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The effect of multidirectional mechanical vibration on peripheral circulation of humans

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Summary

The physiological response of humans to vibration has intrigued researchers for some time, and recently in relation to its potential as a non-pharmacological means to improve peripheral blood flow. A new vibration device [Arapal Technologies Ltd (ATL), Christchurch, New Zealand] for pain relief that purportedly delivers multidirectional vibration waveforms, has been developed. The aim of the study was to quantify the effect of 30 min of mechanical vibration (60 Hz) using two ATL massage devices concurrently upon local peripheral blood flow in healthy humans. On the basis of past work it was expected that acute exposure of the body to the vibratory stimulus would increase local peripheral blood flow. In a randomized cross-over design, mean blood flow (MBF) to the calf was measured using venous occlusion plethysmography before, during 3 min and after 30 min exposure to the vibratory devices or placebo (non-vibratory) devices. Statistical analysis revealed no consistent differences between conditions and considerable individual variability. The MBF increase tended to be higher in the vibration condition than the placebo condition ($P = 0{\cdot}16$, 95% likely range = −14·4% to 82·2%), the mean increase from resting blood flow at the post-test was 26 ± 49% in the vibration condition and 12 ± 39% in the placebo condition. It took approximately 22 min of exposure to the vibratory stimulus to elicit peak blood flow (18 min with the placebo). Improvements in local blood flow may be beneficial in the therapeutic alleviation of pain or other symptoms resulting from acute or chronic musculoskeletal injuries.

Introduction

Researchers have been intrigued by the physiological response of humans to vibration for some time, and recently in relation to its potential as a non-pharmacological means to improve peripheral blood flow. From an occupational health perspective, it has been shown that chronic whole-body vibration combined with other factors, such as awkward postural demands, can adversely affect the health and well being of workers (see a review by Kittusamy & Buchholz, 2004). For example, a common condition called hand-arm vibration syndrome seems to result from long-term damage to peripheral circulation, muscles and joints of the upper body through high-magnitude vibration. Importantly, Helmkamp *et al.* (1984) acknowledged that the health effects of occupational vibration are heavily dependent on the characteristics of the vibration exposure (e.g. vibration frequency, direction and amplitude). Indeed, brief exposure to low magnitude mechanical vibration may have a number of benefits particularly with respect to enhancing local muscle blood flow. Kerschan-Schindl *et al.* (2001) examined the circulatory responses of participants who stood on a platform (Galileo 2000, Novotec GmbH, Germany) vibrating at 26 Hz (3×3 min sets). Despite the brief duration of the exposure, mean blood velocity to the quadriceps and gastrocnemius muscles was doubled. Further, the resistive index of the popliteal artery was decreased compared with resting levels. According to the authors, the imposed vibration (amplitude = 3 mm, peak acceleration = 78 m^{-1} s^{-2}), evoked rhythmical muscle contractions which caused alterations in peripheral circulation without significant cardiovascular changes as indicated by a lack of change in HR and blood pressure.

Stewart *et al.* (2005) provided additional evidence that localized vibration can be effective for the treatment of painful conditions such as osteoporosis. In their study, 18 women,

(aged 46–63 years), placed their right foot on a vibrating customized foot plate apparatus (McLeod, LDM Associates, San Jose, CA, USA), whilst in a supine position with a 35° upright tilt. The plate was attached to an actuator which delivered sinusoidal vertical displacements of up to 2 mm. A vibration frequency of 45 Hz for 5–7 min was sufficient to cause significant increases in calf blood flow of up to 46% as measured by strain gauge plethysmography. It was argued that plantar vibration enhances venous drainage as well as peripheral blood flow and lymphatic flow (Stewart *et al.*, 2005). In a similar study, Zhang *et al.* (2003) used a brief (3 min) vibratory stimulus (LING V650; Ling Electronics, Anahaim, CA, USA) that emitted random acceleration of constant power density between 5 and 2000 Hz. Six healthy participants rested their foot against a vibrating plate and blood flow to the tibialis anterior muscle was quantified using photoplethysmography. Local muscle blood flow was increased by an average of 20% as a consequence of the brief vibration stimulus.

