

Cutaneous electrical stimulation may enhance sensorimotor recovery in chronic stroke

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Received 13th February 2002; returned for revisions 15th April 2002; revised manuscript accepted 30th June 2002.

Objective: To investigate whether cutaneous electrical stimulation has a role in the enhancement of sensorimotor function in chronic stroke.

Subjects and setting: Fifty-nine patients with chronic stroke received cutaneous stimulation during their three-week-long inpatient rehabilitation. Thirty-two received active treatment in the paretic hand and eight received no-current placebo treatment in the paretic hand. Nineteen patients received active stimulation of the paretic foot. None received stimulation in both upper and lower limbs.

Intervention: Cutaneous stimulation was delivered twice daily via a special glove/sock electrode.

Main outcome measures: Modified Motor Assessment Scale, 10-metre walking test, paretic limb function, limb skin sensation and somatosensory evoked potentials (SEP) were performed before and after the treatment.

Results: Modified Motor Assessment Scale ($p < 0.001$), 10-metre walking test ($p < 0.05$), paretic hand function ($p < 0.01$), upper limb skin sensation ($p < 0.01$) and SEP normality classification of paretic upper limb ($p < 0.01$) and paretic lower limb ($p < 0.5$) improved significantly in the treatment group ($n = 51$) after three weeks of stimulation. When active hand treatment and placebo hand treatment were compared, a significant improvement in the sensory and motor function was observed only in the actively treated group.

Conclusions: Cutaneous stimulation had positive effects in the motor performance, limb sensation and the configuration of SEP of the paretic limb in chronic stroke patients.

Introduction

Impairment of voluntary motor function is common after cerebral infarction.¹ The severity of motor impairment and the patterns of motor recovery are similar for the upper and lower limbs.² Exercise therapy is the most common

form of therapy provided for stroke patients. It primarily induces treatment effects in those exact abilities that are trained. The improvement of ambulation is known to be dependent on the intensity of gait training, whereas the relationship between the intensity of arm rehabilitation and functional improvement in the upper extremity is not so clear.³

It has been shown that neuromuscular and sensorimotor stimulation enhances motor recovery in both acute and chronic stroke survivors.^{4–7}

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Sensorimotor stimulation was most effective in patients with a severe motor deficit and hemianopia or hemi-inattention. On the other hand, Hummelsheim *et al.*⁸ noted that, with the exception of spasticity in hand and finger flexors, repetitive suprathreshold electrical stimulation of the hand did not improve biomechanical and functional motor parameters in their patients. In these rare previous studies, cutaneous stimulation of the affected limb after stroke resulted in the reduction of undesired muscle tone, facilitation of voluntary movements and reduction of neglect.⁹⁻¹¹ A glove or sock electrode stimulates cutaneous and muscle afferents of a large area and motor fibres of intrinsic muscles and may facilitate cortical synaptic reorganization and increase the contribution of the remaining motor structures in the restoration of voluntary activity. Cortical reorganization may have a role in the improvement of the motor and sensory functions of the stimulated limb.

Recently the effect of cutaneous stimulation of the hand was studied with six healthy patients using functional magnetic resonance imaging (MRI) during a motor task.¹² A finger-to-thumb tapping was performed, and after 20 minutes of cutaneous stimulation of the hand in rest, an identical motor task was performed again. The afferent stimulation, delivered below sensory threshold, was associated with increased signals in the primary and secondary motor and somatosensory areas, including the supplementary motor area (SMA). Thus it appears that sub-threshold stimulation is sufficient to prime cortical networks so that more activation appears while performing the required motor task. The purpose of the present study was to investigate whether cutaneous electrical stimulation has a role in functional recovery of the paretic upper or lower limb of chronic stroke patients. We used functional tests and somatosensory evoked potentials to assess the treatment effect.

Methods

The study was performed with 59 stroke patients (42 males and 18 females, mean age 54.4 ± 10 years) during their yearly inpatient intensive rehabilitation period. The patients participated in

these inpatient rehabilitation periods in order to be able to continue living at home. Twenty-four had left-sided and 35 right-sided hemiparesis. The mean time since the onset of stroke was 3.3 years (range 7 months to 14 years). Thirteen of them moved mainly with a wheelchair, 22 used a cane and 24 walked without any support (dynamic orthosis allowed). Patients gave a written informed consent and the local ethical committee had approved the study.

