A venous occlusion plethysmography using a load cell as the sensing element

Yoshitake Yamamoto* Tatsuma Yamamoto†
P. Ake Oberg‡ Akiharu Yoshida**

*Okayama University
†Okayama University
‡Linkoping University
**Omron Institute of Life Science. Inc.

Venous Occlusion Plethysmography Using a Load Cell as the Sensing Element

YOSHITAKE YAMAMOTO, MEMBER, IEEE, TATSUMA YAMAMOTO, MEMBER, IEEE, P. ÅKE ÖBERG, MEMBER, IEEE, AND AKIHARU YOSHIDA

Abstract—**This paper presents an application of the load cell as a sensor in venous occlusion plethysmography, a well-established method for limb or digit blood flow measurements. In this method the limb volume changes that follow venous occlusion are transferred into the volume change of a water pool. The hydrostatic pressure as well as the water surface level is measured and used for the calculation of the volume change. By using this method the influence of water pressure on limb blood flow is avoided together with drift and leakage of the sensing element. The load cell has the advantage that it measures the weight of the displaced water volume which simplifies the design principles of the plethysmography. The plethysmography is found to be sensitive, highly linear, and easy to handle. It has been evaluated in several subjects and the results of these studies are in agreement with earlier results.**

I. Introduction

PERIPHERAL blood flows in limbs, or blood flows in particular organs and tissues are measured by methods such as plethysmography utilizing the change in tissue volume due to blood inflow, the impedance method using conductance change, and the clearance method calculating the blood flow volume from the rate of clearance of a certain substance, etc. [1]. An excellent method, the laser Doppler method, is also available but this method can be applied only to specified sites such as the skin [2] and blood vessels [3]. Among these methods, plethysmography, which is used for blood flow measurement in legs, fingers, etc., may be divided into water-displacement, air-displacement and mercury strain-gauge plethysmography [4]. From a clinical point of view, however, none of these plethysmography techniques are satisfactory blood flow meters with respect to accuracy and easiness in handling.

In the relatively popular water-displacement plethysmography, changes in water level and water pressure have been utilized for the measurement of tissue volume changes [5], [6]. However, the disturbance of blood flow due to compression of the target site and insufficient sensitivity and accuracy have been the problems of this method.

For the purpose of improving the reliability of plethysmography, we here propose an entirely new method utilizing a load cell sensor as an element for detecting tissue volume changes. Owing to the high resolution, good linearity, etc. of this sensor, a highly reliable instrument was developed in the present study. The results of actual blood flow measurements in forearms and fingers using a manufactured water-displacement plethysmography are presented below.

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Y. Yamamoto and T. Yamamoto are with the Department of Electrical Engineering, Okayama University, Okayama 700, Japan.

P. Å. Öberg is with the Department of Biomedical Engineering, Linköping University, S-581 85 Linköping, Sweden.

A. Yoshida is with the Omron Institute of Life Science, Inc., Kyoto 600, Japan.

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II. Water-Displacement Plethysmography and its Sensor

A. Venous Occlusion Method

The venous occlusion method, which is a fundamental technique for quantitative measurement of blood flows in limbs and digitals, is described first [5]. The principle of the method is illustrated in Fig. 1. A cuff is placed on the central part of the target body member, and a pressure P which is in-between the arterial pressure, P_a, and venous pressure, P_v, is applied. Under this condition, arterial blood can flow into the tissue peripheral to the cuff, but venous blood flow is stopped by the compression, resulting in venous blood accumulation. When the blood volume (V) is increased by ΔV for time Δt, the ratio of $\Delta V/\Delta t$ estimates the blood flow.

Water-displacement plethysmography utilizes this venous occlusion method and has been a reliable method for measuring the volume of accumulated blood in the limb. In this method, the limb is inserted into a water trough, and the volume change due to venous occlusion is detected by the change of the height of a water column (water level). The water level is measured either directly or via a pressure measurement.

It is necessary in this method that the pressure change caused by tissue volume change due to venous occlusion must be made as small as possible at the target site. For this purpose, it is preferable to make the cross-sectional area of the water column as large as possible. However, the larger the cross section, the smaller the height change, which results in greater difficulty in measurement.

