Simultaneous Measurement of a Blood Flow and a Contact Pressure

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Abstract: Although a number of laser Doppler blood flow sensors have been developed over the past few decades, they remain uncommon in practice. This is because the contact pressure between the skin and the sensor is not measured simultaneously with blood flow, despite the fact that blood flow is greatly affected by contact pressure. Thus, reliable and highly reproducible measurement of blood flow could not yet be realized. In addition, changes in beam conditions or body temperature also have an effect on blood flow measurement. Therefore, we fabricated a micro electro mechanical system (MEMS) blood flow sensor which can measure contact pressure, beam power, and body temperature, for reliable and highly reproducible measurement.

1 INTRODUCTION

Continuous health monitoring systems using biomedical sensors have been widely studied recently to prevent certain diseases. Laser Doppler blood flow meter has been studied to enhance health monitoring systems because the monitoring of peripheral blood flow just beneath the skin is intimately correlated with health conditions and the nervous systems (Wolfman Doehner et al., 2002. Julian M. Stewart et al., 2004. M. Yasushi et al., 2003).

The laser Doppler flow meter is a non-invasive method for measuring blood flow in the micro circulation of biological tissue, and was established by Stern et al. in 1977 (Stern, M. D. et al., 1977). The device has been widely used in clinical medicine, microcirculation, dermatology, and autonomic function research. There are commercialized blood flow meters such as the ADMEDEC Laser Doppler blood flow meter (ALF21; ADVANCE CO., LTD), stationary and optical fiber type blood flow meters (OMEGAFLO; OMEGAWAVE, INC), and fiber-less blood flow meter (RBF-101; Pioneer Corporation). Moreover, the development of blood flow meters using micro electric mechanical systems (MEMS) techniques are currently the focus of active study to achieve the goals of low power consumption, downsize the dimensions of the sensor, and maintain low cost. In an earlier study, the present authors fabricated an integrated sensor for use in laser Doppler blood flow measurement systems without optical fibres by mounting laser diode and photo diode on silicon substrate (E. Higurashi et al., 2003). Since then, smaller blood flow sensors have been fabricated using system line or wafer level packaging techniques (W. Iwasaki et al., 2010. Y. Kimura et al., 2010).

Although a number of blood flow sensors have been developed over the past few decades, they are used in only medical field. This is because contact pressure has not been considered while measuring blood flow, despite the fact that blood flow is greatly affected by it.

Figure 1 shows blood flow when contact pressure is increased every 20 mmHg. When contact pressure is lower (0-40 mmHg), the blood flow is larger and the blood amplitude is smaller. Blood flow decreases a little, but the amplitude increases when contact pressure is between 60mmHg and 80mmHg. Finally, blood flow is about one tenth of what is measured in the 0mmHg case, and the amplitude decreases again when it exceeds 100 mmHg. This is because the skin tissue and vessels are elastic and their deformation via contact pressure can change the blood stream. Contact pressure increases linearly, but blood flow and amplitude change in a non-linear fashion. Furthermore, the influence of contact pressure on blood flow measurement is dependent on individual differences such as the hardness of the skin tissue and blood pressure. Therefore, simultaneous measurement of contact pressure is important for optimizing blood flow measurement.

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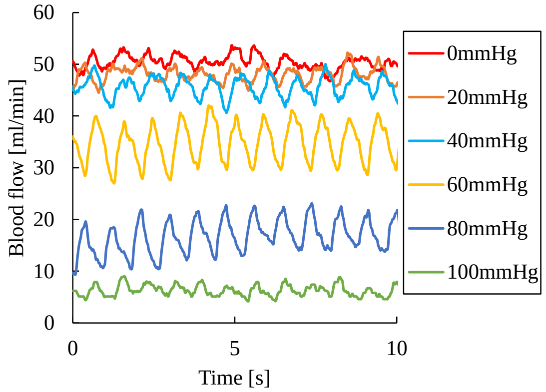


Figure 1: Blood flow under different patterns of contact pressure.