Cutaneous stimulation treatment was delivered to alleviate sensory and motor symptoms due to hemiparesis. Cutaneous stimulation was delivered to the affected hand or foot twice daily, 20 minutes each time, in addition to the regular rehabilitation programme during the three-week inpatient period. Stimulation was given with a glove or a sock electrode. This electrode was connected as a common anode while a surface carbon electrode (diameter 6 cm), placed 2.5 cm proximal to the wrist or ankle, served as a cathode. The stimuli were monophasic constant current twin pulses at 50 Hz (Prizm Medical Inc., Duluth, Georgia, USA). Before each treatment, sensory threshold was measured and stimulation intensity was adjusted just below sensory threshold. In those cases that the patient could not sense the stimulation, it was delivered in the sensory threshold of the healthy side. For each 20 minutes a given intensity was used, but the intensity could differ from one treatment session to the next. Placebo stimulation was delivered in the same way as active stimulation, but no current was applied. Because the active stimulation was also below sensory threshold no difference in perception of sensation was possible between active and placebo stimulated groups. Patients were sitting during the stimulation.

Fifty-one patients with chronic stroke received active treatment in hand ($n = 32$) or foot ($n = 19$), and an additional eight patients received no-current treatment in the hand. During the first year of the research, every patient received active stimulation, during the second year every third patient was selected to no current (i.e. placebo group). Patients were assessed before treatment began and at the end of the three-week rehabilitation period each time by the same masked raters, physiotherapists and nurses, using the Modified Motor Assessment Scale (MMAS),¹³

paretic limb function assessment, limb skin sensation and 10-metre walking speed. Somatosensory evoked potentials (SEPs) were recorded before and after treatments and analysed later by a neurophysiologist.

The MMAS items, scored from 1 to 7 with a maximum of 56 points, were supine to side-lying, supine to sitting over side of bed, balanced sitting, sitting to standing, walking, upper arm function, hand movements and advanced hand activities. In addition, the paretic arm was clinically evaluated by testing picking up the pencil, all fingers extension, pinch, wrist extension and skin sensitivity. The paretic leg was clinically evaluated by testing toe flexion, toe extension, lifting the affected leg over the healthy knee and skin sensitivity. The skin sensitivity was measured with a 0–20 visual analogue scale. The patients were asked to assign a number in the scale while considering that the healthy sensation in arm or leg was represented by number 20. In the 10-metre walking test the patient was asked to walk as quickly as possible. Patients were allowed to use walking aids, for example a dynamic orthosis, or a cane. The SEPs were recorded in the neurophysiology laboratory. The upper-limb SEPs were performed in those patients who received hand stimulation. The stimulus was a constant current square wave pulse delivered to the median nerve at the wrist and the intensity was sufficient to produce a definite twitch of the thumb. Responses were recorded with surface electrodes over the somatosensory cortex. The SEPs were recorded following consecutive stimulation of both upper limbs. The lower-limb SEPs were performed in those patients who received foot stimulation. The stimuli were delivered to the posterior tibial nerve at the ankle. The recording was performed over the somatosensory cortex of the leg. Both lower limbs were consecutively stimulated and cortical responses were registered. The latencies and amplitudes of the following components: N20, N30, N60 (upper limb), P40, N80 (lower limb) were analysed and each recording was also classified according to its overall normality/abnormality features (1 = normal, 2 = minor change, 3 = abnormal). Minor change in SEP was indicated by a decreased/increased individual component amplitude or a delayed latency and abnormal SEP was indicated

by a total loss of components or delayed all components.

Statistical analysis was carried out using SPSS 10.0 for Windows. The normal distributions of the results were tested by Kolmogorov–Smirnov or Shapiro–Wilk test. The differences between tests before and after treatment were compared with paired samples *t*-test or nonparametric Wilcoxon and marginal homogeneity test. The measured sensory thresholds and delivered stimulation levels were compared with patients' subjective opinions with crosstabs and kappa.