As a method to overcome this problem, we propose the method illustrated in Fig. 1, in which a load cell sensor is used to convert the volume change into a weight change. Since the weight change ΔW is detected in this system and there is no need to measure the water level change, the cross section of the water column (A) can be increased freely. Thus the effect of pressure on the tissue volume can be markedly improved.

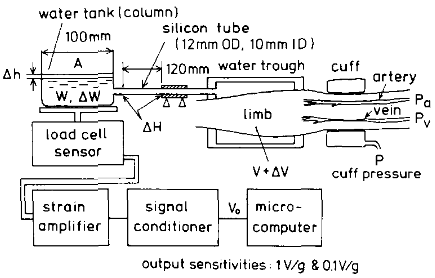

Fig. 1. Principle method of water-displacement plethysmography using a load cell as the sensing element.

B. Improved Sensor

A load cell sensor (ISHIDA, DLC-6L, 600 g rated capacity, with a temperature-compensating circuit) for electronic balances was utilized. Table I shows the specifications of this sensor. The linearity of the sensor itself was very high, and the sum of nonlinearity and hysteresis was ±0.015% of the rated value (600 g · f). The temperature coefficient was 0.02%/°C of the rated value. These properties indicate that this sensor is far superior to sensors of conventional methods in accuracy and stability. When used as a sensor for plethysmography, the water tank for volume detection on the sensor is connected with an elastic silicone tube (12 mm in outer diameter, 10 mm in inner diameter, 120 mm in length) to the water trough for converting the tissue volume change into a water volume change. When the volume of the limb is increased to send more water into the tank, the table of the sensor is lowered to possibly cause an error in measurement. The changes of the table level due to 0-600 g loading were actually measured using a laser displacement meter. The change was 320 μm by 600 g loading, that is, 0.53 μm/g. This means that a level lowering of only about 10 μm may occur with about 20 ml volume change in a forearm in the case of blood flow measurement. Then, the tube connecting the water tank and the water through was changed by ΔH from the horizontal state, and the output sensitivity of the load cell was measured. As a result, the sensitivity was found to be little changed when ΔH was within ±20 mm, and was maintained constant with a width of 1 ± 0.005 V/g. Thus it was confirmed that the sensitivity and accuracy of the load cell was not spoiled by the presence of tube connection between the water tank and trough.

The properties of the sensor under a fully equipped practical condition were then examined. Like water-displacement plethysmography, a column was placed on the load cell which was connected to a water-displacement tank using a silicone tube (same sizes as before). The finer and softer this connecting tube is, the smaller is its disturbance of the sensor. However, rapid conduction of a volume change requires a greater diameter, and accurate conduction needs a constant diameter. Therefore, a relatively large diameter and thick silicon tube as mentioned above was used here.

The stability and resolution of the sensor were first examined. In general, vibrations must be avoided for this sort of measurement, but no particular varibration-free table was used from a practical point of view and an ordinary laboratory table was utilized under a still condition. As a result, the magnitude of the total noise voltages was found to be about 5 mVpp (i.e., 5 mgpp), indicating that the resolution was nearly 10 mg. The resolution can be increased by using a sensor with a smaller rated capacity, but a rated capacity of 600 g is recommended taking measurement of either human limbs or digits, and ease in handling into account.

The volume changes in limbs and digitals induced by venous occlusion are thought to be in the order of 20 and 0.5 ml, respectively. These volume changes correspond to about 20 g and 0.5 g of water, provided that the specific density of water is 1 g/ml. Thus both changes can be measured by this sensor. Although output fluctuations thought to be caused by external vibrations may be noted, such fluctuations have little influence on the blood flow evaluation by the venous occlusion method.

For calibration, weights (ΔW) within a range of ±10 g were placed on the load cell table and the outputs (ΔV_0) were measured. As shown in Fig. 2 the response is quite linear. In fact, the nonlinearity was less than ±0.5%, and it was thus confirmed that the linearity was sufficiently preserved even under the attachment of the connecting tube.

