Vibration induced neurophysiological and electron microscopical changes in rat peripheral nerves

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Abstract
This study was conducted to clarify the effects of vibration on the peripheral nerves. Rat tails were exposed to vibration (acceleration 56·9 m/s², frequency 60 Hz, amplitude 0·4 mm for two or four hours daily, six days a week. The maximum motor conduction velocity (MCV), the amplitude of evoked response, and the motor distal latency were measured on rat tail nerves every two months. Thin sections of tail nerves were examined under the electron microscope after 200, 500, and 800 hours of vibration. Neurophysiological and ultrastructural changes in tail nerves increased with the dose of vibration. In the groups exposed to vibration the MCVs were significantly reduced after a vibration time up to 400 hours, whereas the motor distal latency was not delayed significantly until 600 vibration hours. The ultrastructural changes were (1) detachment of the myelin sheath from the axolemma, (2) constriction of the axon, (3) protrusion of the myelin sheath into the axon, (4) accumulation of vacuoles in paranodal regions, and (5) dilatation of the Schmidt-Lanterman incisures. The ultrastructural changes induced by vibration in the paranodal regions and myelin sheaths were possibly responsible for the reduction in MCVs.

Materials and methods
SUBJECTS AND EXPOSURE
Thirty six male Wistar rats weighing about 360 g each were used. They were divided into three groups, each consisting of 12 rats of similar body weight. Group 1 was the control group. Group 2 was exposed to vibration for two hours daily and group 3 for four hours daily, six days a week.

During exposure, each rat was put into a cage with its tail extended out of the cage, and the tail was stuck to the shaker with a piece of 3M porous adhesive tape. Each control rat was put into a cage, placed near the operating shaker, and exposed to its noise for four hours daily. The room temperature was 20° to 25°C in winter and 28° to 33°C in summer. The apparatus for vibration exposure was an electromagnetic shaker producing vertical sinusoidal vibration at a frequency of 60 Hz, with an amplitude of 0·4 mm (root mean square). The vibration acceleration was 56·9m/s² (5·8 g). The noise exposure was 69 dB for the test rats and 67 dB for the control rats.

NEUROPHYSIOLOGICAL MEASUREMENT
The maximum motor conduction velocity (MCV), the amplitude of the evoked response, and the motor distal latency were measured on the tail nerve of each group every two months. The electrophysiological...
measurement was undertaken by the method of Misumi. Figure 1 shows a schematic illustration of electrode arrangement for measuring the motor conduction velocity on the tail nerve of a rat. A and B are the stimulation points, C is the recording point.

EXAMINATION BY ELECTRON MICROSCOPY
After 200, 500, or 800 hours of exposure, two rats from each group were anaesthetised with pentobarbitone (30 mg/kg intraperitoneally). The tail nerve was exposed and fixed in situ with 2% glutaraldehyde (containing 1.5% formaldehyde) in 0.1 M cacodylate buffer (pH 7-4) for 30 minutes. The nerve was cut into 1 mm³ pieces for further fixation and postfixed with 1% osmium tetroxide for two hours. After postfixation, specimens were dehydrated and embedded in epikote (Merck, Germany). Thin cross sections or longitudinal sections made by diamond or glass knives and stained with uranyl acetate and lead citrate were examined under a Hitachi H-500 electron microscope.

The diameters of the nerve fibres were determined in the cross sections of tail nerve by the method of McDonald, described in detail in the previous report.

Results
CHANGES IN MAXIMUM MCV
The MCV of each group became faster during the first two months. Compared with the control group, the MCV of exposed groups became significantly slower in the fourth (group 3) and the eighth month (group 2) of exposure (fig 2).

CHANGES IN MOTOR DISTAL LATENCY
The motor distal latency in group 3 was delayed significantly compared with the control group after exposure for six months (600 hours vibration, fig 3).

CHANGES IN AMPLITUDE OF THE EVOKED RESPONSE
The amplitudes of the distal evoked responses were all higher than those of the proximal evoked responses without any significant difference in amplitudes of either the distal or proximal evoked responses, between the exposed and control groups, except in the group subjected to vibration for eight months (table).