Results

Fifty-nine patients with chronic stroke received cutaneous stimulation: 32 received active treatment in the paretic hand and 19 in the paretic foot and 8 received no-current placebo treatment in the paretic hand. There were no drop-outs in the study during the three-week inpatient period. None of the patients received both upper and lower limb stimulations and each one had only one type of treatment. Unfortunately not all measurements were available from all patients. Each patient received active or placebo stimulation on an average of 21.6 ± 6 (\pm SD) times and individual physiotherapy 10.4 ± 3 sessions. Individual physiotherapy sessions were planned to improve patients' overall motor functions. The physiotherapy did not follow any specific approach. Positive motor function effects were seen in a number of measurements in the hand-stimulated ($n = 32$) and in the foot-stimulated ($n = 19$) patients: Modified Motor Assessment Scale (MMAS), 10-metre walking time, paretic limb function, paretic limb skin sensation and SEPs normality classification of paretic limb (Table 1). MMAS total score improved from 33.7 ± 10 points to 36.0 ± 9 points (individual start and end scores compared, $p < 0.01$) in hand-stimulated patients and from 26.6 ± 12 points to 29.0 ± 11 points in foot-stimulated patients ($p < 0.05$). There was also a significant improvement in five of the eight MMAS subtests among all stimulated patients ($p < 0.05$). These were: supine to side-lying, supine to sitting over side of bed, balanced sitting, sitting to standing and upper arm function (Table 2). Ten-metre walking time shortened

from 36.5 ± 32 s to 31.6 ± 33 s in the hand-stimulated patients ($p < 0.05$). In addition to the improved walking time in many patients, two patients were able to walk 10 metres who could not do it at the beginning. The change in walking time in the foot-stimulated patients was not significant, but one patient was able to walk 10 metres who could not do it at the beginning. Extension of all fingers showed significant improvement in the hand-stimulated patients ($p < 0.05$). Moreover, in 22 out of 32 patients who assessed themselves paretic hand function improved. In twelve out of 19 patients who assessed themselves paretic foot function improved.

Sensory function improvement was observed in upper-limb skin sensation and in SEPs of the hand ($n = 32$) or foot ($n = 19$). Upper-limb skin

sensation improved on visual analogue scale from 11.2 ± 6 points to 13.7 ± 4 points ($p < 0.01$). Lower-limb skin sensation change was not sig-

Table 2 Modified Motor Assessment Scale subtests performed in 23 patients before and after treatment

	Before	After
To side	3.7 ± 2	$3.8 \pm 2^*$
To sit	6.1 ± 1	$6.4 \pm 1^*$
Balanced sit	5.9 ± 2	$6.2 \pm 2^*$
To stand	4.6 ± 2	$5.2 \pm 2^*$
Walk	4.4 ± 2	4.6 ± 2
Arm function	2.8 ± 2	$3.2 \pm 2^*$
Hand movement	2.2 ± 2	2.2 ± 2
Hand function	1.6 ± 1	1.9 ± 2

* $p < 0.05$.

All values are means \pm SD.

Table 1 Modified Motor Assessment Scale (MMAS), 10-metre walking time, change in paretic limb function, limb sensation and SEP paretic limb classification in hand- ($n = 32$) and foot- ($n = 19$) stimulated patients before and after treatment

	Before	After
MMAS		
Hand (mean \pm SD) ($n = 15$)	33.7 ± 10	36.0 ± 9
Foot (mean \pm SD) ($n = 8$)	26.6 ± 12	$29.0 \pm 11^*$
10-m walk		
Hand ^a (m s ⁻¹ \pm SD) ($n = 13$)	36.5 ± 32	$31.6 \pm 33^*$
Foot ^b (m s ⁻¹ \pm SD) ($n = 9$)	54.7 ± 34	48.4 ± 33
Limb function ^c		
Hand ($n = 32$)		
1		22
2		9
3		1
Foot ($n = 19$)		
1		12
2		7
3		0
Limb sensation		
Hand (mean \pm SD) ($n = 32$)	11.2 ± 6	$13.7 \pm 4^{**}$
Foot (mean \pm SD) ($n = 19$)	11.3 ± 4	12.6 ± 5
1	2	7
2	15	18
3 ^d	15	7 ^{**}
Foot ($n = 19$)		
1	0	2
2	10	10
3	9	7 [*]

* $p < 0.05$; ** $p < 0.01$.

^aTwo patients were able to walk 10 metres who could not do it at the beginning.

^bOne patient was able to walk 10 metres who could not do it at the beginning.

^cLimb function: 1 = better, 2 = no change, 3 = worse.

^dSEP: 1 = normal, 2 = minor change, 3 = abnormal.