Past research has tended to employ standard electrodynamic systems to administer the vibration stimulus to one site on the body (i.e. Stewart *et al.*, 2005; Zhang *et al.*, 2003). Such systems emit vibration in the form of pulses solely in the axial direction of the vibrator[1]. ATL has developed two massage devices for pain relief in the form of a cushion and a handheld device. Each device creates a biaxial vibration which delivers two sinusoidal oscillating forces, one normal and one tangential to the contact surface. The manufacturers describe this as a 'wave-like' massage action which is supposed to provide a more efficient stimulation of lymphatic circulation than other vibratory therapeutic devices. Le-Gnoc (2006), on behalf of Industrial Research Limited (IRL, Christchurch, New Zealand), has performed independent testing on the vibration characteristics of the two vibration units and discovered that when the two units are applied to an object together there is an interaction between the oscillations of the vibration waves. This interaction at ''…slightly different frequencies can produce a 'beating' effect…'' (2006, p. 9), allowing the amplitude of the vibration to become larger.

In previous studies (Kerschan-Schindl *et al.*, 2001; Zhang *et al.*, 2003; Stewart *et al.*, 2005) the duration of the exposure to vibration has been acute (i.e. <9-min total) and participants were in prone or supine positions. In contrast the present study followed manufacturers recommendations and exposed participants to the vibratory devices in a seated position for a continuous period of 30 min. The aim of the present study was to quantify the effect of mechanical vibration delivered by the ATL devices upon peripheral circulation in healthy humans. On the basis of past work it was expected that acute exposure (i.e. 30 min) to the vibratory stimulus would increase local peripheral blood flow.

[1]Although, the vibratory device used by Zhang *et al.* (2003) also delivered <20% of its accelerative power in a direction perpendicular to the vibration axis.

Methods

Participants

Twenty healthy participants (10 men and 10 women) aged between 40 and 65 took part in the study after giving informed consent. Participants were non-smokers with no history of cardiovascular disease or illness (e.g. angina, high blood pressure), and were screened for medication that may have affected circulation at the time of testing (e.g. aspirin). All participants reported that they were low–moderate exercisers, although they were asked to refrain from heavy exercise in the 24 h preceding testing. All participants completed the testing with no health concerns. The research was approved by the University of Otago Human Ethics Committee.

Procedure

A randomized crossover design was employed involving two treatment conditions: (i) placebo devices placed under the gluteal muscles and right foot (ATL cushion and hand held devices that were essentially non-vibratory[2]) and (ii) constant vibration with ATL devices placed in the same locations as in the placebo condition. The placebo devices looked and sounded the same as the ATL devices. To control for a Hawthorne effect with the vibratory equipment, participants were informed that they would not feel the placebo device as it delivered sub-threshold vibration.

All testing took place in a temperature and humidity controlled laboratory at 24·0 ± 0·5°C and 50% relative humidity. The participants wore loose clothing (e.g. shorts and t-shirt) during the sessions. Participants were asked to consume a light snack in the hour before testing. Upon arrival at the laboratory the participants were asked to rest in a comfortable seated posture upon the ATL vibration cushion, which was placed on a height adjustable chair, with their knees and ankles flexed at 90°. Each participant's right foot was rested on the ATL massage portable unit, with their left foot placed on a soft foam pad to ensure that both legs rested at the same height.

Participants visited the laboratory on three separate occasions. The initial visit was a familiarization session lasting 45 min. During the familiarization period, participants were informed about the study's protocol, the use of the ATL massage equipment, and any questions they had regarding the study were answered. Participants then sat on the vibration cushion and rested their foot on the hand unit and were exposed to 30 min of vibration. Both units operated at a frequency of approximately 60 Hz (Le-Gnoc, 2006).

[2]The placebo devices were modified vibratory devices with which the generating motor had been detached from the vibratory plate. Hence whilst in operation, the placebo units looked and sounded like the vibratory units. However, it should be acknowledged that it was not possible to dampen vibration completely from the placebo units, and a small residual pulse was possible.

