Wearable Laser Blood Flowmeter

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Abstract

This paper describes a wearable laser blood flowmeter that is a fully functional miniaturized version of a conventional desktop laser blood flowmeter. This innovation was achieved by applying optical telecommunications device technology. Our micro laser blood flowmeter can monitor circadian changes in bloodflow regardless of the time and place, so it will be useful in preventive medical care and in sports medicine.

1. Introduction

The cost of Japan's national healthcare exceeded thirty trillion yen in 2004 and is taking an ever bigger share of the national budget. Other statistics show that the second and third leading causes of death are heart and cerebrovascular diseases*1, respectively, which are both related to the circulatory system, and that the combined number of victims of these diseases equals the number of victims of cancer, the primary cause of death. Therefore, taking the action against these circulatory diseases is very important. More and more doctors are advocating preventive medicine, which aims to prevent lifestyle diseases and maintain health. For preventive medical care, wearable medical sensors that can monitor physical condition regardless of time and place would be very useful. Moreover, being able to use such sensors in combination with telecommunications systems would be very effective for remote health management.

To prevent circulatory diseases, many doctors advise that we monitor our blood pressure at home. For this purpose, various portable blood pressure monitors are commercially available. However, blood pressure data provides neither information about the peripheral vascular resistance related to circulatory diseases nor information about the real bloodflow in tissues. To obtain such information, you need a blood flowmeter. However, conventional ones are desktop-sized pieces of equipment and weigh several kilograms, so they are not really portable and cannot be used for preventive medical care for daily monitoring of the circulatory system. Recently, NTT has invented a portable micro laser blood flowmeter [1], [2], [3] capable of wireless communication as a medical application of photonics device technology originally developed for optical telecommunications. This paper describes this device and presents some experimental data.

2. Laser blood flowmeter

The bloodflow in living tissues was measured using a laser for the first time in 1975 by Michael Stern. He detected and analyzed scattered laser light signals from biological tissue [4]. Nowadays, laser blood flowmeters are manufactured in Sweden [5], the USA [6], the UK [7], and Japan [8] and are widely used in medicine and in other fields [9], [10]. In internal medicine, they are used in the diagnosis of peripheral circulatory disturbances in diabetics. Otorhinolaryngologists*2 depend on them in measuring bloodflow in nasal mucosa, and vascular surgeons depend on them in diagnosing occlusive arterial disease. They are also

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*1 Cerebrovascular diseases: diseases of the blood vessels of the brain.

*2 Otorhinolaryngologist: medical specialist who studies diseases of the ear, nose, and throat.

used in plastic surgery during skin transplants. Moreover, they can monitor relaxation, which is detected by an increase in blood flow, and this has been used in research in the automotive, apparel, cosmetics, and construction industries to determine the level of user comfort [9].

The principle of laser bloodflow measurement is shown in **Fig. 1** [11]. Light from a laser diode passes through an optical fiber and irradiates tissue. The laser light is scattered and reflected by the tissue and by the blood cells in the capillaries. The velocity of the bloodflow, which runs in all directions in the capillary network, has a velocity distribution of 1 mm/s or less. The scattered light from the tissue is conveyed by another optical fiber to a photodiode and converted into an electrical signal. The Doppler effect causes a frequency change in the received scattered light, which is proportional to the velocity of the blood cells. The principle of the bloodflow calculation based on the detected signal is shown in **Fig. 2**. Although the frequency of the laser light itself is too high to be detected (hundreds of terahertz), the frequency difference between the reflected light from moving blood cells (frequency with Doppler shift) and the reflected light from the tissue at rest (frequency without Doppler shift) ranges from a few hundred hertz to several tens of kilohertz. Therefore, when the two lights interfere with each other, a detectable beat signal [I(t)] is produced. In the power spectrum graph of the beat signals [P(ω)], the frequency axis corresponds to blood cell velocity and the power axis to the number of blood cells. Roughly speaking, the bloodflow can be expressed as the total of the products of the number of blood cells traveling at each particular velocity multiplied by that velocity. Therefore, we can calculate the bloodflow by integrating the products of the beat signal power spectrum and frequency.

