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Differential Digital Photoplethysmographic Observations of Finger Vascular Exponential Response to the Arm Position Changes in Humans

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Abstract

TAKEMIYA, T. MAEDA, J. SUZUKI, J. NISHIHIRA, Y. and SHIMODA, M. Differential Digital Photoplethysmographic Observations of Finger Vascular Exponential Response to the Arm Position Changes in Humans. Adv. Exerc. Sports Physiol., Vol. 2 No.2 pp.83-90, 1996. The purpose of this study is to confirm the hypothesis that raising or lowering the human upper limb from the heart level induces the Bayliss effect on the small arteries and arterioles in the fingertips. As a non-invasive method to induce changes in the intravascular pressure, we developed a conventional method of inducing a gravitational potential energy change (GPEC) (ρgh: 0.77 mmHg/cm) and converted digital photoplethysmograms (DPG) to differential digital photoplethysmograms (Δ DPG). The mean value was calculated from the subjects (n = 87, healthy males 21-30 years old) and was compared with the control value at the heart level. Values were expressed as means ± S.E. The ΔDPG-P wave height was highly correlated with DPG-P wave height (r = 0.96). The Δ DPG-P wave height changed gradually after acute position changes, and the changed wave heights were maintained. Δ DPG changes induced by GPEC were also confirmed by comparing simultaneous measurements of finger blood pressure. The ΔDPG-P wave height showed an exponential increase or decrease with linear changes in GPEC. The maximal GPEC decrease or increase after 60 cm (48.20 mmHg) arm raising or arm lowering from the heart level produced 58.1 ± 8.5 % (n=20) increase in ΔDPG ($p<0.01$) and 60.6 ± 2.7 % (n=20) decrease in ΔDPG ($p<0.01$), respectively. Simultaneous measurement of ΔDPG in the bilateral upper limbs confirmed significant changes in the GPEC-induced arm. These findings suggest that changes in ΔDPG after GPEC are derived from the responses proper to the vascular smooth muscle induced by changes in the intravascular pressure.

Key words: Differential digital photoplethysmogram, Gravitational potential energy change, Vascular myogenic response, Arteriolar compliance

Introduction

There have been many studies on the Bayliss effect as a myogenic response (1, 4, 5, 12, 13, 17, 18). Gravity-induced vasoconstrictive changes have been observed by several investigators, indicating a marked decrease in local blood flow or a reduction in the capillary fluid transfer (7, 9, 10, 11, 14, 19). We have shown that a stepwise arm raising or arm lowering from the heart level produces a marked change in differential digital photoplethysmogram (Δ DPG) in human (15, 16, 27). The ΔDPG has been developed to represents the time-dependent change in functional diameter of microvascular pulsatile blood flow column (27). Since gravitational potential energy change (GPEC) produces intravascular pressure change to evoke myogenic response in small artery and arterioles (16,27), we are interested in analysis of GPEC-Δ DPG response for human microvascular functional changes (27) or adaptive changes (23). However, hypothesis that the GPEC-Δ DPG method demonstrates myogenic response remains to be assessed.

The purpose of the present study was to examine whether the GPEC-Δ DPG responses show a linear relationship or not. In addition, to evaluate the possible involvement of the sympathetic nerve activity, Δ DPG was measured simultaneously in the bilateral upper limbs during GPEC performed only in one limb. The reliability of changes in ΔDPG was tested by comparing ΔDPG with the digital blood pressure measured using a Finapres.

Methods

A. Subjects

We investigated firstly a total of 87 healthy male subjects between 21 and 30 years old with no history of vascular disease for the experiment of the effects of gravitational potential energy change on Δ DPG responses. Their blood pressure and heart rate at rest were normal. In additional experiment for the confirmation of sympathetic nervous contribution, measurements were made on 7 healthy male subjects

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(18-24 years old) with no history of vascular disease. Informed consent for the experiment was obtained from all subjects after explaining the purpose and method of the experiment. Experiments were performed in a room with ambient temperature varying from 20 to 26 ℃.

