Anti-spastic effects of the direct application of vibratory stimuli to the spastic muscles of hemiplegic limbs in post-stroke patients

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Abstract

Objective: To investigate whether the direct application of vibratory stimuli inhibits spasticity and improves motor function in the hemiplegic upper limbs of post-stroke patients.

Design: Prospective pilot study.

Setting: University hospital rehabilitation centre.

Subjects: Fourteen post-stroke patients (mean age = 57.3 years; SD = 19.1 years).

Interventions: A hand and forearm stimulation device and an upper-arm stimulation device, consisting of vibrators, a wooden frame and a cloth strap, applied to the upper limbs of subjects.

Main measures: The modified Ashworth scale (MAS) score, F-wave parameters and motor-function parameters (finger tapping, active range of motion and the simple test for evaluating hand function).

Results: Subjects showed significant and potentially durable improvements in MAS score ($p < 0.01$), F-wave parameters ($p < 0.01$) and motor-function parameters ($p < 0.05$). The MAS score, F-wave parameters and motor-function parameters dropped below the baseline values after vibratory stimulation. The MAS score and F-wave parameters remained significantly below the baseline 30 minutes after stimulation.

Conclusions: The direct application of vibratory stimuli is an effective non-pharmacological anti-spastic treatment that could facilitate stroke rehabilitation. These results provide good evidence of potential short-term benefits of anti-spastic vibratory therapy in post-stroke patients in terms of decreased muscle tonus and improved motor function.

Keywords: F-wave, motor function, rehabilitation, spasticity, vibratory stimulus

Introduction

Spasticity is defined as a pathological increase in muscle tonus and is a hallmark of upper motor neuron lesions, which is easy to identify but difficult to quantify and to treat. Increased muscle tonus of the upper limb is a major obstacle to the rehabilitation of hemiplegic patients with stroke and can seriously impair activities of daily living, even if hemiplegia is comparatively slight. Spasticity in affected limbs often hinders occupational therapy for the treatment of stroke and central nervous disorders. It is thus important to control muscle tonus, especially in occupational therapy, to improve voluntary finger movements. Conventional therapies, such as muscle stretching and thermotherapy, have short-term effects. Moreover, recent approaches, such as an intrathecal application of baclofen, require specialized technical skills. This has made it difficult to observe spastic changes after load tests (i.e. physiotherapy, gait exercise and thermotherapy).
Several previous studies investigated spasticity in hemiplegic patients with stroke, but found it difficult to quantify and to treat. \(F\)-wave size could be an indicator of motor-neuron excitability \([1,2]\) and alterations of \(F\)-wave parameters in spasticity have been confirmed in experimental animals \([3]\). It has been found that the \(F\)-wave is ‘easier’ to elicit under spastic conditions \([4]\). Several authors have reported increased \(F\)-wave size in spasticity \([5–9]\). Indeed, \(F\)-wave amplitude is more sensitive to changes of lower motor-neuron excitability during spasticity than both the \(T\)-reflex and the \(H\)-reflex \([7,10–13]\). The \(F\)-wave amplitude/M-response amplitude ratio (\(F/M\) ratio) is correlated with the muscle-tonus increase in cases of spasticity due to stroke \([14]\). Thus, even small changes in muscle tonus should be represented by changes in \(F\)-wave parameters. Precise assessments of \(F\)-wave parameters have been used to investigate the effects of physiotherapy \([15]\), drugs \([16,17]\) and various physiological conditions \([18]\).

Vibratory stimulation is a useful tool for the treatment of motor disorders. Vibration stimulates the primary muscle spindle endings, causing Ia afferent impulses to be conducted to alpha motor neurons and Ia inhibitory interneurons in the spinal cord. This afferent pathway produces involuntary contraction in the vibrated muscle (tonic vibration reflex) \([19]\) and inhibits the antagonist muscle. Therefore, vibratory stimulation is currently applied to the antagonist of the spastic muscle, in order to decrease the spasticity of a hemiplegic limb \([20,21]\).