TABLE I
SPECIFICATIONS OF LOAD CELL SENSOR

rated capacity	600 g·f
non-linearity + hysteresis	±0.015 %
temperature coefficient	0.02 %
stress in table of load cell	0.53 μm/g
output sensitivity ΔV/ΔW	
(-10g ≤W ≤ 10g)	1±0.005 V/g
(-100g ≤W ≤100g)	100±0.5 mV/g
bandwidth	0 - 10 Hz (-3dB)

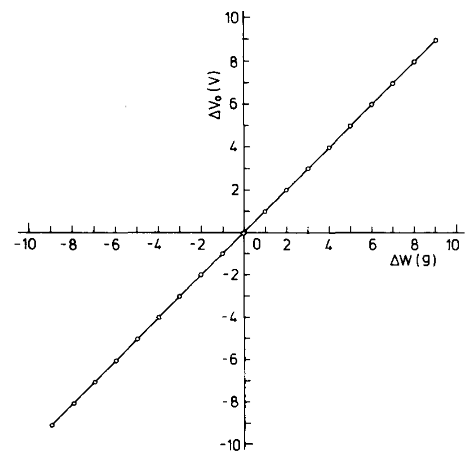

Fig. 2. Linearity of this device.

III. System Construction

The measurement block diagram for water-displacement plethysmography is illustrated in Fig. 1. A volume

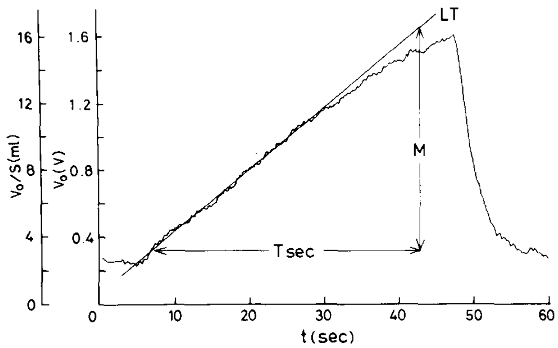

Fig. 3. Result of limb volume increased by venous occlusion for forearm (V_t = 335 ml, evaluated blood flow = 7.0 ml/100 ml · min).

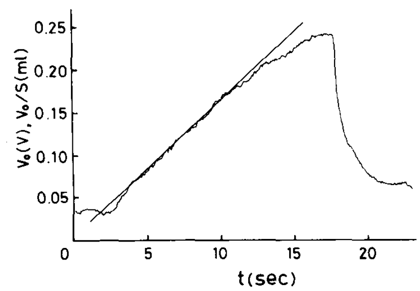

Fig. 4. Result of digit volume increased by venous occlusion for the middle finger (V_t = 6.5 ml, evaluated blood flow = 14.1 ml/100 ml · min).

change in the forearm was detected by the load cell and passed through a low noise strain amplifier and a signal conditioner, then the output (V_0) was processed with a microcomputer and a data recorder. Since the signal magnitude ratio between a limb and a digit is more than 10, two output gains of 0.1 and 1 V/g must be used. As the load cell is sensitive to air flow and temperature changes, the sensor unit was placed in a temperature isolated box. The amplifier was also placed in a double-wall box in order to minimize variations due to temperature changes. The inner diameter of the water trough (acrylic pipe) was 10 cm for a forearm and 3 cm for a middle finger, with the same box wall thickness of 5 mm. Automatic temperature control would be necessary for a practical system used clinically to prevent disturbing the subject's physiological condition. However, no such control was made in this experimental system. Instead, the water controlled to the appropriate temperature was poured into the water trough. As for the portion contacting the forearm, the target site of a testee was molded in plastic silicone, and the molded frame was snugly attached to the corresponding position. The space between this silicone frame and the trough was closed with Vaseline to prevent water leakage.

The blood flow per minute in the limb (F) is usually expressed in terms of ml/100 ml · min tissue. The method for estimating the value of F from the waveform showing a volume change in a limb by means of the venous occlusion method is described as follows (see Fig. 3):

1) determine a tangent (LT) to obtain the rate of volume increase;
2) obtain the height (M) increased in T s;
3) measure the volume (V_t) of the limb being measured.

Calculate the F value using the following equations:

$$F(\text{ml}/100\ \text{ml} \cdot \text{min}) = \frac{(M/S)(60/T)}{(V_t/100)} = \frac{6000 \cdot M}{V_t \cdot S \cdot T} \tag{1}$$

where S is the sensitivity of the load cell sensor.

In conventional plethysmography, the sensitivity of the sensor is not high enough, and therefore correction must be made at every measurement by adding a constant volume of water using a syringe, etc. This is a troublesome task and the correction signal itself is not so accurate. Because the sensitivity of our method is maintained constant, no such procedure is needed and the accuracy is also high.

