Engineering

Electrical Engineering fields

Okayama University *Year* 1990

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A VENOUS OCCLUSION PLETHYSMOGRAPHY USING A LOAD CELL AS THE SENSING ELEMENT

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Abstract: This paper presents an application of the load cell as a sensor in venous occlusion plethysmography, a well established method for limb or digital 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 as well as 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.

1. Introduction

Peripheral blood flows in limb, or blood flows in particular organs and tissues are measured by plethysmography utilizing the change in tissue volume due to blood inflow, by the impedance method using conductance changes and also by the clrearance method calculating the blood flow volume from the rate of clearance of a certain substance, etc.[1]. An excellent method, laser Doppler method, is also available, but this method can be applied only to specified sites so 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 mercuey strain-gauge plethysmographies[4]. From a clinical point of view, however, none of these plethysmographies are satisfactory blood flow meters as for accuracy and easiness in handling.

In 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 a target site and insufficient sensitivity and accuracy have been the problems of this method.

For the purpose of improving the reliability of plethysmography, we propose here 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 from forearms and fingers using a manufactured water-displacement plethysmography are presented below.

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, The principle of the method is illustrated in Fig.1. A cuff is placed on the central side of a target site, and the 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 accummlation. When the blood volume (V) is said to be increased by ΔV for time Δt, the ratio of ΔV/ Δt equals to 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, a 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.

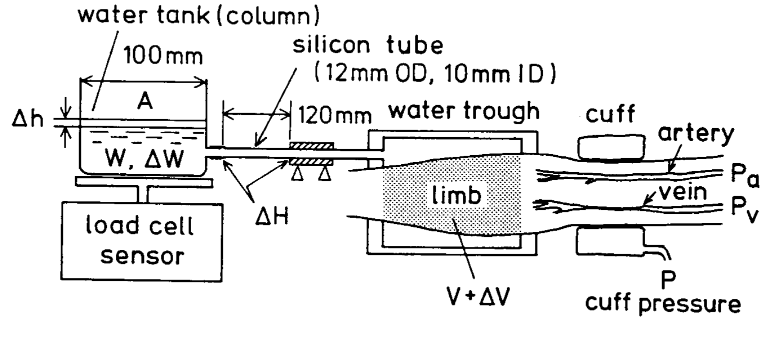

Fig.1. Principle method of water-displacement plethysmography using a load cell as the sensing element.

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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 section area of the water column as large as possible. However, the large is the cross section, the smaller is the height change, resulting in greater difficulty in measurement (see Appendix).

As a method basically overcoming this problem, we propose the method illustrated in Fig.1, in which a load cell sensor is used to convert a volume change into a weight change. Since the weight change ΔW is detected in this system and there is no need to care 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 markedly be improved.

B. Improved sensor

The load cell sensor (ISHIDA, DLC-6L, 600 g rated capacity, with a temperature-compensating circuit) for electronic balances was utilized. Table 1 shows the specifications of this sensor. The linearity of the sensor itself was very high, and the sum of non-linearity and hysteresis was +0.015% of the rated value. 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 change detection on the sensor is connected with an elastic silicon tube (12 mm in outer diameter, 10 mm in inner diameter, 120 mm in length) to the water trough for converting a 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. Actually, however, the table was found to be lowered only by 0.53 μm/g. This means that a level lowering of only about 10 μm may occur in the case of blood flow measurement (see Appendix). Then, the tube connecting the water tank and the water trough 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 silicon tube (same sizes as before). The finer and softer is this connecting tube, the smaller is the disturbance to the property of the sensor. However, rapid conduction of a volume change requires a greater diameter, and accurate conduction needs no change in diameter. Therefore, such a relatively large and tough silicon tube as mentioned above was used here.

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 sencitivity ΔV/ΔW	
(-10g ≤ W ≤ 10g)	1 ± 0.005 V/g
(-100g ≤ W ≤ 100g)	100 ± 0.5 mV/g
responsibility	0 - 10 Hz (-3dB)

The stability and resolution of the sensor were first examined. In general, vibrations must be avoided for this sort of mesurement, but no particular vibration-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 size of total noises 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 that with a rated capacity of 600 g is recommendable taking a possibility of simulataneous measurement for human limbs and digitals and easiness in handling into account.

The volume changes in limbs and digitals induced by venous occlusion are thought to be an order of 20 ml and 0.5 ml, respectively. These volume changes correspond to about 20 g and 0.5 g of water, provided the specific density of water is assumed to be 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 are little influential to the blood flow evaluation by the venous occlusion method.

Then, 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 non-linearity was less than ±0.5%, and it was thus confirmed that the linearity was sufficiently preserved even under the attachment of the connecting tube.