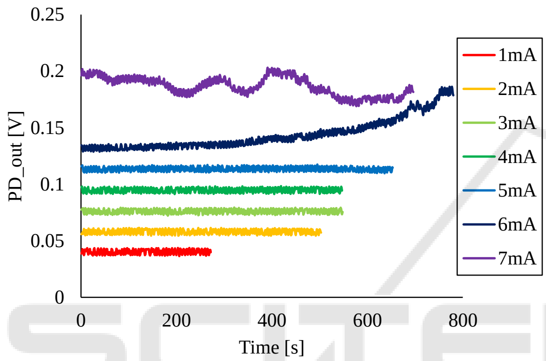


Figure 2: beam monitoring under different patterns of drive current.

In addition, Figure 2 shows the output of PD for monitoring the laser beam from the vertical cavity surface emitting laser (VCSEL) used in the blood flow sensor. The beam power unsteadily changes in response to a drive current and drive time and can also be changed by environmental temperature. Unstable beams undermine the authenticity of the data from blood flow measurement. Therefore the simultaneous monitoring of beam power is also important for optimizing blood flow measurement.

A deep body temperature does not change dramatically, but a temperature of contact point between the sensor and the skin changes easily. A blood flow is changed by blood vessel constriction based on surrounding temperature. Thus, measurement of contact point temperature is also important for improving it.

In this study we propose a new structure for an integrated blood flow sensor which can measure blood flow and contact pressure simultaneously. Moreover, the sensor has a monitoring system that includes beam conditions and contact point temperature to enhance blood flow measurement.

2 SENSOR

The integrated blood flow sensor chip was fabricated by using a ceramics multi-stratified technique, and consists of a vertical cavity surface emitting laser (VCSEL), three photo diodes (PDs), Op-Amps, several resistors and capacitors on the multi-layer ceramics board, and is 6.5mm×6.5mm×1.3mm in size, as shown in Figure 3. The blood flow sensor module size is 10mm in diameter and 6.7 mm in thickness, and is composed of a covering for the integrated blood sensor chip with a metal cap and a deformable cap which includes a polypropylene sheet, an acrylic lug and a thermistor to measure the contact point temperature (Figure 4).

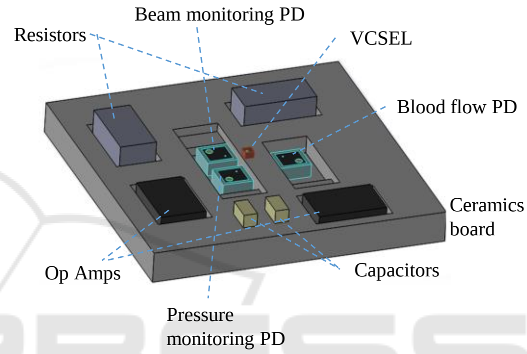
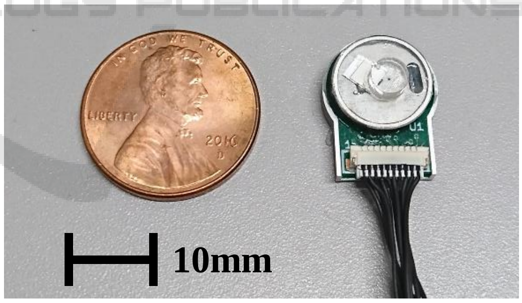
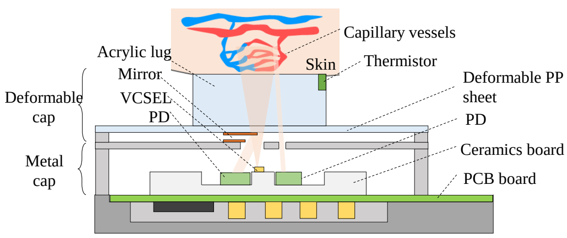


Figure 3: A schematic of developed integrated blood flow sensor chip.



(a)



(b)

Figure 4: (a) Blood flow sensor module and (b) diagram of the cross section view of the sensor module and of the measurement principle.

