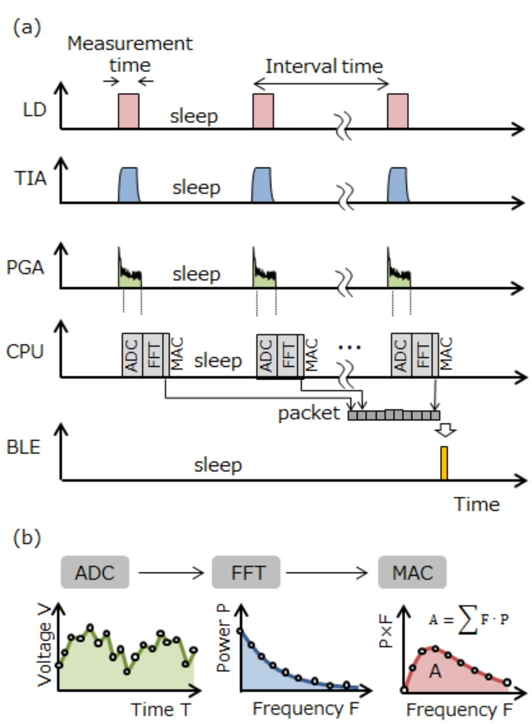


Figure 3. Signal processing in the sensor device.

### C. *Signal Processing*

The sensor device features intermittent laser Doppler signal processing to reduce power consumption. All power-consuming components are enabled only when necessary and are disabled otherwise. Fig. 3(a) illustrates the signal processing flow in the device. First, the LD driver, TIA, and PGA are enabled by the core module. After short stand-by time to allow convergence of the PGA's output DC voltage level, an ADC starts sampling AC signals. After the AC signal conversion is completed, DC signal is also converted once. The measurement time is typically about 8 ms. Then, the LD driver, TIA, and PGA are disabled for power saving. Next, the sampled time-domain AC signals are converted to frequency-domain signals by fast Fourier transform (FFT), and blood flow is calculated by multiplication and accumulation (MAC) of the frequency–domain signals as shown in Fig. 3(b). The principle of the blood flow calculation method is described in the literature [9]. These operations are repeated with an interval of typically 0.1 s. Because the measurement time is much shorter than the interval, the intermit operation reduces power consumption substantially. After several repetitions, calculated blood flow values are collected to construct a packet, which is sent to the smart phone via BLE. Transmitting the data not one by one but altogether improves the power efficiency.

In the intermittent signal processing, key parameters, such as the interval between measurements and the measurement time can be configured from the smart phone via BLE, making it possible to adjust the tradeoff between data accuracy and power consumption according to the application of the blood flowmeter.

## III. Results

### A. *Fabrication Results*

The fabricated wearable blood flowmeter appcessory is shown in Fig. 4. The size of the main unit is 4.0 x 3.0 x 1.25 $cm^3$ and the size of the sensor head is 1.5 x 1.3 x 0.62 $cm^3$. The total weight of the sensor device is only 15 g. With these small sizes and the light weight, the sensor device can be attached to

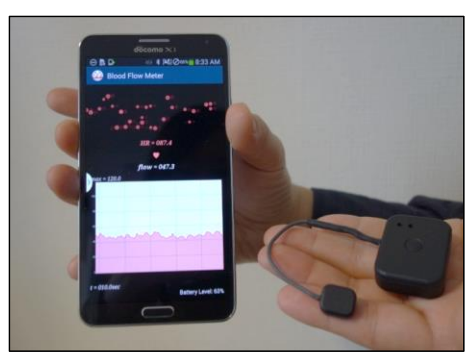

Figure 4. Photograph of the wearable blood flowmeter appcesory.

various parts of the body, such as a fingertip or earlobe, as shown in Fig. 5.

Fig. 6 is a screen capture of the smart phone application. The application displays a time-series graph of blood flow data. The blood flow is also visualized as animation. In addition, the heart rate is analyzed from the fluctuation of the blood flow and displayed as a number and an animation of the heartbeat. While the measured data is transmitted intermittently, the application makes them continuously and visualizes smoothly. All the measured data is stored in the memory of the smart phone.

