Effects of Pulse-Synchronized Massage With Air Cuffs on Peripheral Blood Flow and Autonomic Nervous System

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Background There are almost no reports on the physiological effects of the various electric massage devices available on the market. This report describes the effects on peripheral vascular circulation and autonomic-nervous system activity of a pulse-synchronized air-massage (PS-AM) device in which cuffs apply air pressure cyclically to the lower limbs only during the cardiac diastolic phase.

Methods and Results The PS-AM device consists of a main unit with a pulse-wave detector that uses the pulse-wave to activate an air pump only during the cardiac diastolic phase. Pressure is applied sequentially from the feet to the thighs by 4 pairs of cuffs attached to the main unit. The study was carried out on 55 volunteers (19 males, 36 females). A laser Doppler flow-meter attached to the subjects' toes was used to measure blood flow (BF), while ECG, blood pressure and cardiac autonomic nerve activity [parasympathetic nerve activity (high-frequency component (HF))] were measured by a multibiomedical recorder (TM2425). The measurements were made for a total of 45 min consisting of three 15-min periods: before massage, during PS-AM, and after massage. BF increased 139 ± 33 (SD) % in males and 154 ± 44 % in females during PS-AM, with a significant correlation being observed between BF and HF during PS-AM ($p < 0.01$).

Conclusions PS-AM significantly increased peripheral vascular BF in the lower extremities, a change that may affect venous return and cardiac parasympathetic nerve activity. (Circ J 2006; 70: 1159–1163)

Key Words: Autonomic nervous system; Electric massage device; Peripheral vascular circulation; Plethysmogram

Numerous vibrator and air-cuff (pneumatic) massage devices for relieving fatigue and muscular stiffness are currently available on the market in Japan. However, as practically no research has been undertaken to investigate the effects of these devices on peripheral vascular circulation, their therapeutic mechanism remains unclear. In order to increase knowledge in this field, in 1994, in collaboration with a company named Advance (Tokyo, Japan), we developed a pulse-synchronized transpercutaneous electric muscle stimulator called a 'Venous Pump'!¹ This device is a type of low-frequency electrical muscle-stimulator that measures the descending phase of the pulse-wave in the earlobe and provides low-frequency electrical stimuli to the muscle during the diastolic phase of the heart. The stimuli cause muscular contraction and promote the muscle-pump action² in the peripheral circulation. At about the same time, working with Advance Co, we developed a second prototype of the system, a pulse-synchronized air-massage (PS-AM) device (Kaikan Slim) that provides pressure-stimuli to the lower extremities only during the cardiac diastolic phase. We anticipate that the PS-AM device accelerates venous return of blood in the lower extremities and changes parasympathetic system activity. The present study was designed to examine the

physiological effects of PS-AM on peripheral circulation and autonomic nervous system activity.

Methods

The main unit of the PS-AM device consists of a photo-pulse sensor for the earlobe or the tip of a digit and an air pump that analyzes the pulse signal and inflates the cuffs round the lower limbs at the time of the cardiac diastolic phase (Fig 1). In addition, 4 hoses and 4 cuffs, one for each limb, transmit air pressure. Cuff pressure is released when blood is pumped from the heart to the peripheral arteries,

Fig 1. Pulse-synchronized air-massage device. Pulse sensor, air pump, air-cuffs. The 4 pairs of air-cuffs are programmed to apply sequential pressure (beat-to-beat) continuously, starting from the feet to the thighs (from 1 to 4).

(Received December 26, 2005; revised manuscript received June 20, 2006; accepted July 7, 2006)

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Fig 2. Increases in cuff-pressure are synchronized with a photo-plethysmogram. Cuff pressure is applied only during the descending segment of the pulse wave, which corresponds to the cardiac diastolic phase. No pressure is applied when arterial blood flows into the lower limbs during the cardiac systolic phase.