The laser beam from the VCSEL is emitted radially, and as a result, the beam penetrates into skin tissue or is reflected by the mirror on the metal cap and on the back-side of the deformable cap. The laser beam that is diffused into the skin tissue is back-scattered. The backscattered light has two forms: Doppler-shifted light caused by moving particles (mainly the red blood cells of the capillary and arteriole) and non-Doppler shifted light caused by static tissue. The light was interfered with by the PD, and intensity modulations related to blood velocity were observed on the PD. The power spectrum of the intensity modulations includes the random characteristics of the velocity vector of blood perfusion in the vessel. In such cases, blood flow is calculated using the following formula.

$$< \omega >= \int \omega P(\omega) d\omega \tag{1}$$

The blood flow is proportionate to the averaged velocity multiplied by the concentration, of Doppler scattering particles. P(ω) is the power spectrum of the frequency distribution, and $< \omega >$ is the first moment of the power spectrum of the frequency distribution. The statistically derived value, $< \omega >$ is used as the blood flow as shown in Figure 5 (Y. Kimura et al., 2010).

When contact pressure occurs between the acrylic lug and skin tissue, the deformable polypropylene sheet (PP sheet) bends down, the mirror attached to the back of the PP Sheet also moves down in a vertical direction, and the light reflected on the mirror is detected by the pressure monitoring PD. The monitoring PD output is changed in correspondence to the vertical displacement which is related linearly to the contact pressure (T. Iwasaki et al., 2015). Ensuring that one light beam emitted from a VCSEL chip functions as the light source for both the laser blood flow sensor and laser displacement sensor means that blood flow and contact pressure can be measured simultaneously.

The mirror is attached to the top of the metal cap. The light reflected on the mirror is detected by the beam monitoring PD. Due to this, the sensor can continuously check the beam power of the VCSEL.

Further, the acrylic lug can improve the repeatability of blood flow measurement. The acrylic lug can fix the contact area and the measurement position. In a previous study, blood flow was measured ten times; the mean blood flow and the average of the ten measurements, with or without the acrylic lug, are shown in Figure 6. The standard deviation (SD) is improved dramatically by attaching the acrylic lug (Ryo Inoue et al., 2016).

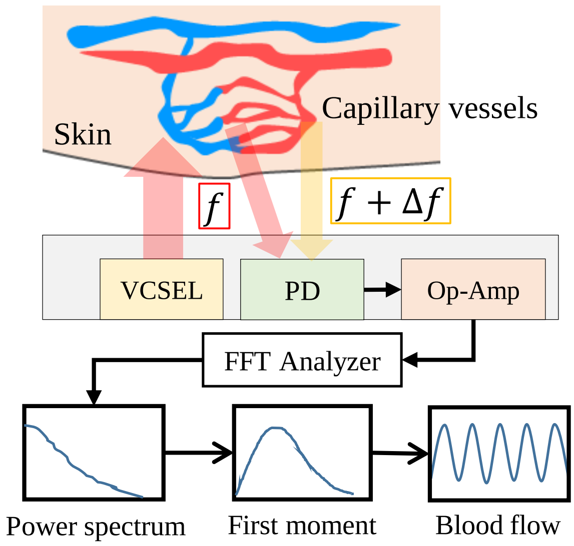


Figure 5: Principle of blood flow measurement.

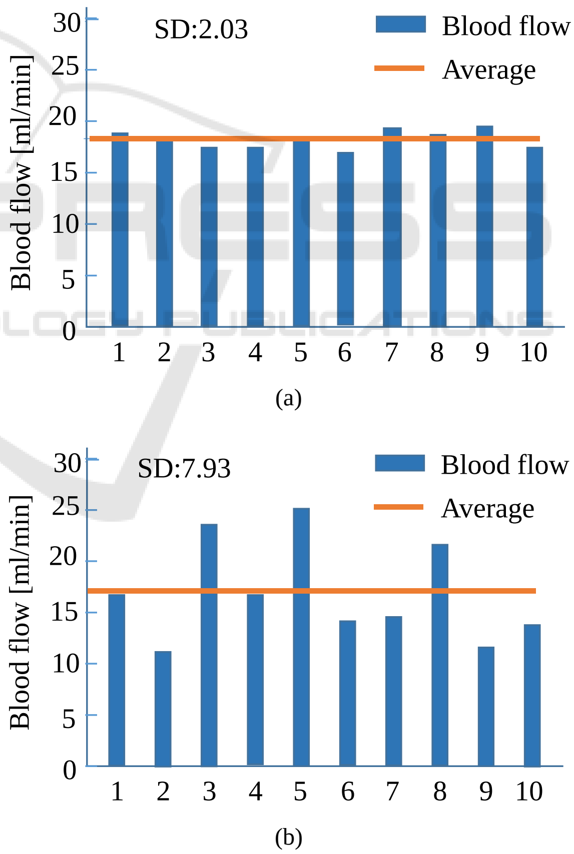


Figure 6: Measurement of mean blood flow with the acrylic lug attached (a) and without the lug (b).