The subsequent two sessions were used for data collection, with each session lasting approximately 60 min. Data were obtained from each participant for blood flow, blood pressure, HR and local skin temperature (two points, lower back and upper gastrocnemius head). The arterial blood pressure, HR and skin temperature data of each individual were monitored throughout experimentation for safety reasons. Baseline data were collected for 1 min before the vibration or placebo condition was applied to provide an indication of potential diurnal variations in blood flow. Data were then collected at 5-min intervals for 30 min, and at 3 min following the cessation of each condition. The duty cycle of measurement was 5:8 s (inflated:deflated). At each data collection period, the average of five blood flow readings using venous occlusion plethysmography was used to measure mean blood flow (MBF). The strain gauge was placed immediately below the inferior border of the gastrocnemius muscle belly. The occluding pressure of the cuff was set at 140 mmHg[3].

Data analysis

Whilst the investigator collecting data was aware of the experimental condition at the time of testing, another investigator blind to the conditions carried out the data analysis. Limb volume changes were calculated from the derivative of the steep linear portion of the plethysmographic signal using visual observation within the CHART™ (AD instruments, Bella Vista, NSW, Australia) 5 software. MBF (ml dl^{-1} min^{-1}) to the right leg was calculated as the unweighted average of up to five blood flow measurements for each recording period. MBF values were normalized with respect to mean baseline readings and are presented as a percentage change from each individual's baseline value. Peak blood flow (PBF) was defined as the maximum MBF attained during each condition. The time at which PBF occurred was also recorded.

At the completion of data collection the blood flow data of two participants (one male, one female) were identified by the SPSS v.13 (SPSS Inc., Chicago, IL, USA) analysis software as extreme cases (i.e. their data deviated from the group mean by more than $\pm 3 \times$ interquartile range). On the basis that equipment failure was likely to have influenced the data of these participants, their data were excluded from further analysis. For the remaining 18 participants, calculation of z-scores confirmed that the data were normally distributed. Repeated measures ANOVA (condition × phase) was used to compare the change in MBF from baseline levels to post-test between conditions. Linear regression was then applied to analyse percentage MBF changes over time in each condition. PBF between conditions was campared with pairwise t-tests. The statistical significance level was set at $P<0{\cdot}05$ for each analysis.

[3]As participants were sat upright throughout testing, the occluded limb was below heart level. To compensate for the increased perfusion pressure associated with this position, an increased occlusion pressure of 140 mmHg rather than the standard 60 mmHg was necessary.

Results

Systolic blood pressure , mean HR, and skin temperature did not show any statistically significant changes between the vibration and placebo conditions (BP_{syst}: 115·6 ± 10·9 mmHg and 113·8 ± 9·3 mmHg, HR: 75·4 ± 8·7 beats min^{-1} and 74·6 ± 10·5 beats min^{-1}, T_{back}: 32·5 ± 2·4° and 33·5 ± 1·9°, T_{gast}: 30·7 ± 1·9° and 30·6 ± 1·3°, respectively). Diastolic blood pressure was higher in the vibration condition (BP_{dias}: 80·8 ± 6·7 and 78·0 ± 7·1 mmHg) however, the effect size (ES) was small ($t(17) = 2{\cdot}3$, $P<0{\cdot}03$, $ES = 0{\cdot}25$)

Mean blood flow

In the vibration condition, the percentage MBF increase from baseline to post-test was 26 ± 49%, the mean increase in the placebo condition was 12 ± 39% (see Fig. 1). A significant main effect of phase was found for MBF increases from pre- to post-test ($F(1,17) = 8{\cdot}42$, $P<0{\cdot}01$, 95% likely range = 0·12–0·74 ml dl^{-1} min^{-1}) However, the MBF change was not significantly different between conditions ($F(1,17) = 1{\cdot}03$, $P = 0{\cdot}33$, 95% likely range = −0·76 to 0·27 ml dl^{-1} min^{-1}). The baseline MBF readings were 17% higher in the placebo condition than the vibration condition (Table 1) although follow-up pairwise comparisons showed that this difference was not significant ($t(17) = 1{\cdot}17$, $P = 0{\cdot}26$, 95% likely range = −1·0 to 0·3 ml dl^{-1} min^{-1})

The individual normalized MBF responses are presented as scatterplots in Fig. 2. Linear regression of MBF over time revealed a strong positive association in the vibration condition (gradient = 0·94, $R^2 = 0{\cdot}86$, $P<0{\cdot}004$) and a very weak relationship in the placebo condition (gradient = −0·14, $R^2 = 0{\cdot}03$, $P = 0{\cdot}69$) when the data were averaged across the group.