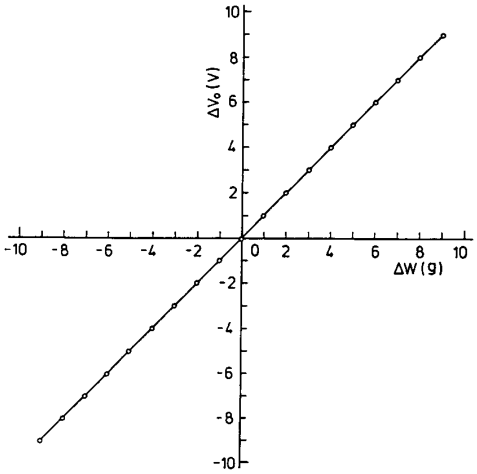

Fig.2. Linearity of this device.

III. System Construction

The composition of water-displacement plethysmography is schematized in Fig.3. A volume 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 size changes more than 10 times between a limb and a digital, two output gains of 0.1 V/g and 1 V/g must be used correspondingly by swiching. As the load cell sensitively reacts to air flow and temperature changes, the sensor unit was placed in a heat-sealed

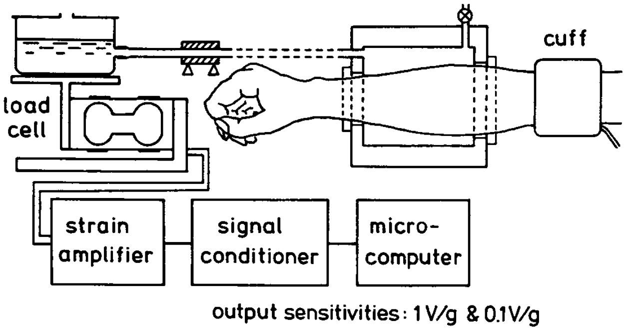

Fig.3. Schematic diagram of water-displacement plethysmography using load cell sensor.

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 thickness of 5 mm. Temperature control would be necessary for a practical system, but no such control was made in this experimental one. As for the portion contacting the forearm, the target site of a testee was modeled in plastic silicon, and the modeled frame was attached to the corresponding position with a slight latitude. The space between this silicon frame and the trough was closed with Vaseline to prevent water leakage.

The blood flow in the limb (F) is usually expressed in terms of blood flow ml/100 ml·min tissue. The method for estimating the value of F from the wave form showing a volume change in a limb by means of venous occlusion method is described here (see Fig.4).

1) Draw a tangent (LT) to obtain the rate of volume increase.
2) Obtain the height (M) increased in T sec.
3) Measure the volume (V_t) of the limb being measured.

Calculate the F value using the following equations:

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

where S is the sensitivity of the load cell sensor, and 1 V/g (i.e. 1 V/ml) if 1 ml of water is assumed to be 1 g.

In conventional plethysmography, the sensitivity of the sensor was 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 troublesome task, and the correction signal itself is not so accurate. As 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 mmHg, and the measurement wave form until reaching this pressure was ignored for blood flow estimation.

Figure 4 shows an example of mesurement wave forms for the forearm. The blood flow volume obtained was 3-10 ml/100ml·min measuring by several subjects. An example of measurement waves form for the middle finger is shown in Fig.5, from which a blood flow volume of 15-20 ml/100ml·min was obtained. Although observed value for the middle finger was greater than that for the forearm, both were within the range previously reported. Wave forms in Figs. 4 and 5 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.4 and 5, 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, Δh, becomes 100 μm

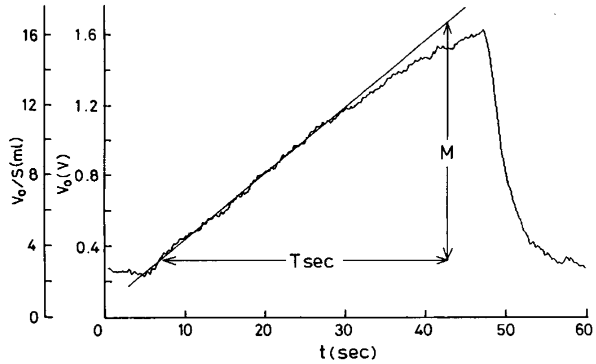

Fig.4. Result of limb volume increased by venous occlusion for forearm (V_t=335ml, evaluated blood flow= 7.0ml/100ml·min).