Changes in the mean (SD) amplitudes (μV) of evoked responses induced by vibration

<table>
<thead>
<tr>
<th>Groups</th>
<th>Before (n = 12)</th>
<th>2 Months (n = 12)</th>
<th>4 Months (n = 10)</th>
<th>6 Months</th>
<th>8 Months (n = 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AC</td>
<td>BC</td>
<td>AC</td>
<td>BC</td>
<td>AC</td>
</tr>
<tr>
<td>Control</td>
<td>696 (388)</td>
<td>873 (623)</td>
<td>1112 (552)</td>
<td>1790 (999)</td>
<td>1017 (572)</td>
</tr>
<tr>
<td>2h/day</td>
<td>595 (415)</td>
<td>816 (604)</td>
<td>1186 (746)</td>
<td>1887 (993)</td>
<td>805 (366)</td>
</tr>
<tr>
<td>4h/day</td>
<td>461 (220)</td>
<td>650 (422)</td>
<td>824 (462)</td>
<td>1490 (756)</td>
<td>954 (576)</td>
</tr>
</tbody>
</table>

*p < 0.05 vs controls. AC = proximal evoked responses; BC = distal evoked responses.
ULTRASTRUCTURAL CHANGES OF THE MYELIN SHEATH AND THE AXON
After 200 hours of vibration, only a fraction of the nerve fibres showed slight disruption of the myelin sheath and detachment of the sheath from the axon. By 500 hours of vibration, the sheaths were appreciably disrupted along the Schmidt-Lanterman incisures, clearly detached from the axolemma, and protruded into the axons (fig 4). When the vibration was up to 800 hours, part of the myelin sheaths disintegrated. Detachment of the sheath from the axolemma was severe and the axon was significantly constricted (fig 5).

ULTRASTRUCTURAL CHANGES OF SCHMIDT-LANTERMAN INCISURES
The Schmidt-Lanterman incisures of the tail nerves of control rats were usually closed or slightly open and cytoplasmic spirals seemed regular just the same as in the normal saphenous nerve of rabbits. There were characteristic stacks of desmosomoid structures near the surface of the nerve fibre (abaxial side). As the vibration dose increased, the Schmidt-Lanterman incisures dilated and the pericisural myelin sheath disrupted more severely; also, the density of the incisures increased. After 200 hours of vibration, the incisures dilated from the abaxial side bilaterally. By 500 hours of vibration, as well as severe dilatation of the incisures, cytoplasmic spirals showed an irregular arrangement (fig 6). When the vibration dose was up to 800 hours, part of the pericisural myelin sheath disrupted (fig 7).

ULTRASTRUCTURAL CHANGES IN THE NODE OF RANVIER
After 200 hours of vibration, the paranodal end loops seemed irregular. By 500 hours of vibration, many vacuoles accumulated in the nodal gap, the paranodal end loops showed an irregular arrangement, and some loops were detached from the paranodal axolemma (fig 8). When the vibration dose was up to 800 hours, the changes seemed more severe and part of the axon was destroyed (fig 9).

Discussion
Chronic exposure of a rat limb to sinusoidal vibration induces swelling in the nerve, which will lead to permanent damage to the nerve. The motor conduction velocity of the ulnar nerve was decreased among patients with carpal tunnel syndrome supporting the idea that entrapment neuropathies in the hands may be due to tissue swelling caused by vibration at work. An increase in fibroblast activity in rat peripheral nerves exposed to vibrations has been found. The fibroblast activity was more prominent in distal nerve branches than in the proximal portion. This indicates that nerves close to the vibration had most damage. After 20 hours of vibration, unmyelinated fibres in the plantar nerves of rats showed distinct changes, including deranged axoplasmic structure or accumulation of smooth endoplasmic reticulum. Lundborg et al suggested that the structural findings correlated well with functional tests, showing increased potential for regeneration based on a "conditioning lesion" induced by the vibration trauma. Our present study gives a new insight into ultrastructural changes in the peripheral nerve as a result of vibration and suggests that some of these changes may be responsible for the neurophysiological findings.

Our results indicate that prolonged vibration induces several ultrastructural changes in rat tail nerve: (1) detachment of the myelin sheath from the axolemma, (2) constriction of the axon, (3) protrusion of the myelin sheath into the axon, (4) accumulation of vacuoles in paranodal regions, and (5) dilatation of the Schmidt-Lanterman incisures.
Figure 6 Longitudinal section of rat tail nerve after 500 hours of vibration. Schmidt-Lanterman incisures showed severe dilatation and cytoplasmic spirals were irregular (arrow). (Originally × 16 800) Scale bar = 1 μm

Figure 7 Longitudinal section of rat tail nerve after 800 hours vibration. Schmidt-Lanterman incisures showed severe dilatation and cytoplasmic spirals were very irregular (star). The detachment of the myelin sheath from the axolemma was prominent (arrows). (Originally × 15 200) Scale bar = 1 μm.

These are the same as findings in rabbit's saphenous nerve.

It has been proposed that these changes caused by vibration may lead to peripheral nervous disturbances. Operation of vibrating tools, which involves exposure to combined stressors of local vibration, heavy work, climate, and noise, will affect the faster myelinated nerve fibre activity.