B. Arm position change

Generally, GPEC is given by ρgh, and the coefficient determined with consideration to the gravity and blood density per unit height (cm) is 0.77 mmHg/cm (3, 8). We developed a method for the practical use of GPEC in which we induced non-invasive changes in intravascular pressure in the human limbs and observed vascular responses (Δ DPG) to these changes. Although measurement can be performed in either the supine or the sitting position, in this study the sitting position was used on all occasions. As a control, the value when the finger-tip-sensor was placed at the heart level was used. After the upper arm-fingertip with a sensor was passively raised (20 cm, 40 cm, 60 cm) from the heart level using a movable plate, measurement in the raised position was performed for about 30-60 seconds. Then the fingertip was returned to the heart level, and measurement was performed. Subsequently, the arm-fingertip-sensor was lowered (-20 cm, -40 cm, -60 cm) using the same movable plate, and measurement in the lowered positions was performed. The fingertip was returned to the heart level, and measurement was performed. One set of measurements required about 5 minutes. Similar GPEC is possible to the toes, and our observations obtained similar to those obtained to the fingers. In this study, only the upper limbs were evaluated. In the basic experiment, changes in the angle of arm raising and lowering were recorded on polygraphs using a goniometer attached to the shoulder (Fig. 1A, B).

C. Measurement of ΔDPG

Experiments were focussed on the digital photoplethysmographic initial upward main wave (P wave) which has been seemed to reflect the dynamic phase of cardiac output. Under a stable condition of cardiac function, we dealt with another function of vascular resistance. Δ DPG was obtained by electrical processing of the conventional DPG output using a differentiating circuit of the preamplifier (MLV-2201, Nihon-Kohden Co. Ltd.). The time constant could be selected in the range of 0.3 sec -0.03 sec, and 0.03 sec was used in this experiment. Based on the results of a preliminary experiment, low-speed measurement using an AC amplifier was performed instead of the conventional measurement using a DC amplifier, and Δ DPG was obtained in this study (Fig. 1A, B). The advantage of this method is the absence of base-line fluctuations, pulsatile pattern with low-speed recording of Δ DPG peak amplitude waves, a high correlation in the wave height between the conventional P waves and differential P waves and serial recording for a long period. The disadvantage was that analysis of waveforms is limited to early upward P waves, and subsequent analysis is impossible. However, in the present study performed by position changes, analysis of P waves was adequately useful.

Δ DPG was measured after application of a sensor to the fingertips. This sensor allows light transmission, and the wavelength of its light source (600nm) is well absorbed by blood Hb. Therefore, a decrease in blood flow after vasoconstriction results in a decrease in light absorption, i.e., an increase in the amount of transmitted light. This decreases the resistance of photo cells, decreasing the terminal voltage, i.e., the height of recorded waves.

To confirm the reliability of changes in Δ DPG, digital blood pressure (BP) was simultaneously measured using a commercial instrument Finapres (Model 2300, Ohmeda Co. Ltd.), which was based on a similar principle.

D. Simultaneous measurement of ΔDPG in the bilateral upper limbs

To evaluate the possible involvement of the sympathetic nerve activity, two sets of Δ DPG measurement were done simultaneously in the bilateral upper limbs during GPEC performed only in one limb.

E. Data analysis

The Δ DPG-P wave height was expressed in terms of mV/V/sec (22, 23). All measurements were performed mainly at a level showing a stable P wave height. The mean wave height in each position in each subject was calculated. All wave heights at the heart level before and after GPEC were regarded as control values. Each value was expressed as the mean ± standard error (mean ± S.E.). Data were analyzed using linear regression and paired t tests. Results were considered statistically significant with $P < 0.05$.