IV. Results and Discussion

Using the system described above, we performed the blood flow measurement in adult male subjects without circulatory disorder. The forearm and middle finger were selected as target sites. The cuff used for venous occlusion was 8 cm in width for the forearm and 1.8 cm in width for the middle finger. The cuff pressure was set to be about 80 mm · Hg, and the measurement wave form was ignored for blood flow estimation until reaching this pressure.

Fig. 3 shows an example of measurement waveforms for the forearm. The blood flow volume obtained was 3–10 ml/100 ml · min measured on several subjects. An example of measurement waveforms for the middle finger is shown in Fig. 4. Here a blood flow volume of 15–20 ml/100 ml · min was obtained. Although the observed value for the middle finger was greater than that for the forearm, both were within the range previously reported. The waveforms in Figs. 3 and 4 are typical of venous occlusion plethysmography, and similar wave forms can easily be reproduced. These features indicate the reliability of this method.

In the cases illustrated in Figs. 3 and 4, the blood volume increased by venous occlusion was about 10 ml for the forearm and about 0.2 ml for the middle finger. Since the cross section of the water column was 80 cm^2, the water level change, h, becomes 100 and 3 μm, respectively. As clearly indicated by these values, hydraulic compression of the target site was almost completely eliminated in this method.

The blood flow volume changes considerably in individuals and is largely affected by physiological conditions and environmental factors. However, it was confirmed that measured blood flow volume in the same subject and for a short time was nearly constant with a variation within several percent. In some cases, a finger cuff might be displaced by its interior pressure to cause a skin dislocation (shift), producing an artifact. Thus in order to measure the blood flow volume in a finger accurately and stably, the cuff must also be improved.

V. Conclusions

The results of the present study are summarized below.

1) A weight detecting method was developed using a load cell sensor as the sensor of water-displacement plethysmography instead of conventional water column height detection or water column pressure detection.
2) The use of a load cell sensor allowed us to design the cross section of a water column to be sufficiently large, and provided neither hydraulic compression of the limb nor disturbance of in vivo blood flow.
3) Since the sensitivity and stability of signal detection was much superior to those of conventional systems, the accuracy and reliability of the venous occlusion plethysmograph was improved.
4) A process of calibration which was needed for conventional systems is not needed for the present method, and since the sensor is solid, handling for the present method, and since the sensor is solid, handling of the system became very easy.
5) Blood flows in the forearm and finger of a testee were actually measured using the water-displacement plethysmography, constructed on an experimental basis, and proved the reliability of the present method.

The new water-displacement plethysmography developed here is sufficient to meet an increased demand for a noninvasive and handy instrument capable of measuring peripheral blood circulation in limbs and fingers, and we believe that the system is well-suited for automatic blood flow determination as well.

Acknowledgment

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References

[1] I. Dahn, "On the calibration and accuracy of segmental calf plethysmography with a description of a new expansion chamber and a new sleeve," *Scand. J. Clin. Invest.*, vol. 16, pp. 347-356, 1964.

[2] G. E. Nilsson, T. Tenland, and P. A. Oberg, "Evaluation of a laser Doppler flowmeter for measurement of tissue blood flow," *IEEE Trans. Biomed. Eng.*, vol. BME-27, pp. 597-604, 1980.

[3] F. Kajiya, G. Tomonaga, K. Tsujioka, Y. Ogasawara, and H. Nishihara, "Evaluation of local blood flow velocity in proximal and distal coronary arteries by laser Doppler method," *Trans. ASME, J. Biomech. Eng.*, vol. 107, pp. 10-15, 1985.

[4] J. M. Porter, and I. D. Swain, "Non-invasive measurement of limb and digit blood flow," *J. Biomed Eng.*, vol. 8, pp. 187-192, 1986.

[5] A. D. M. Greenfield, R. J. Whitney, and J. F. Mowbray, "Methods for the investigation of peripheral blood flow," *Brit. Med. Bull.*, vol. 19, pp. 101-109, 1963.

[6] K. Yamakoshi, H. Shimazu, T. Togawa, and H. Ito, "Admittance plethysmography for accurate measurement of human limb blood flow," *Amer. J. Physiol.* vol. 235, pp. H821-H829, 1978.