The correlation between the amounts of vibration and the decrease in MCV was found among patients with carpal tunnel syndrome. In this study, after 400 hours of vibration the MCV of exposed groups began to decrease significantly compared with the control group. The reduction in MCV may be due to the ultrastructural changes in the paranodal regions and myelin sheaths. It has been shown that the paranodal regions play an important part in nerve conduction. They may act as a Na+ source to control the rise of the action potential at the node of Ranvier. When there was 200 hours of vibration, the paranodal regions were only slightly damaged, which did not seem to have much effect on the function of the Na+ source, so the diminution of MCV was not significant (fig 2). After 500 hours of vibration, part of the paranodal end loops was detached from the axolemma and many vacuoles accumulated in the paranodal regions (fig 8); the Na+ source in paranodal regions might decline and account for the fact that MCV had slowed down significantly (fig 2). After 800 hours of vibration, paranodal end loops showed an irregular arrangement and were detached from the axolemma (fig 9), which resulted in a further decrease in MCVs (fig 2). These findings indicate that the ultrastructural changes in paranodal regions induced by vibration may cripple the cyclic movement of Na+ involved in saltatory conduction at the node of Ranvier, which causes the reduction in MCVs.

The ultrastructural changes in the myelin sheath, the axon, and Schmidt-Lanterman incisures may also be responsible for the diminution of MCV. The nerve conduction velocity of the myelinated fibre is directly proportional to the diameter of the nerve fibre and axoplasm conductance but inversely proportional to membrane capacitance of the myelin sheath. As noted, when the vibration lasted 500 hours, MCV had slowed down significantly. In the meantime, several myelin sheaths were disrupted, some were detached from the axolemma (fig 4), and Schmidt-Lanterman incisures were severely dilated (fig 6). By 800 hours of vibration, the axonal constriction was prominent (fig 5) and part of the peri-incisural myelin sheath was disrupted (fig 7). The dilatation of the Schmidt-Lanterman incisures, disruption of the peri-incisural myelin sheath, and detachment of the myelin sheath from the axolemma may decrease the radial resistance and increase the membrane capacitance. The constriction of the axon reduces the axonal cross section area and thus reduces the conductance of the axoplasm. This will cause the reduction in MCV, so it is suggested that the reduction in MCV induced by vibration may also be due to the destruction of the myelin sheath, the constriction of the axon, and the dilatation of Schmidt-Lanterman incisures.

The destruction of the myelin sheath was present after 200 hours of vibration, but the constriction of the axon occurred as late as after 500 hours of vibration. It seemed that the ultrastructural changes induced by vibration in the myelin sheath appeared before those in the axon. This was confirmed in the neurophysiological examination. The disruption of the myelin sheath is first reflected in the slowing of MCV; however, the degeneration of the axon is reflected in decrease in amplitudes of evoked responses. After 400 hours of vibration, the MCV was reduced significantly, but the amplitudes of evoked...
Figure 8 Longitudinal section of rat tail nerve through the node of Ranvier after 500 hours of vibration. Paranodal end loops were irregular and many vacuoles had accumulated (arrow). (Originally × 28 500) Scale bar = 0.4 μm.

Figure 9 Longitudinal section of rat tail nerve through the node of Ranvier after 800 hours of vibration. Paranodal end loops showed irregular arrangement (arrowhead) and were detached from axolemma (arrow). Part of the axon was destroyed (star). (Originally × 19 000) Scale bar = 1 μm.

responses did not decrease significantly until 800 hours of vibration.

It was found that the myelinated fibres in the rat tail nerve were from 2 to 8 μm in diameter. After 500 to 800 hours of vibration, the sheath-disrupted fibres were mainly from 4 to 8 μm in diameter. This indicated that vibration caused the disruption of the myelinated fibres with larger diameters. The MCV represents the conduction velocity of larger fibres in the proximal tail nerve (A to B), whereas the motor distal latency expresses the conduction of the distal tail nerve (B to C, fig 1), the conduction of the nerve branching from the tail nerve into muscle, and the delay time at neuromuscular junctions. Thus the delay of motor distal latency implies that the smaller fibres at the distal end of the tail nerve and neuromuscular junctions may have been destroyed. The MCV slowed down significantly when the vibration was up to 400 hours (fig 2), but the motor distal latency did not get significantly longer until 600 hours (fig 3), suggesting that larger nerve fibres were destroyed earlier than smaller ones.

Thus, our study confirms that prolonged vibration will induce nerve fibre damage and strongly suggests that ultrastructural changes induced by vibration in the paranodal regions and myelin sheaths may be involved in causing decreased MCV.

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