Results

A. Mechanograms and GPEC-ΔDPG responses

Fig. 1B represents typical example of mechanogram and Δ DPG response during arm rasing and arm lowering. The records showed the alternative Δ DPG responses during arm raising (60 cm) and arm lowering (-60 cm) within 4 minutes, and demons-

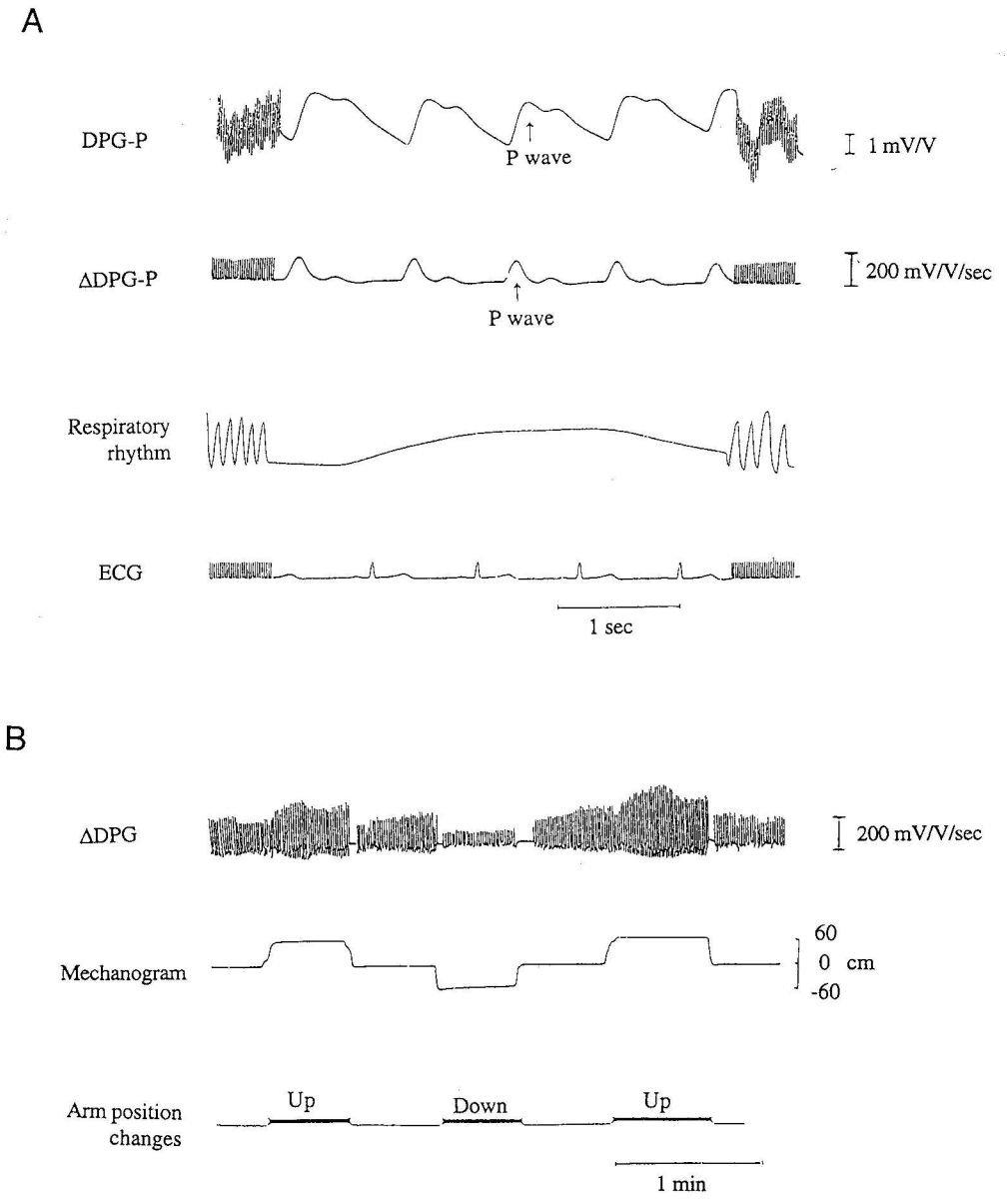

Fig. 1 Digital photoplethysmogram (DPG) and differential digital photoplethysmogram (Δ DPG). The upper figure A represents simultaneous recordings of DPG-P and Δ DPG-P waves. The Δ DPG (mV/V/sec) was obtained by electrical processing of the conventional DPG output (mV/V) using a differentiating circuit of the preamplifier. The time constant 0.03 sec was applied in this experiment. Experimental characteristics in Δ DPG demonstrate a low-speed pulsatile recording and the absence of base-line fluctuations. The lower figure B represents mechanogram of arm position changes and Δ DPG responses. When the fingertips were raised by 60 cm from the heart level (Up), the Δ DPG-P wave height was apparently increased. Conversely, after 60 cm arm lowering (Down) the Δ DPG-P wave height was markedly decreased. This phenomenon was characterized by position dependent occurrence and reproducibility.

trated relative responses of Δ DPG changes against the changes in GPEC mechanograms. In the fundamental experiments, we examined the correlation between the heights of Δ DPG-P wave and of conventional DPG-P wave, in which 36 randomly sampled pairs from the records were compared. The correlation coefficient was 0.96 ($P<0.01$) (Fig. 2). Fig. 3 shows a