These clinical observations revealed that vibratory stimulation applied directly to the spastic muscle produced an initial intense contraction in patients with stroke, followed by a dramatic suppression of spasticity after continuous stimulation for several minutes. However, there are no published reports on the effects of this suppressive phenomenon. To confirm whether this vibratory stimulation has clinical value, a comprehensive assessment of the anti-spastic effects is required. This study measured and compared \(F\)-wave parameters and some clinical evaluations in spastic hemiplegic patients to elucidate the anti-spastic effects of vibratory stimulation. The main aim was to clarify whether the effects of vibratory stimulation therapy in spasticity could be documented using \(F\)-wave parameters.

**Methods**

**Subjects**

Fourteen post-stroke patients with upper-limb spasticity were enrolled (eight males and six females; mean age = 57 ± 19 years; range = 16–74 years). Their characteristics are summarized in Table I.

<table>
<thead>
<tr>
<th>Age, years (mean ± SD and range)</th>
<th>57.3 ± 19.1, 16–74</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender ((n))</td>
<td>Male = 8, Female = 6</td>
</tr>
<tr>
<td>Time since onset (weeks) (mean ± SD and range)</td>
<td>19.7 ± 17.6, 8–76</td>
</tr>
<tr>
<td>Brunnstrom stage of upper limb ((n))</td>
<td>3, 5, 4, 5, 6</td>
</tr>
<tr>
<td>Brunnstrom stage of finger ((n))</td>
<td>2, 3, 4, 1, 7</td>
</tr>
<tr>
<td>Modified Ashworth scale ((n))</td>
<td>1, 2, 4, 8</td>
</tr>
</tbody>
</table>

The patients were recruited from among inpatients admitted to the Kirishima Rehabilitation Centre of Kagoshima University, Japan, between 1 September 2006 and 31 August 2007. Stroke diagnosis was based on computed tomography (CT) or magnetic resonance imaging (MRI), as well as neurological functions. Six patients were diagnosed with cerebral infarction and eight with cerebral haemorrhage. The mean time since onset was 19 ± 17 weeks (range = 8–76 weeks). Eight patients had right hemiplegia and six had left hemiplegia. All patients had spasticity and hemiplegia of the upper limb and finger and a positive pathological reflex (i.e., the Hoffmann reflex or the Wartenberg reflex) in the affected limb. The median clinical Brunnstrom stage \([22]\) of the hemiplegic upper limb was 4 (range = 3–6). The modified Ashworth scale (MAS) score for the wrist flexor muscle was 1 in two cases, 1+ in four cases and 2 in eight cases. Eight subjects whose Brunnstrom stage of the hemiplegic finger was >4 participated in additional tests to investigate the change of motor function after vibratory stimulation (mean age = 57 ± 18 years; range = 16–74 years; mean time since onset = 11.3 ± 2.7 weeks; range = 8–16 weeks).

The study was conducted without altering the existing medication regimes of the patients. None were receiving either stimulant or relaxant medications (including anti-spasticity medication, anti-convulsion medication and pharmacological injections). Only patients with normal latencies of \(F\)-waves and \(M\)-responses, indicating no peripheral nerve injury, were included. Patients were excluded from the analysis if they were aged >75 years, had experienced onset of stroke <4 weeks previously, had shown abnormal upper-limb movements prior to the onset of stroke according to their past
histories, had a medical condition that limited the completion of vibratory stimulation (such as severe cardiopulmonary disease, severe sensory disturbance or peripheral neuropathy), had severe aphasia that made it impossible to follow verbal instructions or had bilateral hemisphere lesions or dementia that interfered with the outcome assessments. The procedures complied with the 1975 Declaration of Helsinki, as revised in 1983. Informed consent was obtained from each subject according to the ethical guidelines of the hospital, once they fully understood the purpose and methodology. The study was approved by the Ethical Committee of Kagoshima University.