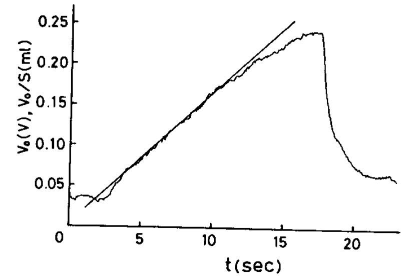

Fig.5. Result of digital volume increased by venous occlusion for the middle finger (V_t=6.5ml, evaluated blood flow=14.1ml/100ml·min).

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 percentages. In some cases, the cuff for a finger might be displaced by pressure application to cause a skin dislocation, 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 summarised below.

1) The 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 neighther 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 results were improved.
4) Since a process of calibration which was needed for conventional systems is not needed for the present method, and also since the sensor is solid, handling of the system became very easy.
5) Blood flows in the foream and finger of a testee were actually measured using the water-displacement plethymography constructed on an experimental basis proved the reliability of the present method.

In spite of earnest demands of a non-invasive and handy instrument capable of measuring peripheral blood circulation in limbs and fingers, there has been no satisfactory instrument. The new water-displacement plethysmography developed here is to sufficiently meet such demands, and we believe that the system is well suited for automatic blood flow determining as well.

We would like to express our sincere thanks to ISHIDA KOUKI Co.Ltd for presenting samples, and Mr. Kiyotaka Yasuhara, the technical official of the Ministry of Education, the Department of Electric Engineering, Okayama University, for his technical corporation for this work.

Appendix

Method for detecting volume changes

Water-displacement plethysmography is the method for the measurement of the volume change of the limb (ΔV) caused by venous occlusion by converting it to a change in the water volume. The water volume change is measured by changes in water level (Δh') or water pressure (ΔP) of the water column. The principle of the method is illustrated in Fig.A-1[1].

In this method, as biological prerequisite, the pressure change at a target site, which is caused by the water level rise due to venous occlusion-induced tissue volume increase, must be minimized, hence it is preferable to make the cross section (A') of the water column as large as possible. From a view point of instrumental engineering, on the other hand, it is desirable to reduce A' to obtain large values of Δh and ΔP. These demands from two view points, however, obviously conflict each other, and make measurement under a desirable condition difficult.

In order to overcome these problems, the method which converts a volume change into a weight change by means of a load cell sensor was developed in the present study as shown in Fig.A-2. In this new method, the cross section (A) of the water column (tank) can freely be increased without spoiling detection sensitivity, since a weight change (ΔW) is to be detected. Relations between parameters in the two methods are as follows:

$$V = A' \cdot \Delta h' \qquad \text{(A-1)}$$

$$= A \cdot \Delta h \qquad \text{(A-2)},$$

where it is easy to make A>>A', hence h<<h'. Thus, the influence of pressure on the limb volume change is greatly reduced in this method.

A load cell sensor for electronic balances with a rated capacity of 600 g was utilized in the present study. The changes of the table level (ΔL) due to zero - 600 g loadings were measured using a

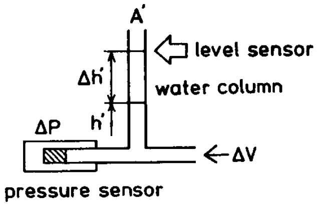

Fig.A-1. Detecting method of conventionally use by level sensor or pressure sensor.

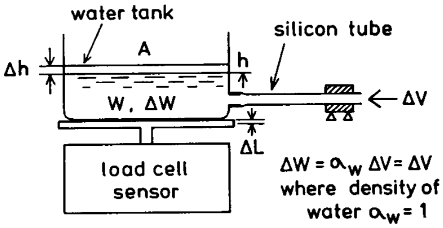

Fig.A-2. New detecting method using load cell sensor.

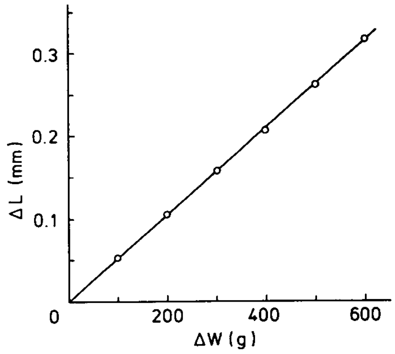

Fig.A-3. Variations in level of load cell sensor table due to zero-600g loading.

laser displacement meter, and the result is shown in Fig.A-3. The table level was found to be changed only by 320 μm by 600 g loading, and slope under this loading was to be 0.53 μm/g. Since the practical ΔL value associated with an about 20 ml volume change in a forearm is estimated to be about 10 μm, and that associated with an about 0.5 ml in a finger is to be about 0.3 μm, the practical value of Δh is very small. Thus, the change of the table level can be considered practically negeligible. By this reason, weight measurement is little disturbed even if the water column (tank) and the water trough are connected with a tube.

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