representative case of blood pressure involved, in which Δ DPG in the second finger and blood pressure in the third finger were simultaneously measured. Arm raising (40 cm) decreased blood pressure but increased Δ DPG. Arm lowering (40 cm) increased blood pressure and decreased Δ DPG. The change in the wave height of Δ DPG and blood pressure was maintained while the arm kept raised or lowered for 30 or more seconds.

In Fig. 4, we compiled GPEC-Δ DPG data from the subjects participated in various experiments, and the mean Δ DPG-P wave by arm raising and lowering were plotted as the function of vertical transfer distance of fingertips. Generally, the coefficient determined in consideration with the gravity and blood density per unit height (cm) of the fingertips is 0.77 (mmHg/cm). The vertical distance multiplied by this coefficient is considered to be the theoretical intravascular pressure. This value was shown in the parentheses on the x axis. Based on the total number of subjects (n), the percent change (%) in Δ DPG wave height after GPEC compared with the pre-GPEC value at the heart level was calculated and plotted on y axis. Δ DPG responses to arm raising (Up) and lowering (Down) formed an exponential curve sym-

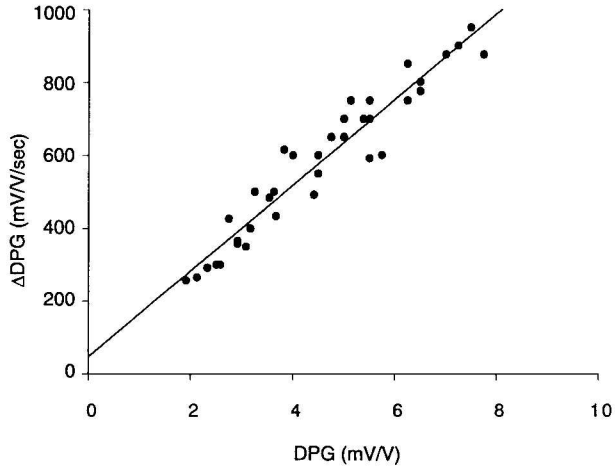

Fig. 2 Correlation between differential digital photoplethysmogram (Δ DPG) and digital photoplethysmogram (DPG). A linear relationship between Δ DPG-P wave height (mV/V/sec) and DPG-P wave height (mV/V) was obtained by measuring the thirty six pairs recorded simultaneously. The correlation coefficient was 0.96.

