Acute effects of vibration on peripheral blood flow in healthy subjects

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Abstract

Objectives—The main objective was to study the acute vascular effects in the hands of normal healthy subjects of a complex vibration spectrum similar to that generated by many industrial hand held tools. The effects of repeated bouts of vibrations and alterations in the intensity of vibration were also studied.

Methods—Blood flow was measured by venous occlusion plethysmography with strain gauges. Vibration across a frequency range of 0·4 to >4000 Hz was generated by a pneumatic chisel and applied to the right hand. Blood flow was measured in both middle fingers, both big toes, or both forearms before, during, and after a two minute period of vibration. Systolic pressure of a finger and heart rate were also measured.

Results—Vibration was associated with a significant bilateral reduction in finger and toe blood flow (P < 0·01 and P < 0·03) and a significant increase in heart rate (P < 0·05) but had no effect on forearm blood flow. The finger response was not abolished by repeated bouts of the vibration but was initially most notable during the first minute of vibration. Increasing the intensity of vibration delayed recovery.

Conclusions—Hand vibration causes a generalised increase in sympathetic tone in the heart and extremities. This may be a factor in the development of vasospastic disease in habitual users of hand held industrial vibrating tools.

Keywords: vibration; hand vibration; finger blood flow

In an attempt to elucidate the underlying mechanisms involved in the development of the vasospastic component, various groups have studied the acute effects of vibration on digital blood flow in healthy volunteers and workers exposed to vibration. Acute vibration in the range 40–200 Hz reduced finger blood flow with the effect being maximal at 125 Hz. Vibration of one finger or hand can cause vasoconstriction in both hands, the response being abolished or reversed by digital nerve block. These results suggest that vibration may elicit a centrally mediated sympathetic reflex in the hands with Pacinian corpuscles being the most likely sensory receptor. Most of the laboratory investigations have used electromagnetic generators to produce pure sinusoidal vibration so that frequency and amplitude could be carefully controlled. However, the power tools used in industry typically produce a complex spectrum of frequencies. The present study attempted to reproduce vibratory patterns of similar frequency and complexity to those experienced by industrial users. The effects of these were studied in the peripheral circulation of healthy volunteers under laboratory conditions.

Methods

SUBJECTS

Measurements were made on 34 healthy male volunteers aged 20–34. All were non-smokers and had no history of peripheral vascular disease or of injury to the neck, trunk, or upper limbs. None were taking any medication at the time of the study, and none had previously experienced any significant exposure to hand transmitted vibration. The study was approved by the Faculty of Medicine Ethics Committee and all subjects gave informed consent.

All experiments were carried out in a laboratory maintained at 24·0 ± 0·5°C. The subjects lay recumbent on a couch between two water perfused blankets (Blanketroll 2, Hawksley and Sons) maintained at a temperature of 33·0 ± 1·0°C and there was an equilibration period of 30 minutes before any measurements were made.

In all experiments, the subjects lay with both arms and hands supported slightly above heart level. The right hand rested on a steel plate the upper surface of which was covered with a thin layer of insulating material to prevent conduction of heat away from the hand. The lower surface of the plate was rigidly attached to a pneumatic chisel (Pnumat,
Warrington) which was driven by compressed air (fig 1). Reproducible intensities of vibration were induced with a flowmeter (KDG 2000) by accurately controlling air flow to the chisel at rates of 65 l/min (low intensity) or 75 l/min (high intensity). The subjects wore double hearing protection throughout the experiment, which rendered them unable to hear any noise associated with the vibration. The investigators (while out of the subject’s range of vision) inserted small ear plugs just before the vibration.

MEASUREMENT OF FINGER BLOOD FLOW AND PRESSURE
Blood flow was measured by venous occlusion plethysmography with indium/gallium strain gauges (PMS Inst, SG 6) on the middle finger of each hand just proximal to the nail bed (fig 1) with the collecting cuff placed on the middle phalanx. Four blood flow measurements were made per minute.

Figure 2  Recordings of middle finger blood flow in the right (vibrated) and left (non-vibrated) hands of a normal healthy subject before and during two minutes of low intensity vibration of the right hand. The value above a particular flow represents blood flow (ml/100 ml/min).