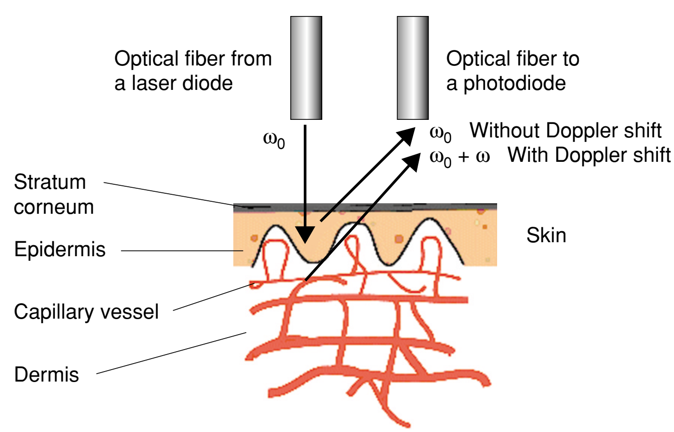

Fig. 1. Principle of laser blood flow measurement.

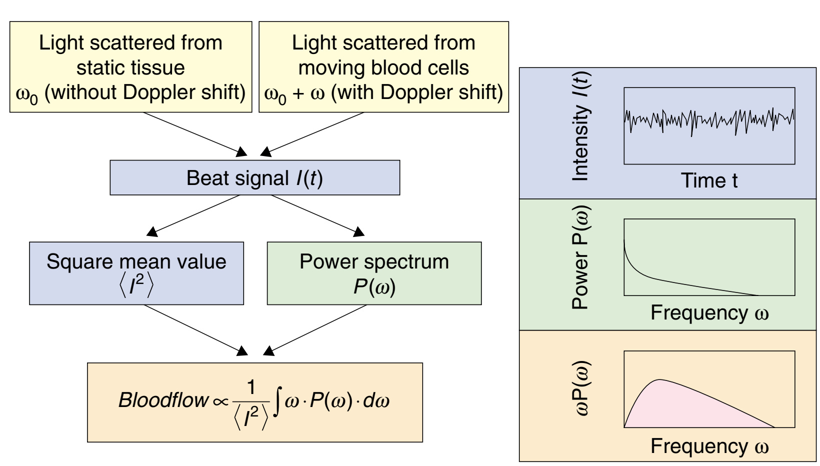

Fig. 2. Principle of bloodflow calculation.

The structure of a conventional optical fiber laser blood flowmeter is schematically shown in **Fig. 3**. The equipment weighs several kilograms and is several tens of centimeters wide and long. Although the probe itself is very small, vibration of the optical fiber influences the measured data. Moreover, the laser diode and photodiode are each sealed inside a bulky housing with a heat sink. Besides the laser diode and photodiode, the optical system requires lenses and fibers, and each optical axis of each optical component must be aligned. The assembly process is time-consuming, which has made it difficult to reduce the cost. The other parts—the amplifier, analog-to-digital (A/D) converter, digital signal processor (DSP), and laser drive circuit—are electronic parts. Although it is technically possible to reduce the size of the electronic parts by constructing them as an integrated circuit, the difficulty of miniaturizing the optical parts has been an obstacle to reducing the total device size. Thus, the conventional blood flowmeters used in clinics and hospitals are desktop equipment that cannot be freely moved.

3. Technology for miniaturization

To solve these problems we eliminated the optical fibers, decreased the number of parts, and simplified the module assembly process. The sensor chip is shown in detail in **Fig. 4**. It is fabricated as follows. First, electrodes, solder film, and an optical waveguide are patterned onto a silicon substrate chip (2 mm × 3 mm) by photolithography. Then, the laser diode and photodiode chips are integrated onto the chip surface with high precision (±1 µm) [12]. Then, a light-shading silicon cap is bonded to the chip. The laser diode chip is a single-mode InGaAsP/InP dis-

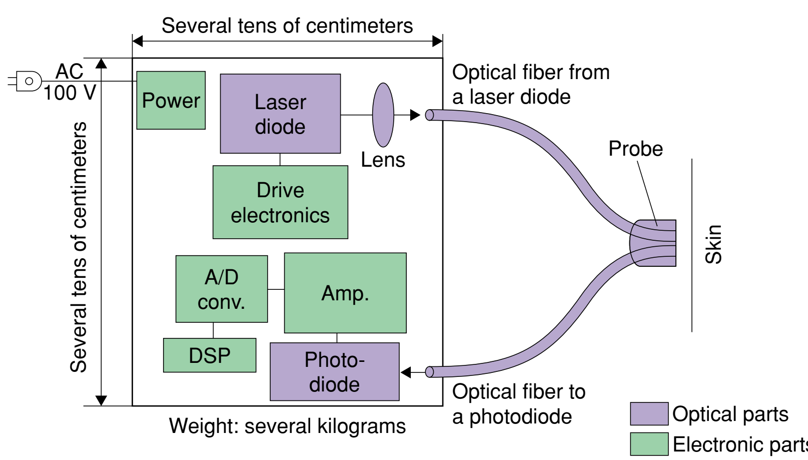

Fig. 3. Structure of a conventional laser blood flowmeter.