Fig 3. Changes in toe blood flow (BF) measured using a laser blood flow-meter. PS-AM, pulse-synchronized air-cuff massage; Before, pre-PS-AM stage; After, post-PS-AM stage.

corresponding to the systolic phase. The cuff inflates only during the diastolic phase when venous blood is returning to the heart, thereby reinforcing the muscle-pump action on the peripheral circulation of venous blood and lymph. Arterial pulse waves detected in the earlobe or digit tip determine the cardiac phases and activate the air pump to transmit pressure to the cuffs only during the diastolic phase (Fig 2). The diastolic phase is detected by the photo-pulse sensor that measures the peak and bottom of the arterial wave and triggers the air pump. Pressure in the cuffs can be regulated at 3 designated levels: low (≈ 40 mmHg), normal (60 mmHg) or high (80 mmHg). This makes it possible to select a pressure that feels comfortable for the subject and only constricts the veins without affecting the arteries. The 4 cuffs applied to the legs (ie, a total of 8 cuffs) are programmed to apply sequential pressure for 15 min starting from the feet and continuing to the thighs in recurring cycles (beat-to-beat) (Fig 1). The subject lies prone on a bed and during the initial 15-min stage (pre-PS-AM stage) no cuff-pressure is applied. The PS-AM is then activated for 15 min (PS-AM stage), followed by a further 15-min during which no cuff-pressure is applied (post-PS-AM stage).

Peripheral blood flow (BF), blood pressure (BP), and cardiac autonomic nerve activity were measured in this study by the following methods. Peripheral BF was measured continuously by a laser Doppler flow-meter (ALF21 model, Advance Co, Japan), with a BF laser sensor^{3,4} being applied to the underside of the third toes. The high-sensitivity photoelectric BF laser sensor uses an invisible semiconductor laser with a wavelength of 785 nm. The flow-meter measurements expressed in units of 0–100 ml/min per 100 g were then entered into an Excel program on a personal com-

puter and analyzed with WAAP-WIN software (ELMEC Co, Japan) that was capable of processing large volumes of data at high speed. Examples of BF curves derived from the Excel program are shown in Fig 3.

BP and cardiac autonomic-nervous system activity were measured from recordings of indirect BP and electrocardiograms (ECG) using a Multi-biomedical Recorder⁵ (TM2425, A&D Co, Japan). BP was measured every 3 min during the PS-AM test. To obtain heart rate (HR) and cardiac autonomic nerve activity, the ECG-RR interval spectrum was analyzed. The low-frequency component (LF) was set between 0.4 and 0.15 Hz, and the high-frequency component (HF) between 0.15 and 0.40 Hz. The HF component was considered to represent parasympathetic-nervous activity and the LF/HF component to represent sympathetic-nervous activity. We have reported previously on the accuracy and methodology of these measurements⁵.

All the subjects in the study were volunteers, and ranged in age between 19 and 71 years (mean $34.4 \pm \text{SD } 12.7$ years). The 19 males and 36 females were studied separately, because mean BF levels differ between males and females. The study protocol was approved by the Ethics Committee of the School of Medicine of the Yokoyama City University, with informed consent being obtained from all participants prior to the study.

As a preliminary study, we selected 10 subjects (3 males, 7 females) from the original study group of 55 subjects and repeated the protocol using application of pressure at 1-s intervals without pulse synchronization. In the preliminary study, the BF in the toe increased marginally to $123 \pm 28\%$ during the air massage stage. In contrast, cuff pressure with pulse-synchronization caused a significantly greater in-

Table 1 Effects of PS-AM on BF and LF/HF

	Before	PS-AM	After
Males (n=19)			
BF (ml/min per 100 g)	8.8±4.4	12.0±6.4**	11.9±6.0**
SBP (mmHg)	114.8±9.4	114.2±11.0	114.2±11.4
DBP (mmHg)	71.2±12.1	68.7±11.9	68.8±12.1
HR (beats/min)	62.7±10.8	59.3±10.0**	59.9±9.6**
LF/HF (ratio)	1.8±0.5	1.3±0.7**	1.7±0.6
HF (ms/Hz ^{1/2})	32.1±17.4	39.0±19.7**	35.4±17.4*
Females (n=36)			
BF (ml/min per 100 g)	7.4±6.2	10.1±7.5**	9.2±7.8**
SBP (mmHg)	106.2±8.4	106.3±8.2	106.6±7.9
DBP (mmHg)	64.4±5.9	63.7±7.3	63.7±7.3
HR (beats/min)	66.8±7.9	65.8±8.7**	65.9±8.8**
LF/HF (ratio)	1.3±0.5	0.9±0.4**	1.3±0.4
HF (ms/Hz ^{1/2})	29.3±11.6	35.9±13.4**	34.9±13.9**

Data are mean±SD.