Finger systolic pressure was measured in the middle finger of each hand with a 24 mm wide pressure cuff. Inflation of the cuff to 200 mm Hg resulted in a constant finger volume due to the occlusion of the arterial inflow and venous outflow. On controlled deflation of the cuff, the sudden increase in finger volume indicated the restoration of arterial inflow. The cuff pressure at which this increase started was the finger systolic pressure.

Hand and finger skin temperatures were monitored with thermocouples attached to the dorsum and pulp of the index finger of both hands. Temperature readings were displayed with an electronic thermometer (Comark).

The electrocardiogram (ECG) was recorded from three chest electrodes and heart rate was derived by a computerised recording system.

ORGANISATION OF THE INVESTIGATION
There were four different experimental protocols to examine various effects of acute hand vibration. Each protocol was carried out on a different subgroup of the 34 healthy subjects.

(1) Effects of repeated applications of vibration
These experiments were carried out on 10 volunteers. After measuring resting flows for two minutes, two measurements of resting finger systolic pressure were made. Finger blood flow was then measured during two minutes of application of low intensity vibration to the right hand. Immediately vibration ended, finger systolic pressure was remeasured. After a rest period of 10 minutes during which the subject was allowed to move his shoulders and hands gently, the programme of measurements was repeated. A third complete set of measurements was made after a second 10 minute rest period. Finger skin temperatures and heart rate were also measured throughout.

Control experiments were performed on six of the subjects on another occasion. The experimental protocol was identical to that described except that no vibration was applied to the right hand.

(2) Effects of low and high intensity vibration on finger blood flow
Twelve different volunteers attended the laboratory on two occasions. One level of vibration was applied to the right hand on the first visit, and the other on the second visit, the order being randomly determined. Blood flow was measured in both middle fingers during a two minute control period, during two minutes of vibration of the right hand, and continuously for five minutes recovery and for one minute at 10, 15, and 20 minutes after the end of vibration. Finger skin temperatures were also monitored throughout.

(3) Effects of hand vibration on forearm blood flow
In six new subjects, blood flow was measured in both forearms by strain gauge venous occlusion plethysmography before, during, and after two minutes low intensity vibration of the right hand. After three minutes rest, forearm blood flow was measured before, during, and after a two minute period of mental arithmetic.
(4) Effects of hand vibration on toe blood flow

In another six subjects, blood flow was measured in both big toes before, during, and after two minutes low intensity vibration of the right hand.

**FREQUENCY ANALYSIS**

An accelerometer (Bruell and Kjaer, type 4372X) was attached to the plate beside the middle finger and the frequency spectra for the vibrations induced by air flows of 65 and 75 l/min through the chisel were recorded with a real time frequency analyser (Bruell and Kjaer, type 2143).

**STATISTICAL ANALYSIS**

In the first group of experiments, which investigated the effects of repeated bouts of vibration on finger blood flow, finger systolic pressure, and finger skin temperature, the results were analysed with a repeated measures analysis of variance. The finger blood flow analysis was carried out with log transformed values to counteract the wide range of resting finger blood flow values found. Any significant results were analysed more closely with Wilcoxon signed rank tests.

In the second, third, and fourth groups of experiments, results were analysed with the Wilcoxon signed rank test.

**Results**

(1) **REPEATED APPLICATIONS OF VIBRATION**

Figure 2 shows typical recordings of blood flow in the experimental and control fingers before and during the first bout of two minutes of vibration to the right hand. It was found that whole hand vibration caused an immediate fall in blood flow in both fingers and that flow rapidly increased to levels before vibration when the vibration stopped. To calculate the results, the resting value of blood flow before vibration was taken as the mean of the eight control measurements and a mean value was calculated for each minute of vibration.

Figure 3 shows a computerised recording of heart rate before, during, and after the first two minute vibration period in one subject. It can be seen that heart rate increased when vibration started and quickly fell to resting levels when vibration ended. Results were calculated by comparing the mean heart rates over 50 R-R intervals (a) before vibration, (b) after the start of vibration, (c) before the end of vibration, and (d) after vibration stopped.