3 EXPERIMENTS

The experimental system was set as shown in Figure 7. The sensor was connected to the electric circuit board. The power sources of the op-amp and VCSEL were also connected to the board and the circuit sent the data to the PC. LabVIEW was used to calculate blood flow from the signal of the PD, as shown in Figure 5, and to indicate and log the data of blood flow, contact pressure, beam power, and contact point temperature simultaneously.

Three experiments were conducted to check the performance of the sensor. In the first experiment, the simultaneous measurement of four data samples was conducted using the experimental system. In addition, the forearm of the subject was compressed with a cuff to reduce the blood flow purposely. It took 10 seconds to increase the pressure of the cuff from 0 mmHg to 300 mmHg. The cuff was then released after 15 seconds.

Next, a blower was used in place of putting the finger in the experimental system. The blower blew hot air (40 degrees) onto the sensor in order to check the change of beam conditions using the beam monitoring PD.

Finally, the subject pressed the sensor in three stages of the contact pressure. The blood flow was measured simultaneously while the contact pressure changed continuously and stepwise.

4 RESULTS

Figure 8(a) shows the four data points given by the simultaneous measurement using the sensor. Blood flow was measured while keeping the output of the pressure monitoring PD at about 50mV. When the cuff started to compress the forearm of the subject, blood flow decreased gradually. When cuff pressure was kept at 300mmHg, blood flow did not change dramatically. Then, blood flow suddenly increased to the original value following release of the cuff. Further, the beam power and contact point temperature values measured by the sensor stayed constant.

Figure 8(b) shows the output of the beam monitoring PD when the temperature around the sensor was increased by the blower. Increasing the temperature decreased the beam power. When the blower was removed, a tendency to recover gradually to the original voltage was shown. This indicates that the beam of VCSEL is effected by operating temperature and our sensor can measure it change simultaneously.

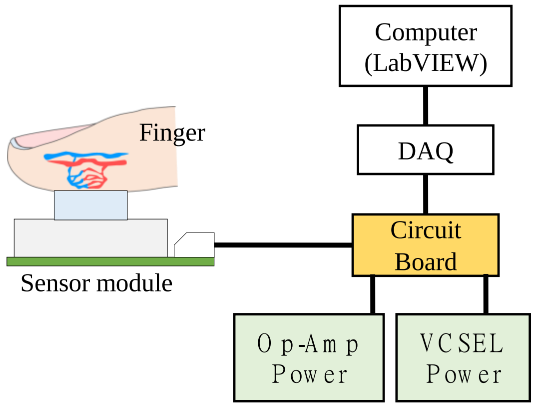


Figure 7: Experimental system used to measure the blood flow, the contact pressure, the beam power and the body temperature simultaneously.

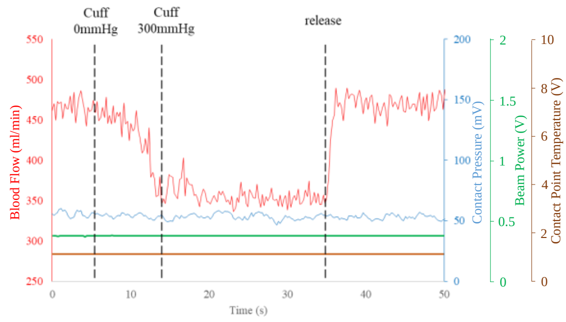
The blood flow in three stages of contact pressure is shown in figure 8(c). The blood flow decreased corresponding to the change of the contact pressure. The blood amplitude also changed. It got larger by increase of contact pressure (100 mmHg), and then became smaller by the strongest press (200mmHg).