PS-AM, pulse-synchronized air-massage; BF, blood flow; LF/HF, ratio of low frequency component of heart rate (HR) variability to high frequency component of HR variability; SBP, systolic blood pressure; DBP, diastolic blood pressure.

* $p<0.05$, ** $p<0.01$ vs Before.

Fig4. Percentage change in blood flow (BF) caused by pulse-synchronized air-massage (PS-AM). Before, pre-PS-AM stage; After, post-PS-AM stage. ** $p<0.01$ vs Before.

crease in the BF in the toe ($165\pm42\%$, $p<0.01$). The subjects also found the pulse-synchronization method more comfortable and for this reason it appeared pulse-synchronized air-cuff massage was the most effective method for increasing BF.

Standard statistical methods including paired 2-sample

Fig5. Relationship between mean blood flow (BF) and mean high frequency component (HF) of heart rate variability during pre-PS-AM stage (Before) (Upper panel) and PS-AM stage (Middle panel), and between the percentage changes of BF [$\Delta\%BF=(BF \text{ during PS-AM}-BF \text{ during pre-PS-AM})/(BF \text{ during pre-PS-AM})\times100\%$] and HF [$\Delta\%HF=(HF \text{ during PS-AM}-HF \text{ during pre-PS-AM})/HF \text{ during pre-PS-AM}\times100\%$] (Lower panel). PS-AM, pulse-synchronized air-massage. Male; Female.

[A] Systolic phase

[B] Diastolic phase: compression of vein under cuff 1

[C] Next diastolic phase: compression of vein under cuff 2

Fig 6. Hypothesis of the effects of the pulse-synchronized air-massage (PS-AM) device. BF, peripheral blood flow; Pa, arterial blood pressure; Pv, venous blood pressure; R, total peripheral vascular resistance. The decrease in Pv caused by the PS-AM device may enhance BF and increase venous return, thereby stimulating parasympathetic nervous activity through a baroreflex function.

t-tests, non-paired t-tests, F tests, ANOVA, and least-squares linear regression analysis were used in the analyses. The SPSS 11.0 for Windows (SPSS Japan Inc, Tokyo, Japan) program was used for these calculations. Values are expressed as mean $\pm$ SD, with values of $p < 0.05$ considered significant.

Results

Table 1 shows the mean BF values in the toe, systolic BP, diastolic BP, HR, and cardiac autonomic nerve activity measured in the pre-massage resting stage, the PS-AM stage, and the post-massage resting stage in the male and female groups. Although no significant changes were observed in BP during the PS-AM stage in either group, BF increased significantly ($p < 0.01$) during both the PS-AM and the post-massage stages compared to the pre-massage stage. Assuming the BF in the pre-massage stage was 100%, the mean percentage change in BF during the PS-AM stage in males was $139 \pm 33\%$ and in females $154 \pm 44\%$ (Fig 4). These levels of percentage increases persisted during the 15-min post-massage stage (Table 1, Fig 4).

In contrast, HR decreased during PS-AM and tended to remain low throughout the post-massage stage. LF/HF also decreased significantly ($p < 0.01$) during the PS-AM stage (Table 1). It is thought that changes in HF exert a greater influence than changes in LF. We observed individual differences in the rate of BF change (Fig 4) and HF change. With the aim of determining the causes of these differences we measured the correlation coefficients (r) between the variables and showed a significant correlation between the mean BF and HF (males $r = 0.72$; females $r = 0.42$; all subjects $r = 0.53$, $p < 0.01$) and percentage changes in BF and HF (males $r = 0.83$; females $r = 0.68$; all subjects $r = 0.79$, $p < 0.01$) during PS-AM stage. However, there was no correlation between BF and HF during pre-PS-AM stage (Fig 5), which suggests that the rate of BF change contributes to cardiac autonomic nerve activity.