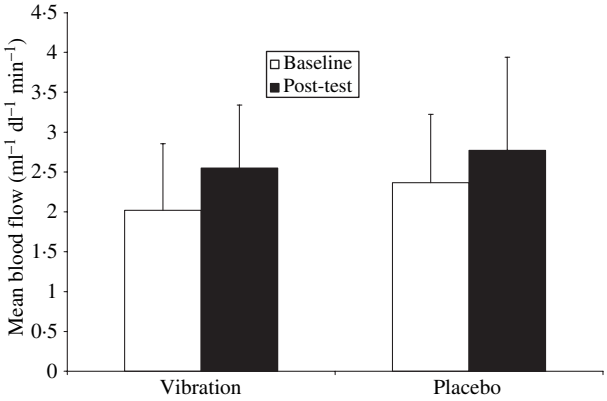

Figure 1 Comparison of percentage mean blood flow (MBF) at baseline and post-test (3 min after treatment) between the vibration and placebo conditions.

Table 1 Blood flow data for each participant by condition.

	Vibration			Placebo		
Participant	Baseline (ml dl^{-1} min^{-1})	Normalized PBF (%)	Time to reach PBF (mins)	Baseline (ml dl^{-1} min^{-1})	Normalized PBF (%)	Time to reach PBF (mins)
1	2·25	3	5	1·89	91	5
2	2·19	34	15	1·65	127	5
3	1·07	161	25	2·62	14	5
4	1·89	108	25	1·55	76	10
5	4·02	−16	10	1·58	71	30
6	1·52	70	33	1·76	191	20
7	0·63	328	33	2·97	63	15
8	1·83	107	33	3·18	29	25
9	2·62	210	25	2·42	−23	25
10	2·09	20	15	1·84	92	25
11	3·58	8	30	2·27	66	33
12	1·27	278	30	2·54	23	20
13	1·91	4	10	1·80	16	25
14	1·76	−4	33	2·36	60	30
15	2·63	50	33	4·45	63	25
16	2·04	14	5	4·12	−9	5
17	1·13	36	33	2·19	81	5
18	1·90	5	5	1·43	63	10
Average	2·02	78·7	22·1	2·37	60·8	17·7
SD	0·83	102·1	11·2	0·86	50	10·1

PBF, peak blood flow.

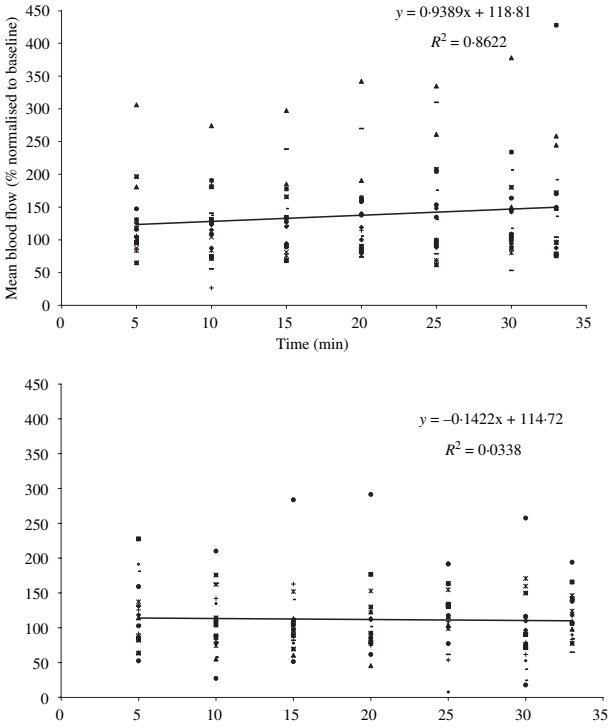

Figure 2 Individual mean blood flow (MBF) changes over time from: (a) vibration condition and (b) placebo condition. N.B. 100% MBF corresponds to no change from baseline levels.