**Vibratory stimulation**

The authors developed a hand and forearm stimulation device (Figure 1(a)) and an upper-arm stimulation device (Figure 1(b)), which consisted of vibrators, a wooden frame and a cloth strap for fixation to the upper limb. Each vibrator had a spherical rubber vinyl-covered head (diameter = 5 cm) and pulsed at a frequency of 91 Hz with an amplitude of 1.0 mm (Thrive MD-01: Thrive Co., Ltd, Osaka, Japan). In the hand and forearm stimulation device, the wrist and metacarpophalangeal joint were fixed to the frame at the maximal extension position (Figure 1(a)). Vibrations were delivered to the abdominal side of the second, third, fourth and fifth fingers, the palm and the flexor tendon of the wrist. In the upper-arm stimulation device, two vibrators were set 12-cm apart in a moveable frame (Figure 1(b)). A 1-kg sandbag was placed on each vibrator, to ensure they stimulated the belly of the biceps brachii muscle with a constant force (equal pressure). Each subject lay in a supine position (Figure 1(c)) and all of the flexor muscles of the upper limb were stimulated simultaneously by the devices, once only, for 5 minutes.

**Measurement of muscle tonus**

The extent of spasticity was measured using the MAS score [23] for the biceps brachii, wrist flexor muscles and finger flexor muscles. The MAS is an established and reliable instrument, which uses a 5-point scale to score the average resistance to passive movement for each joint. MAS 0 indicates ‘no increase in muscle tonus’. MAS 4 indicates ‘affected part(s) rigid in flexion or extension’ [23]. To facilitate data analysis, the MAS scores (0, 1, 1+, 2, 3 and 4) were assigned numerical values designated as ‘computed MAS scores’ (0, 1, 2, 3, 4 and 5, respectively) [24,25].

**Electromyographic examination: F-wave study [5,10,12]**

For these experiments, each subject was in a supine position with both arms supported in a
relaxed position. A one-channel recording from the abductor pollicis brevis (APB) allowed instantaneous comparison of simultaneously evoked F-waves in the spastic muscle, to evaluate the effect of vibratory stimulation.

A Nihon-Koden Neuropack with a band-pass filter of 10 HZ to 10 kHZ and a sensitivity of 5 mV and 200 uV/division was used for recording compound muscle action potentials (CMAPs) and F-waves, respectively. Paired Ag–AgCl surface electrodes were taped to the belly and tendon of the APB after lowering the skin resistance to <5 kΩ. The median nerve was stimulated at 1 Hz with a rigid bar electrode strapped securely to the wrist and the cathode was positioned 3 cm proximally from the most distal wrist crease. Stimuli were 0.1 ms in duration and ranged from 10–50 mA when set to 20% higher than the intensity that elicited the largest CMAP. One hundred F-waves were recorded following supramaximal current pulses. A stainless-steel surface electrode placed on the dorsum of the hand served as the ground.

Peak-to-peak measurements were made of the M-response amplitude and the amplitude of the 100 averaged F-responses (F-wave amplitude) for the affected limb of each subject both before and after vibratory stimulation. The F-wave variables that were recorded for evaluation were the F-wave amplitudes and the M-response amplitudes. The following values were calculated: the trial averaged F-wave amplitude (F-wave amplitude) and the ratio of the F-wave amplitude to the M-response amplitude (F/M ratio).

Measurement of motor function

Finger tapping. The number of taps made with the second finger was measured for 30 seconds by an electronic tapping tester, which sensed infrared light (Takei Co., Ltd, Japan). For these measurements, the subject’s arm was placed on a table with the elbow flexed to 90° and the wrist in a neutral position [26].

Active range of motion [27]. The active range of motion (active angle test) of extension at the wrist was evaluated. For this measurement, the wrist was placed on a rest and the fingers were fixed to the extension position by a splint, with the elbow flexed at 90° (Figure 2). The mean active range of motion was calculated based on three measurements made using a protractor goniometer. When the movement was completed (maximal extension was continued for 3 seconds), the degree of joint motion was recorded. The angle between the forearm shaft and the fifth metatarsal bone was measured [28].

The simple test for evaluating hand function (STEF) [29]. The STEF was designed to evaluate the speed of manipulation of objects using an upper limb. Here, participants were required to catch or to pinch objects of 10 different shapes and sizes and to carry them to a designated area. The objects were spheres (70 mm diameter, n = 5; 40 mm diameter, n = 6; 5 mm diameter, n = 6); disks (20 mm diameter × 10 mm height, n = 6; 20 mm diameter × 2 mm height, n = 6); boxes (100 × 100 × 47 mm, n = 5; 35 × 35 × 35 mm, n = 6; 14 × 14 × 14 mm, n = 6), thin pieces of cloth (90 × 80 mm, n = 6) and pins (3 mm diameter × 42 mm length, n = 6) [30].