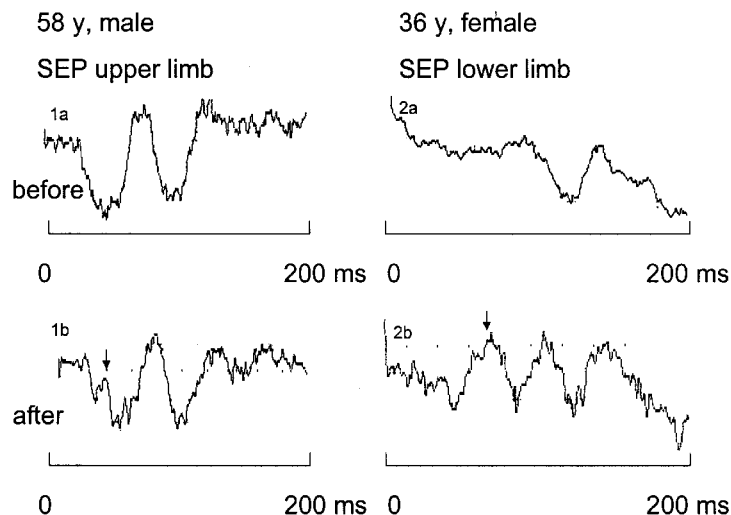


Figure 1 Somatosensory evoked potentials of individual stroke patients who received stimulation treatment: 58-year-old man (left) and 36-year-old woman (right) at the beginning (top) and end (bottom) of rehabilitation.

nificant. SEP normality classification improved significantly in paretic upper limb ($p < 0.01$) and in paretic lower limb ($p < 0.05$) in the stimulated group ($n = 51$) after three weeks of rehabilitation. At the end of the three weeks specific SEP com-

ponents were measurable in seven patients, who showed none of these components at the beginning (Figure 1).

No significant improvement in motor and/or sensory function was observed in the hand placebo group (Table 3). MMAS total score change from 31.7 ± 13 points to 33.3 ± 13 points (individual start and end score compared) was not significant in the placebo stimulated hand group, neither was the 10-metre walking time change. The patient's assessment of paretic hand function was better in 3/8 cases, and 5/8 indicated no change. None of the clinical test movements changed significantly in the placebo group. The upper-limb skin sensation change was not significant (10.1 ± 4 points versus 8.6 ± 4 points) in the placebo group. SEP normality classification of the paretic upper limb did not change, however, a previously unidentifiable component was seen in one patient at the end of the rehabilitation period.

Table 3 Modified Motor Assessment Scale, 10-metre walking time, change in paretic function, limb sensation and SEP paretic hand classification at the beginning and end of the rehabilitation course in patients who received placebo stimulation in the hand

	Before	After
MMAS ($n = 7$)		
Mean \pm SD	31.7 ± 13	33.3 ± 13
10-m walk ($n = 6$)		
m s ⁻¹ \pm SD	15.9 ± 9	13.7 ± 6
Limb function ^a ($n = 8$)		
1		3
2		5
3		0
Limb sensation ($n = 8$)		
Mean \pm SD	10.1 ± 4	8.6 ± 4
SEP ^b ($n = 8$)		
1	0	0
2	3	3
3	5	5

^aLimb function: 1 = better; 2 = no change; 3 = worse.

^bSEP: 1 = normal; 2 = minor change; 3 = abnormal.

Discussion

This study showed that cutaneous stimulation may improve the motor and sensory function of

Clinical messages

- Subthreshold sensory stimulation may improve limb function late after stroke.
- It may also alter central responsiveness to sensory stimulation, altering somatosensory evoked potential.
- These changes followed only brief treatments, 20 minutes twice daily over three weeks.

the paretic limb even years after stroke. Cutaneous stimulation had positive effects on the motor performance and/or limb sensation in those 51 chronic stroke patients who received active stimulation. Also the configuration of SEP of the paretic limb normalized in some of the patients. Similar positive effects were observed when looking at the groups of active hand stimulation, but there were no significant sensorimotor changes in the hand of the placebo-stimulated group. We recognize that the placebo group is small and no real randomization was done throughout the project. However, the unchanged hand status of our placebo group gives an indication that the observed effects originated from stimulation and not from the extra attention to the patients.