Table 1 shows the mean blood flow values for all 10 subjects during the three vibration periods, V1, V2, and V3. Vibration caused a significant decrease in blood flow in both fingers during all three vibration periods. The level of blood flow was not significantly different during V1, V2, and V3, but the size of the response seemed to decrease partly because of the downward trend in the resting flows before vibration. This downward trend was also found in the six control experiments in which no vibration occurred (table 2). During V1, the reduction in blood flow was significantly

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**Table 1** Mean (95% CI) middle finger blood flow (ml/100 ml/min) in 10 normal subjects during hand vibration in three vibration periods V1, V2, and V3

<table>
<thead>
<tr>
<th>Vibration period</th>
<th>Vibrated hand</th>
<th>Resting hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>18.1 (11.2-24.9)</td>
<td>14.9 (8.7-21.2)</td>
</tr>
<tr>
<td>1st Min</td>
<td>4.9 (3.0-6.7)</td>
<td>5.8 (3.5-8.1)</td>
</tr>
<tr>
<td>2nd Min</td>
<td>6.7 (4.5-8.9)</td>
<td>7.2 (5.4-10.0)</td>
</tr>
<tr>
<td>P = 0.0051</td>
<td>P = 0.0051</td>
<td></td>
</tr>
<tr>
<td>V2:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>14.6 (8.8-20.4)</td>
<td>11.4 (7.3-15.5)</td>
</tr>
<tr>
<td>1st Min</td>
<td>5.6 (3.4-7.7)</td>
<td>6.0 (1.9-10.2)</td>
</tr>
<tr>
<td>2nd Min</td>
<td>8.5 (3.9-13.2)</td>
<td>7.9 (3.3-12.4)</td>
</tr>
<tr>
<td>P = 0.0093</td>
<td>P = 0.0069</td>
<td></td>
</tr>
<tr>
<td>V3:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>13.9 (7.3-20.6)</td>
<td>11.2 (5.4-16.9)</td>
</tr>
<tr>
<td>1st Min</td>
<td>7.2 (3.3-11.1)</td>
<td>7.1 (2.7-11.5)</td>
</tr>
<tr>
<td>2nd Min</td>
<td>8.4 (3.7-13.1)</td>
<td>8.3 (2.4-13.9)</td>
</tr>
<tr>
<td>P = 0.0166</td>
<td>P = 0.0125</td>
<td></td>
</tr>
</tbody>
</table>

P values = blood flow from level before vibration.

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**Table 2** Mean (95% CI) middle finger blood flow (ml/100 ml/min) in six normal subjects in the absence of applied vibration during three vibration periods V1, V2, and V3

<table>
<thead>
<tr>
<th>Vibration period</th>
<th>Right hand</th>
<th>Left hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>18.5 (5.2-31.7)</td>
<td>19.6 (8.3-30.8)</td>
</tr>
<tr>
<td>1st Min</td>
<td>18.3 (5.3-31.7)</td>
<td>17.9 (7.3-28.4)</td>
</tr>
<tr>
<td>2nd Min</td>
<td>14.7 (7.5-21.9)</td>
<td>14.7 (8.3-21.0)</td>
</tr>
<tr>
<td>V2:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>12.1 (3.9-20.3)</td>
<td>11.4 (6.2-16.5)</td>
</tr>
<tr>
<td>1st Min</td>
<td>13.9 (5.3-22.3)</td>
<td>13.0 (6.4-19.6)</td>
</tr>
<tr>
<td>2nd Min</td>
<td>12.1 (5.2-18.9)</td>
<td>10.0 (5.5-14.4)</td>
</tr>
<tr>
<td>V3:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>11.9 (5.9-18.0)</td>
<td>10.7 (7.3-14.1)</td>
</tr>
<tr>
<td>1st Min</td>
<td>10.3 (4.0-16.5)</td>
<td>9.3 (5.5-13.1)</td>
</tr>
<tr>
<td>2nd Min</td>
<td>9.7 (3.5-15.9)</td>
<td>8.3 (3.3-13.3)</td>
</tr>
</tbody>
</table>
greater during the first minute of vibration than during the second minute (P = 0.0284), but this effect had disappeared by V3.

Mean finger systolic pressure measured before vibration started and immediately after it ended did not alter significantly throughout. Finger skin temperature measured immediately after vibration ended was slightly reduced in most subjects, but the decrease was not significant.

Mean heart rate was significantly increased during all three vibration periods (table 2).