Fig. 7 shows the power consumption of the device with and without intermittent operation with the measurement interval of 0.1 s. Without intermittent operation, the LD driver circuit, TIA, and PGA are always enabled. With intermittent operation, the power consumption is reduced to only 7 mW, resulting in battery life of about 50 hours. The power consumption can be further reduced by making the interval longer.

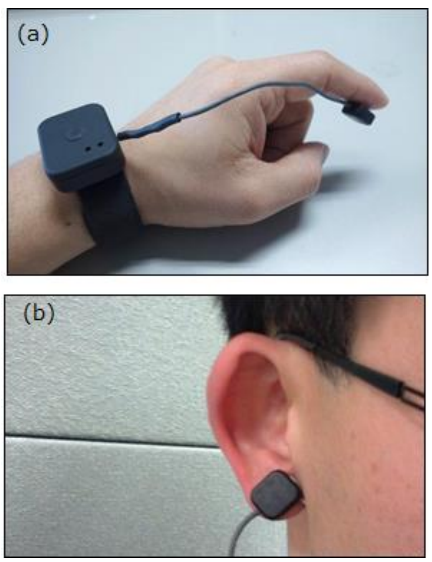


Figure 5. Photographs of the sensor device attached to (a) finger tip and (b) earlobe.

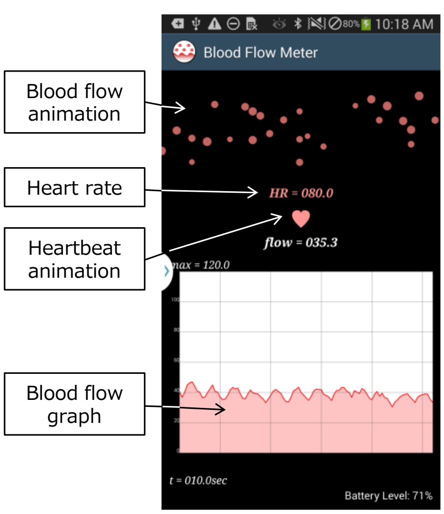


Figure 6. Screen shot of the smart phone application.

## B. Measurement Results

To demonstrate the feasibility of our device, we measured blood flow in various situations as shown in Fig. 8–10. Fig. 8 shows blood flow at a fingertip with a blood pressure cuff on the upper arm. The blood flow decreased when the cuff was inflated and increased when it deflated. Fig. 9 shows blood flow at an earlobe. There are oscillations at two frequencies as shown in the power spectrum. The oscillation at the higher frequency of around 1.1 Hz is caused by the heartbeat, and the

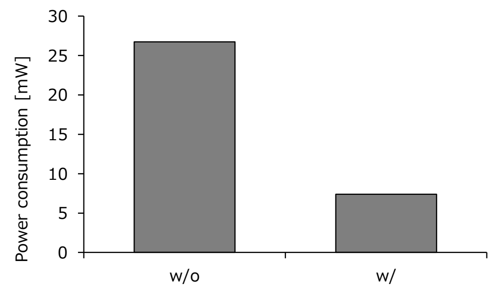


Figure 7. Power consumption of the sensor device with and without intermittent operation.

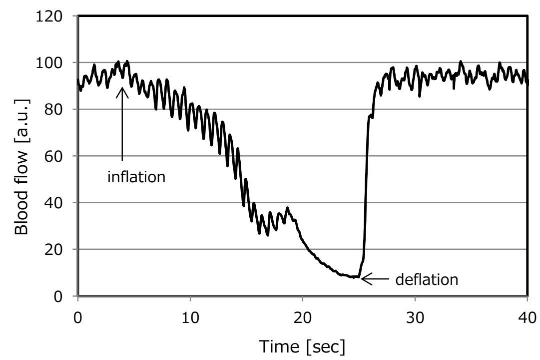


Figure 8. Measured blood flow at finger tip with a blood pressure cuff.