Procedure

Muscle tonus, F-wave parameters (by electromyographic examination) and motor-function parameters (finger tapping, active range of motion and STEF score) were assessed. MAS measurements of all participants were performed before, immediately after and then 30 minutes after vibratory

Figure 2. Active range of motion.
stimulation. Electromyographic examinations of all patients were performed before, immediately after and then every 5 minutes up to 30 minutes after vibratory stimulation. Eight subjects whose Brunnstrom stage of the hemiplegic finger was >4 participated in motor-function tests (i.e. finger tapping, AROM and STEP), which were performed before and immediately after vibratory stimulation.

Data analysis

All values are given as the mean ± standard deviation (SD). Statistical analyses were performed using the Wilcoxon test for MAS scores and the paired t-test for the other measurements. $p < 0.05$ was considered statistically significant. All analyses were performed using STAT view 5 software (SAS Institute, Cary, NC).

Results

None of the subjects experienced discomfort before, during or after the vibratory stimulation. All assessments were completed safely in all subjects. Figure 3 shows the changes in MAS scores. Figure 4 shows the changes in F-wave parameters before and after the vibratory stimulation. Figure 5 presents a summary of the changes in motor function before and after the vibratory stimulation.

Muscle tonus

The mean values assigned for MAS scores of the biceps brachii before, immediately after and 30 minutes after vibratory stimulation were 2.1 ± 1.0, 0.2 ± 0.4 and 1.0 ± 1.0, respectively (Figure 3(a)). The mean values of the wrist flexor muscles before, immediately after and 30 minutes after vibratory stimulation were 2.5 ± 0.6, 0.2 ± 0.4 and 1.1 ± 1.0, respectively (Figure 3(b)). The values for the MAS scores of the biceps brachii, wrist joint flexor muscles and finger flexor muscles decreased markedly to below the baseline values immediately after vibratory stimulation ($p < 0.01$). Although the values showed a tendency to increase over time, they remained significantly below the baseline, even 30 minutes after vibratory stimulation ($p < 0.01$).

F-wave study

In all subjects, the amplitude and the duration of the F-wave amplitude were reproducible across consecutive runs.

The F-wave amplitude values for the subjects before, immediately after and every 5 minutes until 30 minutes after vibratory stimulation were 593 ± 255, 417 ± 282, 360 ± 234, 368 ± 249, 351 ± 238, 366 ± 205 and 367 ± 202 μV, respectively. The F-wave amplitude decreased markedly immediately after vibratory stimulation and remained below the baseline for up to 30 minutes ($p < 0.01$) (Figure 4(a)).

The F/M ratio for the subjects before, immediately after and every 5 minutes until 30 minutes after vibratory stimulation were 4.9 ± 1.8, 3.6 ± 2.5, 3.1 ± 2.0, 3.1 ± 2.2, 3.1 ± 2.1, 3.0 ± 2.2, 3.1 ± 1.8 and 3.1 ± 1.7%, respectively. The F/M ratios decreased markedly immediately after vibratory stimulation and remained below the baseline for up to 30 minutes ($p < 0.01$) (Figure 4(b)).

![Figure 3. MAS. The mean values assigned for MAS scores of the biceps brachii (a), wrist flexor muscles (b) and finger flexor muscles (c), before, immediately after and 30 minutes after vibratory stimulation. The values for the MAS scores of each muscle decreased markedly immediately after vibratory stimulation and remained significantly lower than the baseline, even 30 minutes after vibratory stimulation (*$p < 0.01$).](image-url)
**Motor function**

**Finger tapping.** The baseline mean number of finger taps with the index finger for 30 seconds before vibratory stimulation was 39\(^\text{±}\)28. Immediately after vibratory stimulation, this increased significantly to 59\(^\text{±}\)31 (\(p < 0.05\)) (Figure 5(a)).

**Active range of motion.** The baseline mean angle of active motion at the wrist before vibratory stimulation was 27\(^\text{±}\)19\(^\circ\). Immediately after vibratory stimulation, this increased significantly to 35\(^\text{±}\)20 (\(p < 0.05\)) (Figure 5(b)).