(2) COMPARISON OF LOW AND HIGH INTENSITY VIBRATION

Figure 4 shows mean blood flow in the middle fingers of both the vibrated and the non-vibrated hands of all 12 subjects before, during, and after vibration produced by air flows of 65 and 75 l/min through the chisel. These subjects were a new group of people, which may help to explain the higher mean resting finger blood flow in this group compared with the values in table 1. The experiments were carried out under experimental conditions identical to those of the people whose results were described already. Before either intensity of vibration started, there was no significant difference in finger blood flow in the vibrated and non-vibrated hands.

Low intensity vibration caused significant reductions in blood flow in the right and left middle fingers during the first (P = 0.0022 and 0.006, respectively) and second minutes (P = 0.0014 and 0.0342, respectively) of exposure. In the vibrated hand, the reduction was more obvious (P = 0.006) during the first minute. Recovery was immediate in both hands when vibration ended and was still present five minutes after the end of vibration. However, at 10, 15, and 20 minutes after vibration, blood flow in both fingers had fallen significantly (P = 0.0022 and P = 0.0414) from the levels before vibration similar to the findings during repeated exposures to vibration described in the group 1 experiments.

High intensity vibration also induced significant reductions (P = 0.0022) during the two minute exposure to vibration (fig 4). In both fingers, the reduction was more notable (P = 0.015) during the first minute. Recovery was less complete in that blood flow in both fingers remained significantly lower than the levels before vibration at 5, 10, 15, and 20 minutes after the end of vibration (P = 0.0022 and P = 0.0186).

There was no significant alteration in finger or hand skin temperature throughout either level of exposure to vibration.

(3) EFFECT OF HAND VIBRATION ON FOREARM BLOOD FLOW

In a group of six subjects, two minutes of vibration of the right hand did not significantly alter forearm blood flow from the mean level before vibration of 3.9 (95% confidence interval (95% CI) 3.3–4.4) ml/100ml/min in the right forearm and 3.8 (3.0–4.7) in the left. Mental arithmetic, however, significantly increased (P = 0.0277) mean flows to 9.2 (4.9–13.5) ml/100 ml/min in both forearms.

(4) EFFECT OF HAND VIBRATION ON TOE BLOOD FLOW

In another group of six subjects, low intensity vibration of the right hand significantly (P = 0.0277) reduced toe blood flow during the vibration from 10.9 (2.9–18.9) to 7.3 (1.6–12.9) ml/100 ml/min in the right toe and from 11.1 (0–22.0) to 7.0 (0–14.0) ml/100 ml/min in the left toe. Toe blood flow returned to the levels before vibration immediately after the vibration ended.

FREQUENCY ANALYSIS OF APPLIED VIBRATION

Both rates of air flow to the chisel produced a complex vibration frequency spectrum (fig 5).
Acute effects of vibration on peripheral blood flow in healthy subjects

Discussion

The findings in the present study generally confirmed previous findings that vibration of one hand is associated with a significant decrease in finger blood flow in both hands of healthy subjects. The bilateral nature of the response and its absence after digital nerve block suggest that a central sympathetic vasoconstrictor reflex elicited by vibration is involved. Greenstein and Kester further reported that vibration caused vasodilatation in healthy subjects after digital nerve block and three minutes of vibration produced vasodilatation in some healthy subjects even without nerve block. They suggested that acute vibration may stimulate both a vasoconstrictor reflex and also induce active local vasodilatation, with these two independent mechanisms competing against each other.

Pure sinusoidal vibration was used as the stimulus in most of the previous laboratory studies. In the present study, a pneumatic chisel was used as the vibration source to mimic more closely the complex vibration spectrum to which industrial users are habitually exposed. The reduction in finger blood flow during acute exposure to this vibration was of a similar magnitude to that reported by Welsh in healthy subjects. Thus the complex spectrum of frequencies did not seem to differ from pure sinusoidal vibration in its effects.

The immediate recovery of finger blood flow to resting levels before vibration after low intensity vibration has also been reported previously. The bilateral reduction in finger perfusion found at 10, 15, and 20 minutes may be related to the vibration or may be due to prolonged inactivity in the fingers and reflect the gradual fall found in the group 1 control experiments. The absence of complete recovery that followed the high intensity vibration may have been associated with the more pro-
nounced peaks in the 31·5 to 100 Hz frequency range.