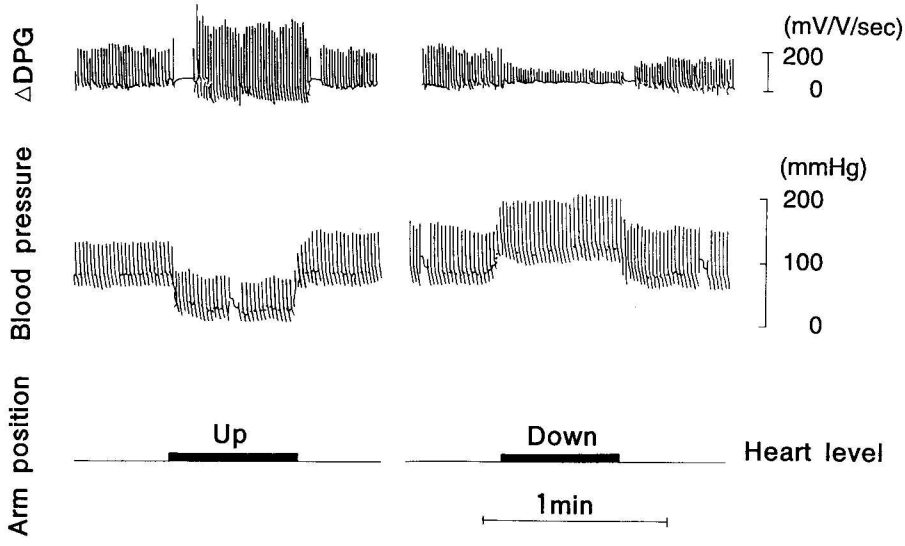

Fig. 3 Typical changes in differential digital photoplethysmogram (Δ DPG) and the finger blood pressure after arm position changes (gravitational potential energy change: GPEC). Arm raising increased Δ DPG-P wave height, decreased finger blood pressure, and slightly decreased the pulse pressure. Arm lowering markedly decreased Δ DPG-P wave height but increased finger blood pressure and slightly increased pulse pressure.

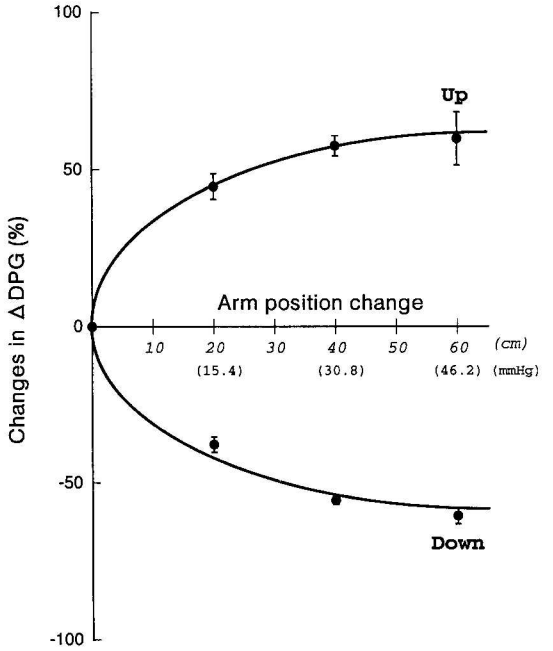

Fig. 4 Mean percent change (%) in the differential digital photoplethysmogram (Δ DPG-P wave height) after stepwise arm raising or lowering from the heart level. The x axis represents the distance (cm) between the sensor on the fingertips and the heart level, and the intravascular pressures (mmHg) in the figure were calculated values (cm x 0.77 mmHg/cm). The y axis represents changes in Δ DPG-P wave height after arm raising or lowering. Changes in the amplitude were nearly symmetrical with respect to the x axis, showing exponential responses.