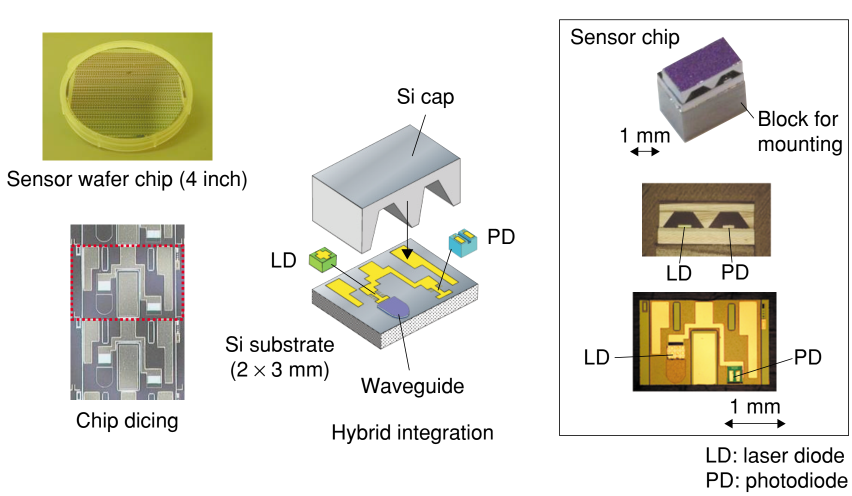

Fig. 4. Fabrication process and sensor structure.

tributed feedback semiconductor laser diode with a lifetime of 100,000 hours or more. The optical waveguide is made of fluorinated polyimide [13] which is inexpensive and easy to fabricate. The photodiode is an edge-illuminated refracting-facet photodiode [14]. Whereas the wavelength used by the conventional laser blood flowmeter is 0.6–0.8 µm, these optical devices operate at 1.3 µm, which enables better transmittance through skin because very little of the light is absorbed by melanin and hemoglobin [15]. In addition, the distributed feedback semiconductor laser diode is very suitable for optical measurement because it emits laser light of a single mode and the frequency is very stable. To obtain a higher signal-to-noise ratio, a conventional blood flowmeter uses an optical fiber as a spatial filter for incoming light. We were able to eliminate this optical fiber in our micro blood flowmeter because the small light receiving area of the edge-illuminated refracting-facet photodiode works as a spatial filter. The light-shading silicon cap prevents stray light from the laser diode reaching the photodiode, which decreases the background noise.

For the micro laser blood flowmeter, we built a surface integrated sensor chip that contains no discrete components and no optical fibers. We achieved this by using optical semiconductor devices and integration technology originally developed for optical telecommunications. The sensor chip was mounted on a circuit board with a preamplifier to amplify the light signal received from the photodiode. Then, the sensor chip was packaged and fitted with a sensor head, which makes contact with the skin. The packaged chip is shown in **Fig. 5**. The sensor head is 17 × 12 × 6 mm^3. It weighs 9.6 grams.

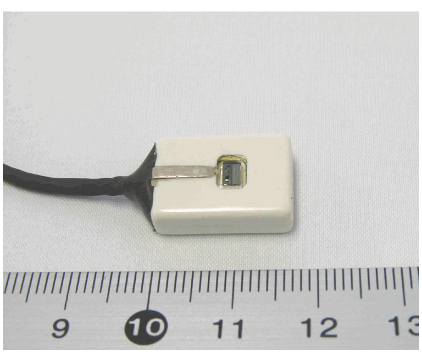

Fig. 5. Sensor head.

4. Micro laser blood flowmeter

A photograph of the blood flowmeter being worn on the wrist is shown in **Fig. 6**. The main unit on the arm is 63 × 45 × 20 mm^3. It weighs 55.8 grams. A liquid crystal display on the main unit's case indicates the bloodflow. The main unit contains the electronic parts: the amplifier, A/D converter, DSP, laser driving circuit, display panel controller circuit, secondary cell, and Bluetooth radio communication circuit. To make maximum use of its portability, we added a radio communication function for remote measurement.