The circulation in the finger and hand is known to be very responsive to even minor alerting or stressful stimuli and responds with a sympathetically mediated vasoconstriction. It seemed possible that at least part of the fall in finger blood flow during hand vibration in normal people could be due to a non-specific arousal response rather than to the effects of vibration acting directly on the blood vessels or sensory receptors in the hand. Such an alerting effect might be expected to diminish with repetition.

When the exposure to vibration was repeated three times, there seemed to be a fall off in the response both within and between vibration periods. During the first exposure, V1, the reduction in finger blood flow during the first minute was significantly greater than that during the second minute. However, this effect had disappeared by the third exposure, V3, suggesting that some form of adaptation had taken place. With repeated vibration, the finger blood flow response during successive exposures seemed to diminish, especially in the non-vibrated finger, although the actual levels of finger blood flow during the three periods of vibration were not significantly different. The downward trend in resting finger blood flow between exposure to vibration contributed to the apparent decrease in response. However, this downward trend was also found in control experiments and so was not thought to be related to vibration itself. Neither environmental nor skin temperatures changed significantly throughout experiments and the prolonged immobility of the subjects may have been responsible for the gradual fall in resting flows. Overall, the decreasing response during a vibration period and the trend towards less reduction in blood flow from V1 to V3 suggested that some degree of adaptation was occurring. Thus at least part of the response to acute vibration in healthy volunteers may in fact be a non-specific response to sensory stimulation. This contrasts with previous findings in which neither healthy control subjects nor workers exposed to vibration seemed to adapt to repeated presentations of whole hand vibration.

The vascular changes were accompanied by a small but significant increase in heart rate during exposure to vibration. This may be part of a generalised sympathetic response to vibration or represent an increased state of arousal of the subject during vibration. However, the effect did not seem to diminish with repetition of vibration.

It is well recognised that changes in blood flow in the finger and hand reflect predominantly changes in skin blood flow. As discussed earlier, stress may cause sympathetically mediated cutaneous vasoconstriction and therefore a fall in finger or hand blood flow. However, in the forearm, vascular responses in the muscle circulation tend to predominate unless thermal stimuli are involved. Stress therefore normally results in a sympathetically mediated increase in forearm blood flow due to vasodilatation in skeletal muscle. There was no evidence in the forearm of either vasoconstriction induced by vibration or vasodilatation induced by stress during exposure to vibration although a normal vasodilator response to emotional stress was found in all subjects during mental arithmetic.

The toes also reflect predominantly changes in the skin circulation and the vasculature in the toes has a similar pattern of innervation and regulation to the fingers. Vibration of the right hand caused a reduction in blood flow in the big toes in five of the six subjects studied. In one subject a reduction followed by an increase in flow was found. It is interesting to note that this subject had high resting toe blood flow and thus was in a state more comparable with the nerve blocked subjects reported by Greenstein and Kester who showed vasodilatation during vibration.

The experiments measuring forearm and toe blood flow were only carried out on a few subjects. However, as the responses to vibration in the toes and to mental arithmetic in the forearms were consistent, the number of subjects was deemed to be adequate for statistical analysis. The number may be too small to determine non-significance of the effect of hand vibration on forearm blood flow. However, resting forearm blood flow showed very little flow to flow variation in any of the individual subjects (as would be expected). Hand vibration did not alter this pattern in any of the six subjects.

Four different groups of experimental subjects were tested in this investigation. It was not possible to recruit one group of subjects who were prepared to attend on six separate occasions. Accordingly, it seemed preferable to investigate each subject not more than twice so that the groups were not a mixture of first time subjects and relatively more experienced subjects. This factor may represent a complication for the interpretation of the physiological responses to vibration stress.

Although no patients with vibration white finger were included in the present investigation, earlier results with the same technique in chain saw operators and matched controls showed no significant differences between the chain saw and control groups in the patterns of response to or recovery from whole hand vibration. Furthermore, the response to vibration in those who tested positive for vasospasm was not obviously different, confirming the findings of Olsen and Petring that the acute response to vibration is not altered in patients with vibration white finger.

In summary, acute vibration generated by an industrial tool applied to one hand of healthy subjects was associated with a significant reduction in finger blood flow in both hands. Increasing the intensity of the vibration delayed recovery. The response to low intensity vibration showed a tendency to diminish with repeated applications and was initially most notable during the first minute. A similar response was found in the toes and this pattern, together with the increase in heart rate, suggest that hand vibration causes a gener-
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