**STEF.** The baseline mean value assigned to the STEF score before vibratory stimulation was 29\(^\text{±}\)28. Immediately after vibratory stimulation, this increased significantly to 38\(^\text{±}\)31 (\(p < 0.05\)) (Figure 5(c)).

**Discussion**

Here, spasticity was assessed using MAS scores and F-wave parameters. In the MAS study, the direct application of vibratory stimulation to spastic muscles resulted in a significant reduction in muscle tonus and the effects remained below the baseline,
even after 30 minutes. In the F-wave study, the baseline F-wave values for the post-stroke patients were in agreement with those reported previously [9,12,14]. Briefly, before vibratory stimulation, the F-wave amplitude and the F/M ratio were higher in the post-stroke patients than those reported for healthy humans in previous studies [14,31,32]. The F-wave amplitude and F/M ratio decreased significantly after vibratory stimulation and remained below the baseline, even after 30 minutes. In addition, significant improvements in motor-function parameters were seen after vibratory stimulation.

Spasticity is found in the majority of post-stroke patients. These results showed a significant negative correlation between muscle tonus and motor function (finger tapping ability ($r = 0.621$, $p < 0.01$) and active range of motion at the wrist ($r = 0.500$, $p < 0.02$) and STEF score ($r = 0.419$, $p < 0.01$)), which was in agreement with previous reports [33,34]. Reducing spasticity might thus result in improvements of motor function.

To the authors’ knowledge, the anti-spastic effects of vibration applied directly to the muscle in post-stroke patients have not previously been reported. This study confirmed that vibratory stimulation decreased spasticity, as indicated by a decrease in the F-wave parameters. One major reason for the use of vibratory stimuli in post-stroke patients with spasticity is the suggestion that it decreases muscle tonus and facilitates neuromuscular function. However, care must be taken, because some patients can experience increased muscle tonus caused by the vibratory stimulus, especially during the initial period of treatment. In the present study, the effects of vibration-induced muscle tonus and various other related factors were minimized, while the intensity and frequency of vibratory stimulation were maintained. None of these subjects complained of excessive vibratory stimulation or discomfort. Thus, it is believed that using a comfortable intensity and frequency of vibration and optimizing the duration of stimulation result in less physiological response.

In a previous study, vibratory stimulation induced inhibition of the antagonist muscle by reciprocal inhibition (known as ‘VTR’) in subjects with motor disorders [19]. Ageranoti and Hayes [35] reported that vibration of the extensor tendons significantly decreased flexor electromyographic activity and concluded that the therapeutic application of vibration was effective in providing short-term symptomatic relief of wrist joint muscle-tonus in patients with spastic hemiparesis. Their study showed marked reductions in both flexor and extensor integrated electromyographic values immediately after the vibration of extensors. The current results are in agreement with these findings. Furthermore, Hendrie and Lee [36] reported that vibration of flexor muscles of the forearm reduced the amplitude of the monosynaptic reflex response. Although they mentioned that the mechanisms for this type of inhibition were not clear, the methodology was the same as that used in this study.

The development of validated and reliable outcome measures for spasticity rehabilitation has been hampered by difficulties with quantifying functionally important parameters, including pain, ease of care and mobility [37]. Nonetheless, a combination of measures designed to assess technical and functional outcomes, patient satisfaction and cost-effectiveness of treatment can be used to evaluate status and to track changes in spasticity management, including treatment programmes involving botulinum toxin. Recently, F-wave amplitude and F/M ratio were proposed as precise measures to evaluate changes in lower motor-neuron excitability in spasticity. The F/M ratio has also been shown to correlate with the increase in spasticity or muscle tonus due to stroke [14]. The F/M ratio recorded from APB muscle was $\sim 1–2\%$. The F/M ratio recorded using surface electrodes might be due to repeated activation of a few specific neurons or infrequent responses of most anterior horn cells [9]. Fisher et al. [38] published normal values for F-wave amplitudes, with a mean F/M ratio of 2.2 $\pm 0.7\%$ (range $= 1.2–3.5\%$). Therefore, the F/M ratio in these patients was clearly increased before vibratory stimulation and remained normal range thereafter.