5. Bloodflow measurement

We performed some measurements of blood perfusion from the fingertip. **Figure 7** shows an example of bloodflow data obtained simultaneously with the wearable blood flowmeter (upper curve) and a conventional one (lower curve). The sensor head was attached directly to the fingertip using double-sided tape to avoid external pressure. Data from the micro laser blood flowmeter was sent wirelessly to a notebook personal computer by using the Bluetooth transmission protocol, and the graph was displayed on the

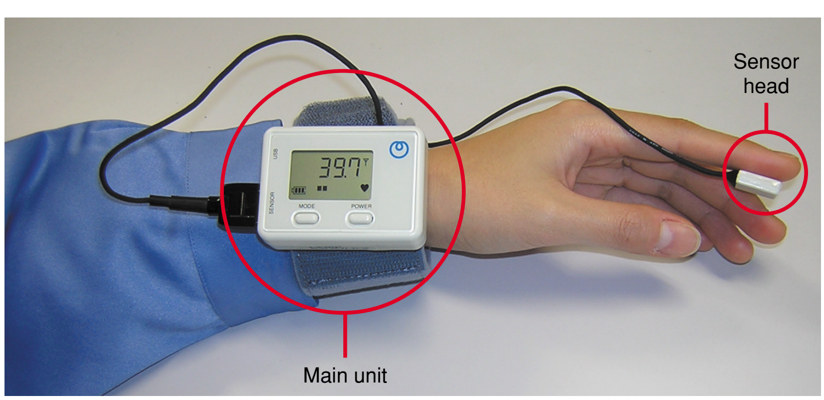

Fig. 6. Micro laser blood flowmeter.

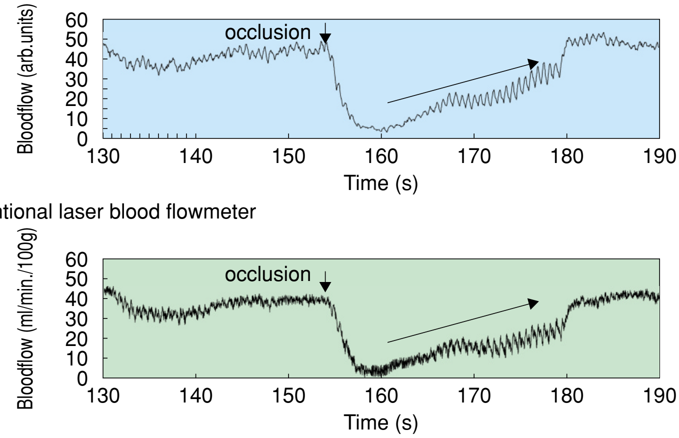

Fig. 7. Bloodflow data obtained with NTT's micro laser blood flowmeter and with a conventional one.

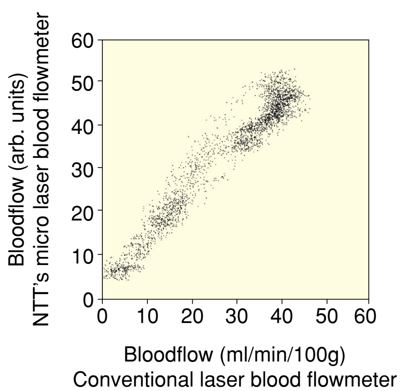

Fig. 8. Correlation plot.

monitor in real time. To test the dynamic response of microcirculation, the wrist was occluded with a pressurized cuff and the pressure released gradually. The results clearly indicate that the bloodflow rapidly decreased when the wrist was occluded and recovered gradually as the pressure was released. The bloodflow signal curves show small variations with the heartbeat. The signal curve from the micro laser blood flowmeter agrees well with the one from the conventional laser blood flowmeter.

A correlation plot for the two flowmeters, shown in **Fig. 8**, shows clear correlation. From the results of Figs. 7 and 8, we conclude that the differences in indicated values are small and the trend is similar. Therefore, the micro blood flowmeter is by no means inferior to the conventional one.

6. Conclusion

We have applied optical telecommunications device technology to develop a wearable micro laser blood flowmeter with wireless communication capability. This flowmeter will make it possible to monitor changes in bloodflow regardless of time and place. Bedside monitoring in hospitals and home health monitoring of elderly people living alone with this device will allow medical professionals to ascertain physical conditions in real time and implement necessary measures. Another use will be in the prevention and management of lifestyle diseases at the individual level through telemedicine and long-term monitoring. Applications in sports medicine are also expected because the device enables restraint-free physiological data acquisition in training and competition. This device and others produced utilizing telecommunications technology and ubiquitous networks should usher in a drastic change in medical services from hospital-centric ones to home-centric ones and shift the focus from treatment to prevention.

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