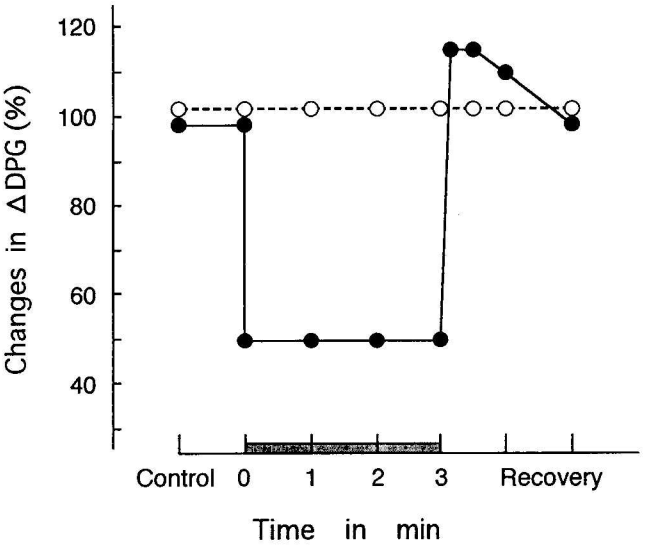

Fig. 5 Typical patterns in simultaneous measurement of differential digital photoplethysmograms (Δ DPG wave height). Two sensors were applied to the fingertips of the bilateral arms. The control arm fixed at the heart level (○) showed no change in Δ DPG-P wave height during 3 min contralateral arm lowering (●) in which Δ DPG-P wave decreased markedly. The results indicate that sympathetic vasoconstrictor was less worked. Post contraction hyperemia was observed in the recovery.

metrical with respect to x axis. The increase of mean Δ DPG-P wave height in each arm raising position (mean ± S.E., n) was 44.7 ± 4.1 % (30) after 20 cm arm raising, 57.6 ± 3.2 % (87) after 40 cm arm raising and 58.1 ± 8.5 % (20) after 60 cm arm raising. By contrast, the decrease of mean Δ DPG-P wave height in each arm lowering position was 37.8 ± 2.5 % (30) after 20 cm arm lowering, 55.6 ± 1.4 % (87) after 40 cm arm lowering and 60.6 ± 2.7 (20) after 60 cm arm lowering.

B. Simultaneous measurement of Δ DPG in the bilateral upper limbs

Changes in Δ DPG may be due to the effects of gravity given only to the limb on the GPEC side. However, possible neuro-hormonal effects could not be excluded. Then, Δ DPG was simultaneously measured in the bilateral upper limbs. Fig. 5 shows a representative graph obtained by simultaneous measurement of Δ DPG in the bilateral upper limbs (○, ●) after adjusting the sensitivity of the two channels of the polygraph to the same. After position changes only in one limb (●), Δ DPG decreased only in the lowered fingertip and maintained during arm lowering period. The Δ DPG showed post contraction hyperemia for 1 minute immediately after recovery, then returned to the control value. These findings were confirmed in 7 subjects (Fig. 6). When the pre-GPEC value was regarded as control (0 %) in both upper limbs, 40 cm arm raising significantly increased Δ DPG in the fingers on the GPEC side (27.1 ± 4.7%, 7) ($p<0.001$) but decreasingly affected Δ DPG in the contralateral fingers (-7.0 ± 1.4%, 7) ($p<0.01$). Similarly, 40 cm arm lowering significantly decreased Δ DPG in the fingers on the GPEC side (-45.0 ± 7.4%, 7) ($p<0.001$) but negligibly changed Δ DPG in the contralateral fingers (-1.9 ± 2.5%, 7).