Eisen and Oduote [5] reported a significant correlation between the F-wave and the M-response ($r = 0.53$). All of the post-stroke patients in the present study were abnormal in the sense that their F-wave amplitude values were too high relative to their M-response amplitudes before vibratory stimulation (Figure 4). Using the same methodology, this group has previously clarified the effects of thermotherapeutic treatment in spasticity [4].

In a previous study, the T-reflex and H-reflex were inhibited by the spinal mechanism of pre-synaptic inhibition induced by vibratory stimulation in normal subjects [39]. Milanov [8] proposed that alpha-neuron excitability, as measured by F-wave amplitudes, usually develops as a secondary effect after the alteration of some other segmental mechanism in spasticity (for example, increased gamma-motor neuron activity, altered inter-neuron activity or decreased pre-synaptic inhibition). Thus, several different mechanisms might have led to the alteration of F-wave amplitudes observed in the present study. These results clearly showed a marked reduction in both F-wave amplitude and F/M ratio after vibratory stimulation (Figure 4), in parallel with the improvement of MAS (Figure 3) and motor
function (Figure 4). In this experiment, both the $F$-wave amplitude and the $F/M$ ratio decreased after vibratory stress, indicating a reduction in motor neuron excitability. Therefore, the anti-spastic effect of vibratory stimulation can be documented by recording $F$-waves as well as MAS scores and motor functions. Spasticity associated with a chronic hemiparesis was present to a similar extent in all of the patients before vibratory stimulation and muscle tonus decreased significantly after the treatment. Vibratory stimulation is thought to lower the activities of gamma-afferent fibres through a nervous-system response, in addition to strengthening and relaxing muscular and soft tissues. This process might decrease impulses from the muscle spindles to the afferent fibres. This could explain the observed changes in $F$-wave parameters. Further studies will be necessary to determine whether vibratory stimulation changes $F$-wave parameters according to the extent and type of spasticity. As expected, the results of this investigation revealed decreased $F$-wave amplitude and $F/M$ ratio values in response to vibratory stimulation. Alterations in $F$-wave parameters in spasticity remain controversial. Most authors have reported the participation of greater numbers of larger motor neurons in the discharge and have suggested that this causes the increased $F$-wave amplitudes [5,38]. However, as shown by these results, $F$-wave parameter alterations in spasticity are complex. The changes in $F$-wave parameters caused by vibratory stimulation might result from decreased motor neuron excitability [9]. The $T$-reflex and $H$-reflex, despite their limitations, have often been used to assess motor neuron excitability. However, $F$-waves are easily recorded in both upper and lower extremities. Therefore, this approach has potential applications in documenting both spasticity and responses to therapy and might provide an objective measure of spasticity in clinically uncertain cases.

The present study had some limitations. First, the sample size was small. A large-scale multi-centre double-blinded study will therefore be needed in the future. Secondly, it remains to be determined whether the present results were due to the effects of vibration alone or to the combined effects of vibration and stretch.

In the present study, acute anti-spastic changes in post-stroke patients were examined soon after vibratory stimulation. The long-term effects of repeated vibration remain of interest. Since the initial study, some patients have shown positive responses to several months of daily vibration (unpublished data). It is believed that repeated vibratory stimulation improves quality of life, by permitting an increase in daily activities and facilitating upper limb movements. However, further investigations will be necessary to confirm the clinical applicability of vibratory stimulation as a non-pharmacological and economical anti-spastic therapy for post-stroke patients with spasticity. The correlation between the vibratory anti-spastic effect and different intensities and frequencies could also provide an interesting topic for further study.

In conclusion, these results provide good evidence for the short-term benefits of anti-spastic vibratory therapy in post-stroke patients in terms of decreased muscle tonus and improved motor function.

**Clinical message**

- These findings suggest that the direct application of vibratory stimuli inhibits spasticity and improves motor function in the hemiplegic upper limbs of post-stroke patients.
- The inclusion of vibratory stimulation in anti-spasticity regimens could be advantageous for stroke rehabilitation.

**Declaration of interest:** The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

**References**