Peak blood flow

The mean increase from baseline blood flow to PBF for all participants was 78% for the vibration condition and 60% for the placebo condition (Table 1) but the percentage PBF change was not significantly different between conditions (t (17) = 0·60, P = 0·55, 95% likely range = −45 to 81%). On average, it took 5 min longer to elicit PBF in the presence of the vibratory stimulus (22·1 min) than in the placebo trials (17·7 min).

From the vibration condition, the participants' data were divided into an early responding sub-group (PBF attained by 15 min) and a late responding sub-group (PBF attained after 20 min). Using this distinction it can be seen that the longer it took to reach PBF, the larger the increase shown (t (10·6) = −3·37, P<0·01, 95% likely limits = −188 to −39·0). Seven participants were early responders, whose average PBF corresponded to a relatively small change from their baseline value (mean = 9%). For the remaining nine late responders, the mean increase in blood flow was +123%.

Discussion

The results indicate that the application of ATL vibration equipment elicited a tendency for an increase in peripheral blood flow that was approximately 14% higher than that shown in the placebo condition (i.e. 26% compared with 12% respectively). It should be noted that considerable individual variability was observed in the MBF responses to the vibration

treatment which resulted in a non-significant comparison ($P>0{\cdot}05$) of the MBF changes between the vibration and placebo conditions. The baseline MBF readings were typically higher in the placebo condition than the vibration condition (by approximately 17%, although $P>0{\cdot}05$) which highlights the importance of reporting MBF values normalized to baseline.

Previous studies examining circulatory response to mechanical vibration have generally found similar increases in blood flow as a result of vibration to that shown in the current study (e.g. 20% from Zhang *et al.*, 2003; 46% from Stewart *et al.*, 2005). Such studies have tended to utilize relatively brief periods of vibration of <9-min total (Kerschan-Schindl *et al.*, 2001; Zhang *et al.*, 2003; Stewart *et al.*, 2005) often in the absence of a control condition. In the present study, as recommended by the manufacturer, participants were exposed to 30 min of vibration. The extended duration of the exposure to vibration allowed some individuals to show greater increases in blood flow (see Fig. 3), although this was not a consistent effect for all participants and the underlying mechanism should be explored in future work.

As stated earlier, the vibration units used in many previous studies created simple vibration pulses in an axial direction (e.g. Zhang *et al.*, 2003; Stewart *et al.*, 2005), whereas the ATL equipment purportedly creates a complex bidirectional vibration pulse (Le-Gnoc, 2006). It is possible the wave-like 'beating' action of the vibrator devices is a more effective means of stimulating blood and lymphatic circulation than unidirectional vibration of one application site. However, the similar levels of MBF change found in the present study do not provide conclusive support to this suggestion. Future research should consider whether other variables associated with different vibratory devices (e.g. Arapel Technologies Ltd, Galileo 2000 platform, LING V650, etc.), such as the vibration frequency, amplitude and the contact surface and area of the device, may influence circulatory response.

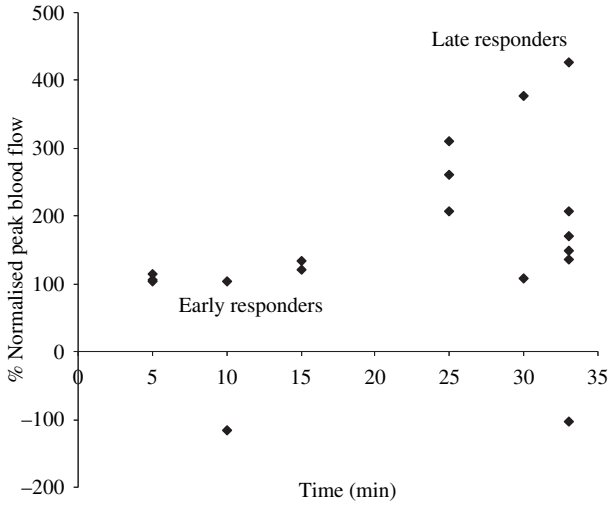

Figure 3 Normalized peak blood flow (PBF) data during vibration condition. For the 'early responders' PBF values were recorded in the first 15 min of the vibration condition, the 'late responders' provided PBF values after at least 20 min of the vibration condition.