Modified Motor Assessment Scale seemed to be a sensitive measure for use during a three-week rehabilitation period. An improvement of 2.3 points in the total MMAS score for actively stimulated patients is clinically significant in this scale. In addition to sensitivity for the rehabilitation effects of the period, MMAS was able to distinguish between actively stimulated and placebo patients. Nugent *et al.*¹⁴ tested the sensitivity of MMAS and stated that MMAS has a dose–response relationship with the amount of weight-bearing exercise in stroke patients.

Ten-metre walking speed improved on an average of 0.04 m s^{-1} in hand-stimulated patients. Previously it was reported that FES stimulation of stroke patients to the peroneal nerve of the paretic foot improved walking speed 0.08 s^{-1} .¹⁵ In light of the current study, we believe that both cutaneous stimulation and functional electrical

stimulation (FES) may activate the same mechanisms controlling walking. The walking time of actively stimulated patients ranged from 6–99 s (beginning) to 8–128 s (end). The wide ranges were due to different walking abilities of the patients. It was observed that slowly walking patients remained slow even after the rehabilitation period, but motor function improved in the paretic lower limb. Sixty-seven per cent of the stimulated stroke patients considered their paretic limb to be better at the end of the rehabilitation period.

Recently, Katrak *et al.* emphasized that hand movement and function tests can be used to measure the function of the paretic arm.¹⁶ Here the paretic hand was evaluated with four tasks. More patients were able to perform finger extension after a three-week rehabilitation period than before it. In addition, finger extension could distinguish actively stimulated from placebo-treated patients. An initially weak motor function of finger extension may also be due to swelling and/or spasticity, which cutaneous stimulation may reduce. Improvement in the sensory function of actively stimulated patients was encouraging. The sensory threshold decreased in 28 patients and increased in 20 patients and the overall sensory change was significant. The elevated sensory threshold in the end of the study may result from the reduced hypersensitivity to sensory stimulus. Only three patients showed no changes in sensory threshold. The sensory threshold measurement by cutaneous stimulation was confirmed by the patient's own rating of skin sensation measured by the visual analogue scale. As mentioned earlier, the stimulation intensity was adjusted each time according to the sensory threshold of the patient.

Kusoffsky *et al.*¹⁷ noted full recovery of arm function in four of five subacute stroke patients with normal SEP, while six patients with poor or almost normal arm function had asymmetric SEP. All the patients with absent SEP had poor arm function. In the present study, the SEP findings confirmed the results of Kato *et al.*¹⁸ with intracerebral haemorrhage patients. Abnormal SEP findings in paretic limb were seen as the absence of cortical responses or delayed latencies and/or decreased amplitudes. In some stroke patients even nonparetic limb SEPs were not

normal. The absence of SEP influenced the statistical analysis of specific components. The situation was anticipated and each SEP recording was classified according to its overall normality/abnormality features. In this way each recording received a value. SEP paretic upper limb classification showed significant improvement after three weeks of rehabilitation. SEPs registered from nonparetic limbs were not different from the beginning to the end, which increases reliability of the analysis. In the present study, SEP and MMAS results were not compared, but both measures showed improvement. One previous study showed that SEP predicted independent functional ability. In that study, patients with normal SEP on admission achieved best mean Barthel scores, while the group with absence of cortical potentials had the worst Barthel scores. In addition, SEP at the time of admission correlated highly with the Barthel outcome score.¹⁹

Golaszewski *et al.*¹² studied the effect of cutaneous stimulation in the immediate post-stimulation period during simple motor tasks with MRI. They reported increased signal in the pre- and post-central gyri after cutaneous stimulation, also the inferior parietal lobule was activated in both hemispheres. It is feasible, that additional afferent stimulation might trigger the remaining plastic capacity for sensorimotor reorganization in the brain and might thus facilitate functional recovery in chronic stroke. Plasticity in the adult motor system is well-documented.^{20,21} One of the possible cellular mechanisms of plasticity is unmasking. Neurons or neural pathways have a larger region of anatomical connectivity than their usual territory of functional influence. Active inhibition may have a role in the control of these territories. If the inhibition is removed, the region of influence may increase or appear unmasked.²² Unmasking of pre-existing connections may be one of the mechanisms by which cutaneous stimulation improves functional recovery. Activity-dependent synaptic changes can also occur in the sensorimotor cortex and such cellular mechanisms as the long-term potentiation or depression are often behind the synaptic changes. Yet another possible process is growth of new neural connections.^{20,22} Sprouting of new axon terminals and formation of new synapses

may also have a role in plastic changes elicited by treatments.

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