Discussion

Our hypotheses regarding the effects of PS-AM massage are described below (Fig 6). However, we consider there may be other unknown mechanisms that also have an influence on the changes we observed. Peripheral BF is expressed by the classical Poiseuille-Hagen equation: $BF = (Pa - Pv)r^4/8L\mu = (Pa - Pv)/R$ ($R = 8L\mu/r^4$), where Pa = arterial pressure, Pv = venous or capillary pressure, r = diameter of artery, L = length of artery, and μ = viscosity of blood (Fig 6A). Cuff 1-pressure (40 mmHg) of the PS-AM device (Fig 6B) is applied to the lower part of the extremities only during the cardiac diastolic phase, with no pressure being applied when arterial BFs during the systolic phase. This intensifies the venous return by forcing blood through the counter current venous valve towards the central parts of the vein (under cuff 2), without disturbing arterial BF (Fig 6B). The vein under cuff 1 collapses, resulting in a decrease in venous pressure (Pv) during the systolic phase, leading to an increase in $(Pa - Pv)$. At the next beat, cuff 2-pressure is also applied only during the diastolic phase, forcing the blood towards the central parts of the vein (Fig 6C). These beat-to-beat actions are then applied sequentially to cuffs 3 and 4. These mechanisms may enhance peripheral BF by decreasing Pv, and also stimulate parasympathetic nervous system activity by increasing venous return as a consequence of baroreflex control.

The BF-promoting effects of the PS-AM device varied greatly between individuals (Fig 4). For example, in 4 males and 3 females, the BF was greater during the post-massage stage than in the PS-AM stage. These subjects experienced a sensation of warming in the lower limbs during the post-massage stage, but the reason for the increase of BF during the post-PS-AM stage in these subjects is unclear.

The ALF21 flow-meter used in this study uses a laser with a frequency of 785 nm that measures changes in BF in fine arteries near the skin surface. Vasomotion of 1–4 cycles/min^{6,7} and the activity of sympathetic nerves in the

skin have a marked influence on these blood vessels, which are known to constrict readily as a consequence of emotional stress.⁸ For this reason, we also measured LF/HF and HF as indices of cardiac sympathetic nerve activity at the same time as BF. HR variability and power spectral analysis were used as indices of sympathovagal balance in the heart.^{9,10} Although LF/HF is not always proportional to skin and muscle sympathetic nerve activity and the reaction to stress,¹¹ we performed these measurements in order to investigate the relationship between BF and LF/HF. During the PS-AM operational stage, LF/HF decreased significantly, whereas HF increased.

Subjects with a high HF, an index of parasympathetic nerve activity, also had high BF during the PS-AM stage (Fig 5). Many subjects reported feeling sleepy during PS-AM massage, possibly as a consequence of the rise in HF stimulating parasympathetic nerves. This indicates that when venous blood is transported towards the heart from lower-limb peripheral vessels, the Frank-Starling mechanism may come into effect. As stroke volume (SV) increases, although the change is a passive one, the baroreflex-control mechanism is activated. It is possible that parasympathetic nerve function is stimulated in order to lower HR and maintain a steady BP. The Frank formula¹² is as follows: $BP = \text{cardiac output} \times TPR = SV \times HR \times TPR$, where $TPR = \text{total peripheral vascular resistance}$. We consider it is possible that HR and TPR decrease as a baroreflex action¹³ in order to maintain a steady BP during the PS-AM stage. This possibility is illustrated in Fig 5 in which the greater the increase in BF (with increasing venous return), the more HF (ie, parasympathetic nerve activity) is stimulated.

We found the PS-AM device was more effective in some cases than in others (Fig 4), possibly as a consequence of psychological tension causing variable degrees of autonomic nerve activity, which in turn would influence the peripheral circulation. The majority of subjects felt comfortable and sleepy when the PS-AM was running, suggesting that this method promotes relaxation.

This study measured BF only in fine arteries near the dermal surface layer. To verify the effectiveness of the method, further studies are required to measure factors such as venous BF, cardiac output, and TPR.

Air massage (pneumatic massage) is already used post-surgically to prevent venous stasis, phlebothrombosis of the lower limbs, and lymphedema of the limbs.^{14–17} As the PS-AM has a demonstrable effects it may be useful for improving peripheral circulation.

Acknowledgment

The authors wish to thank Advance Co, Tokyo, Japan, for creating and providing the pulse-synchronized air-massage device (Kaikan Slim).

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