A number of non-invasive techniques exist to quantify blood flow including Doppler ultrasound, electromagnetic flow meters, and several variants of plethysmography. Venous occlusion plethysmography has become the 'gold standard' assessment method over the last 50 years (Wilkinson & Webb, 2001). The method means that arterial blood can enter the occluded limb but cannot escape, unless venous pressure reaches the occluding pressure. A mercury-in-silastic strain gauge is placed over the widest part of the limb such that a change in limb circumference can be detected as a change in electrical resistance of the gauge. Increases in limb volume are directly related to arterial blood flow providing a reliable estimate of circulation to the measurement site (Proctor *et al.*, 1996). However, the venous occlusion measurement process is not without its limitations and might have also introduced artefacts within the data. For example, venous occlusion plethysmography is sensitive to movement of the limb and induction of local vasomotor changes. Therefore, the veins have to be completely occluded, allowing no leakage. The arterial inflow must not be altered initially and the occlusion artefact has to be small. Whilst participants were asked to remain completely still during testing and also to standardize their pretesting routines, it is possible that some error may have been introduced by non-adherence to instructions.

Peak blood flow occurred at approximately 22 min in the presence of the vibratory stimulus. In certain individual cases, large increases from baseline blood flow to PBF of up to +327% were recorded. In fact the results indicate high individual response variability in both test conditions (see Fig. 2). It should be acknowledged that cardiovascular output has inherent rhythmicity and peripheral blood flow can fluctuate on different time scales, therefore it is possible that much of the variability in the data may be explained by such natural processes. It cannot be discounted that individual variation in terms of expectancy within the vibration and placebo conditions may also have affected the level of comfort or muscular tension experienced by the participant whilst blood flow was recorded. Together such limitations indicate that more than one familiarization session and a multiple repeated-measures testing protocol may be necessary in future work.

Bosco *et al.* (2000) showed that brief exposures to whole-body vibration can cause acute alterations in blood hormone concentrations (e.g. increases in testosterone and growth hormone, decrease in cortisol) in healthy men. Therefore, it is possible that both circulatory and hormonal adaptations to vibration are linked and may jointly contribute to a complex mechanism underlying any therapeutic benefit of such treatments. Another possibility to account for potential elevations in peripheral blood flow is that vibration causes a withdrawal in sympathetic nerve activity and resultant vasodilation.

Finally, whilst vibration therapy may be a valuable treatment for certain less-mobile populations, the magnitude of changes in local blood flow shown in the present study (up to 26%,

approximately 0·5 $l\,min^{-1}$) should also be set within the context of the circulatory changes one might expect to see associated with everyday activities such as physical exercise. For example, a healthy active individual can increase blood flow to the calf by approximately 6 $l\,min^{-1}$ simply by walking at 5 $km\,h^{-1}$ up a moderate slope (Nielsen *et al.*, 1990). In light of the present findings, future research could further investigate: (i) the potential differences in blood flow during and after extended duration exposure (at least 30 min) to a vibratory stimulus at different frequencies; (ii) acute hormonal and sympathetic nerve activity responses to vibration; (iii) how the characteristics of the vibratory device used influence circulatory response and (iv) long-term physiological adaptations to vibration exposure. Whilst not directly tested in the current study such long-term adaptations may be beneficial in the therapeutic alleviation of pain or other symptoms resulting from acute or chronic musculoskeletal injuries (Lundeberg *et al.*, 1984).

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Conflicts of interest

No commercial party has or will confer a benefit upon the authors or upon any organization with which the authors are associated.

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