5 DISCUSSION

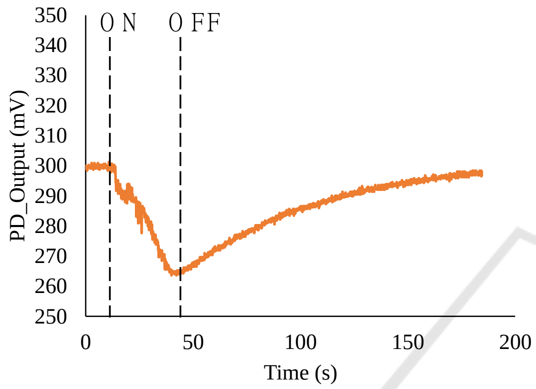
Figure 8(a) verifies the sensor can measure blood flow, contact pressure, beam condition, and contact point temperature simultaneously. In addition, blood flow is changed by the cuff. For contact pressure measurement, the calibration data need to be prepared beforehand, but it will be helpful for blood flow measurement to obtain reliable data. For example, contact pressure data can be used for a feedback control with programmable actuator by a microcontroller in order to maintain appropriate contact pressure range. The combination use this sensor and an actuator can improved blood flow measurement additionally.

Figure 8(b) shows the change of the output of monitoring PD corresponding to operating temperature. Beam power monitored by PD can be also used for a feedback drive using an automatic power control (APC) circuit. Figure 9 shows the APC circuit to adjust the drive current of the VCSEL from the difference between a reference voltage and the output of the beam monitoring PD. This circuit maintains constant beam power to achieve stable blood flow measurement.

Blood flow changes in three stages depending on the change of contact pressure. That also shows the relation among a blood flow, a blood amplitude, and



(a)



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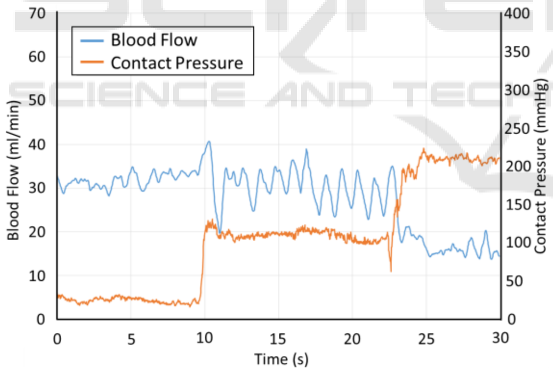

(c)

Figure 8: (a) the blood flow with under contact pressure of 80 mmHg, (b) the output of beam monitoring PD with a hot air by dryer, and (c) the blood flow in three stages of the contact pressure changed continuously and stepwise.

a contact pressure shown in figure 1. An indirect blood pressure measurement method was suggested by using the difference between the intravascular pressure and the external pressure (M. Nogawa et al., 2011). In their work, when this difference was small, blood amplitude increased. When this difference is zero, the blood amplitude vanished. It is difficult to control intravascular pressure, as it depends on health conditions such as whether the subject is being measured before or after exercise or when the subject is on a diet, but it is easy to control the value of the external pressure. This value is controlled by adjusting the contact pressure in this study. The sensor can monitor it simultaneously, so larger and clearer amplitude is obtained easily.

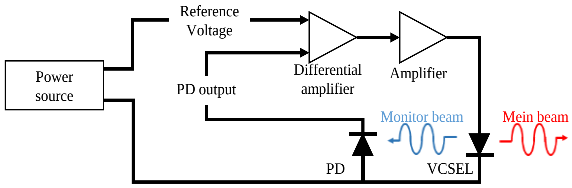

Figure 9: Automatic Power Control (APC) circuit

The sensor can provide new applications due to realizing reliable blood flow measurement. For example, the blood pressure determination conducted by the relation between the intravascular pressure and the contact pressure, and the stress detection by heartbeat interval from blood amplitude (T. Akiyama et al., 2015). In addition, a blood flow in a wave can be obtained as a new biological information.

To use the sensor for various fields like these applications, the error by the sensor should be smaller than by the health conditions such as illness, before and after exercise and so on. Our developed sensor can make the error smaller by measuring four data simultaneously.

4 CONCLUSIONS

The results verify that our new MEMS blood flow sensor can measure blood flow, contact pressure, beam power, and body temperature simultaneously. This performance achieves more reliable blood flow measurement than conventional sensors. Our developed sensor is expected to have a wide range of applications in the future since it is small enough to be attached to the body and enables highly reproducible measurement.

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