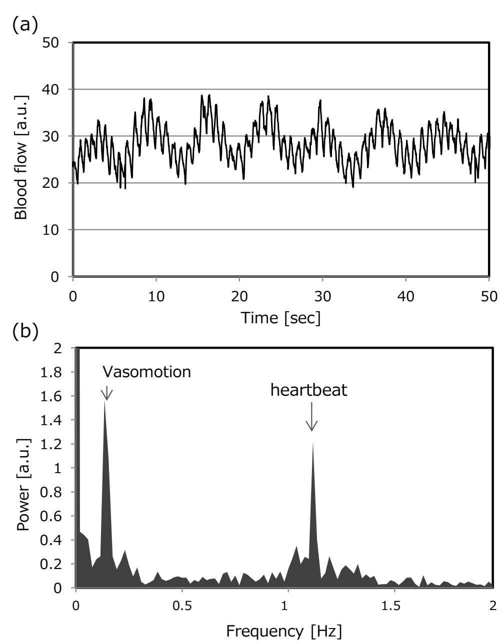


Figure 9. Measured blood flow at earlobe. (a) Time-domain signal and (b) power spectrum.

oscillation at the lower frequency of around 0.1 Hz is caused by vasomotion, which is a change in the diameter of a blood vessel [10]. These results indicate that our blood flowmeter has sufficient accuracy and time resolution for monitoring the changes and oscillations in peripheral blood flow. Finally, Fig. 10 shows the results of 24-h continuous monitoring of blood flow near the first-finger fingernail in daily life. The measured data were low-pass filtered for reducing short-term fluctuations. Heart rate was also measured with a commercially available heart rate sensor. Changes in the blood flow caused by daily behavior, such as eating a meal, driving, studying, and sleeping, are visualized. The long-term continuous monitoring of blood flow in daily life is achieved by innovative size reduction and power saving of laser blood flowmeters.

## IV. CONCLUSION

For a new wearable blood flowmeter appcessory, the system architecture, circuit configuration, and signal processing were designed to reduce the size and power consumption. The appcessory can continuously monitor peripheral blood flow in daily life. With an enhancement of the smart phone applications and cooperation with Cloud technology, new valuable vital-sign information can be used for creating healthcare services to improve our health.

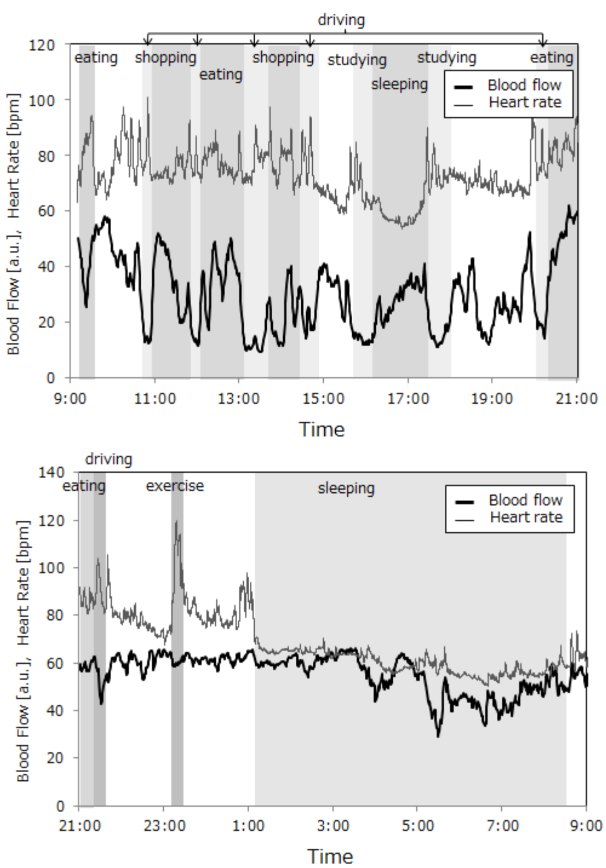


Figure 10. 24-h continuous monitoring of blood flow and heart rate.

## ACKNOWLEDGMENT

The authors thank Dr. Y. Sato for his helpful support and encouragement.

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