Discussion

Our hypothesis is that the Bayliss effect can be demonstrated by a differential digital photoplethysmographic response (Δ DPG) to the gravitational potential energy changes (GPEC) induced non-invasively in humans. The term Bayliss effect has been

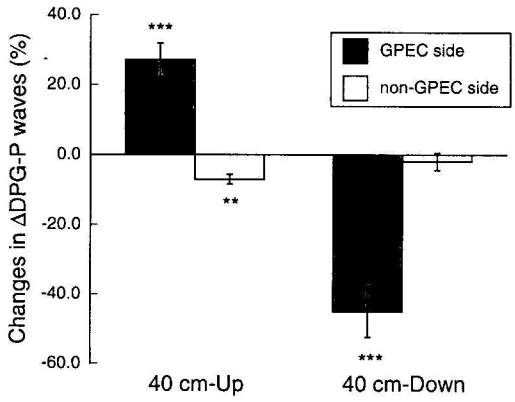

Fig. 6 Simultaneous measurement of differential digital photoplethysmogram (Δ DPG-P wave height) in the bilateral upper limbs after position changes only in one limb.Values: means ± S.E. (n = 7). Statistics: paired Student's t-test. ** $P<0.01$ and *** $P<0.001$ vs heart level. Δ DPG-P wave height in control decreased significantly (-7.0 ± 1.4 %, $P<0.01$) during contralateral arm raising. The result may be due to effect of sympathetic nerve activity during arm raising, although arm changes were conducted passively.

applied as a token of the human myogenic effect. In 1902, Bayliss observed that a brief reduction of perfusion pressure to the hindquaters of the dog caused expansion of the limb beyond its control volume when the pressure was restored. Also, he demonstrated that an isolated segment of carotid artery began to "writhe like a worm" when the internal pressure was raised (1). These observations concerned with the intrinsic property of arterial vessels later have developed as a vascular myogenic response and/or the concept of autoregulation in local circulation. The myogenic effect or response has been studied using in vitro or in vivo experimental model (1, 4, 5, 12, 13, 18). In this paper we tried to develope non-invasive method for observing the myogenic effects in humans. It is our concerns that microvascular myogenic response may play an important role in regulation of muscle microcirculation during endurance exercise. Because of a few human studies (10, 19), we tried to develope non-invasive method for observing the myogenic effects in humans.

Before developing the set of GPEC-Δ DPG response, we had to overcome the difficulty of fluctuations in baseline and solve some experimental problems. First, we have improved the conventional DPG to differential Δ DPG. As a result, the fluctuations were converged on the baseline. However, in applied use of Δ DPG a question rose as to whether the Δ DPG waves display sinusoidal change or not, because their amplitude increases after frequency increases. By observing normal Δ DPG waves and comparing artificial rectangular waves produced by a function generator, Δ DPG waves have been confirmed not to change their configuration markedly during frequency increases. Consequently, a high correlation was observed between the DPG-P wave height and Δ DPG-P wave height with a coefficient of 0.96 (Fig. 2). Second, through the studies of head-up and/or head-down postures we have confronted with the unexplainable problem of Δ DPG changes until we noticed that these changes in Δ DPG may have been due to changes in the relatively locational relationship between the heart position and the Δ DPG-sensor position after head up or head down tilting. Consequently, we have developed the GPEC-Δ DPG method in which gravitational potential energy changes induce the changes in Δ DPG (24, 25).

By the GPEC method, the gravitational effect can be expressed as a pressure of 0.77 mmHg/cm at normal blood density. For instance, raising and lowering the upper extremity 60 cm from the heart level produced changes in intravascular pressure of 46.2 mmHg (60 cm x 0.77 mmHg/cm). As shown in isolated muscle arteriole (21), the changes in intravascular pressure provoke the response of vascular smooth muscle to produce changes in vessel diameter. Furthermore, there was an inverse relationship between the arteriolar diameter and intravascular pressure. Richardson (19) examined the effects of gravity on capillary and regional blood flows in human nailfold vessels of the large toe. The findings indicated that the immediate capillary vessels in the cutaneous circulation of the toe will be consistently vasoconstrictive when the foot is placed in a dependent position. The net effect on vessels governing regional flow in this area, e.g., A-V shunt, appears to result from a competition between dilator and constrictor influences. In our human experiment the change in Δ DPG-P wave amplitude may be equal to the change in small artery-arteriolar vessel diameter, i.e., diameter of blood flow column. In the present study, we repeatedly observed the increase in Δ DPG-P wave amplitude during arm raising and the decrease in Δ DPG during arm lowering, and also confirmed the reproducibility of a time-dependent change in Δ DPG responses proportional to the distance of vertical arm movements (Fig. 1B). Δ DPG increase during arm raising may be evidence of the decrease in vascular pulsatile impedance, whereas Δ DPG decrease during arm lowering may be evidence of the increase in vascular pulsatile impedance. These changes in Δ DPG have been further investigated by

other measurements including laser Doppler blood flow measurement in the finger cushion and ultrasonoraphic blood flow measurement at the site of radial artery (15, 16). Furthermore, these Δ DPG changes were accompanied by dissymmetrical changes in finger blood pressure (Fig. 3). Arm raising 40 cm from the heart level decreased blood pressure but increased Δ DPG. In contrast, arm lowering 40 cm increased blood pressure and decreased Δ DPG markedly. They presented similar findings which confirmed the changes in Δ DPG against the changes in GPEC (24, 25). Therefore, a stepwise GPEC can produce appropriate changes in Δ DPG.

Since simultaneous measurements of Δ DPG and the mechanogram after a stepwise change of arm-finger position from the heart level showed a proportional change, that is, Δ DPG decrease in arm lowering or Δ DPG increase in arm raising, it was conceivable that the relation would be linear in the range of vertical arm position changes. After compiling our data, we noticed the possibility of a nonlinear relationship between Δ DPG and arm position distance from the heart level (Fig. 4). At the same time, as Burton et al. (2) pointed out the changes in rhythmic vasoconstriction and finger-volume magnitude mediated by the sympathetic vasoconstrictor nerve of man, experiments have been carefully performed by considering mental and thermal conditions which exert cardiovascular parameters including cardiac output and vascular resistance at rest and during arm position change. Thus, we concluded that an exponential relationship may exist between Δ DPG and GPEC.

A non-pharmacological technique was examined to exclude the neuro-humoral effect using bilateral parallel measurements of Δ DPG (9). As presented in Fig. 5, two sensors were applied to the fingertips of the bilateral upper limbs. The control arm was fixed at the heart level, and another arm was lowered. Changes in Δ DPG were markedly observed only in the lowered fingertips, showing the absence of effects in the involvement of sympathetic nerve activity and/or the related hormone to the control arm (Fig. 6). On the other hand, Δ DPG in control finger decreased slightly (-7.0 ± 1.4%, $P < 0.01$) during contralateral arm raising. The result may be due to the effect of sympathetic nerve activity during arm raising, although arm changes were conducted passively. However, it is hardly conceivable that sympathetic vasoconstrictor will play a main role in the Δ DPG change during GPEC load. On the other hand, heightened sympathetic nerve activity reportedly constricts small arteries, as well as arterioles (20). In the experiment of contralateral finger immersion in cold water, the cold stimulation reduces Δ DPG amplitude in proportion to the fall in water temperature (22). Furthermore, mental arithmetic activity also decreases the Δ DPG amplitude (26). Thus, it is necessary to keep experimental conditions stable in the measurement of GPEC-Δ DPG response. Therefore, our observations clearly demonstrate that the neuro-humoral effects are secondary to the involvement of arm position change. Vascular compliance in small artery-arteriole was obtained by measuring the change in volume (Δ DPG) produced by a change in transmural pressure (GPEC). Fukase et.al. (6) have calculated vascular compliance by simultaneous measurements of finger blood pressure and Δ DPG.

In summary, it seems reasonable to conclude from these studies that gravitational potential energy changes (GPEC) induce arteriolar myogenic exponential responses which are manifested by changes in finger vascular diameter or the blood flow column diameter, i.e., changes in differential digital photoplethysmogram (Δ DPG). Thus, the Bayliss effect can be demonstrated by Δ DPG changes against the GPEC in human fingers.

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