Regeneration of sudomotor and sensory nerve fibres after digital replantation and microneurovascular toe-to-hand transfer

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SUMMARY. The end-stage sudomotor and sensory recovery in patients with replanted fingers and patients after microneurovascular toe-to-hand transfer was studied using quantitative electrophysiological investigations (recovery of sensory nerve action potentials and the sympathetic skin response), the ninhydrin test and clinical testing of sensory regeneration (light touch, pain, static and dynamic two-point discrimination). 13 adult patients with 22 replanted digits (11 males, 2 females) aged 21–58 years (mean 42.2 years) and 12 adults and adolescents (8 males, 4 females) aged 13–45 years, (mean 26.8 years) following 14 microneurovascular great and/or second toe-to-hand transfers were studied.

The replanted fingers were examined 2–7 years after injury and replantation. The toe-to-hand transfers were examined 2–12 years after injury and transfer.

The results show better end-stage recovery of sudomotor and sensory function following finger replantation when compared to microneurovascular toe-to-hand transfer.

The replanted finger is a completely denervated, sympathectomized and devascularized structure, Thus, it can serve as an excellent model for the examination of digital nerve regeneration.12

In the last two decades the surgical treatment of peripheral nerve lesions has improved considerably, primarily due to the continuous development of microsurgical techniques and ultrafine nonreactive suture materials, as well as to new knowledge and understanding of the neurobiology and neurochemistry of nerve regeneration.4,5 The resulting better functional outcome offers new possibilities for studying motor, sensory and sudomotor recovery by quantitative electrophysiological techniques.6,7

Many microsurgical centres have reported impressive series of successful replantation and toe-to-hand transfers, with survival rates greater than 80% and good functional results.8,9

Apart from recovery of sensation following digital replantation, regeneration of autonomic nerve fibres is essential for the restoration of hand function.10,11 Post-traumatic cold intolerance is a major cause of disability after digital amputation1 and a significant complaint of most patients with replanted digits.14

Loss of sweating is of functional importance, because lack of the adhesion which sweat normally provides seriously interferes with span grasp of smooth cylindrical objects and with finger manipulations in precision or chuck grip.12

The present study was undertaken in order to estimate the end-stage sudomotor and sensory recovery in patients with replanted fingers and in patients after microneurovascular toe-to-hand transfer using quantitative electrophysiological studies (recovery of sensory nerve action potentials and the sympathetic skin response), the ninhydrin test and clinical testing of sensory regeneration.

Patients and methods

Patients

The study was approved by the National Committee for Medical Ethics. There were two groups of patients. The first consisted of 13 adult patients (11 males, 2 females) aged 21–58 years, (mean 42.2 years) in whom one (4 patients) or several (9 patients) digits were replanted. In 4 patients the index finger was replanted onto the thumb site.

The other group contained 12 adults and adolescents (8 males, 4 females) aged 13–45 years (mean 26.8 years) with a total of 14 microneurovascular great and/or second toe-to-hand transfers.

All patients were studied after they were considered to have reached the final stage of their neurological recovery (2–7 years after injury and replantation and 2–12 years after injury and toe-to-hand transfer).

Details of the patients are summarized in Tables 1 and 2.

Methods

A. Evaluation of sudomotor nerve fibre regeneration

Recording of sympathetic skin responses. Measurement of the sympathetic skin response (SSR) is technically simple and non-invasive and does not depend on the patient's interpretation. By this method the function of the autonomous nervous system can be assessed. It also allows monitoring of regeneration of sudomotor fibres after nerve transection and microsurgical repair.
### Table 1: Finger replantations

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age (years)</th>
<th>Sex</th>
<th>Year of injury</th>
<th>Follow-up interval (years)</th>
<th>Mechanism of injury</th>
<th>Amputation (Digit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. DE</td>
<td>50</td>
<td>M</td>
<td>1987</td>
<td>7</td>
<td>Axe</td>
<td>Thumb-2nd</td>
</tr>
<tr>
<td>2. TI</td>
<td>21</td>
<td>F</td>
<td>1988</td>
<td>6</td>
<td>Lawn mower</td>
<td>Thumb</td>
</tr>
<tr>
<td>3. KO</td>
<td>58</td>
<td>M</td>
<td>1988</td>
<td>6</td>
<td>Lawn mower</td>
<td>Thumb-2nd</td>
</tr>
<tr>
<td>4. UR</td>
<td>47</td>
<td>M</td>
<td>1989</td>
<td>5</td>
<td>Lawn mower</td>
<td>2nd-5th</td>
</tr>
<tr>
<td>5. RU</td>
<td>40</td>
<td>M</td>
<td>1989</td>
<td>5</td>
<td>Lawn mower</td>
<td>3rd-5th</td>
</tr>
<tr>
<td>6. MU</td>
<td>44</td>
<td>M</td>
<td>1989</td>
<td>5</td>
<td>Cutter</td>
<td>2nd-5th</td>
</tr>
<tr>
<td>7. JA</td>
<td>58</td>
<td>M</td>
<td>1989</td>
<td>4</td>
<td>Lawn mower</td>
<td>2nd-5th</td>
</tr>
<tr>
<td>8. JR</td>
<td>43</td>
<td>M</td>
<td>1989</td>
<td>4</td>
<td>Lawn mower</td>
<td>Thumb</td>
</tr>
<tr>
<td>9. JB</td>
<td>33</td>
<td>M</td>
<td>1990</td>
<td>4</td>
<td>Steel cord</td>
<td>Thumb</td>
</tr>
<tr>
<td>10. ZU</td>
<td>45</td>
<td>M</td>
<td>1990</td>
<td>3</td>
<td>Lawn mower</td>
<td>2nd 5th</td>
</tr>
<tr>
<td>11. LE</td>
<td>37</td>
<td>M</td>
<td>1991</td>
<td>3</td>
<td>Axe</td>
<td>Thumb</td>
</tr>
<tr>
<td>12. KP</td>
<td>27</td>
<td>F</td>
<td>1991</td>
<td>3</td>
<td>Pulley</td>
<td>Thumb-2nd</td>
</tr>
<tr>
<td>13. MA</td>
<td>45</td>
<td>M</td>
<td>1992</td>
<td>2</td>
<td>Lawn mower</td>
<td>Thumb-2nd</td>
</tr>
</tbody>
</table>

The SSRs were elicited and recorded using a standard technique. A two-channel EMG machine Mystro, Medelec MS 20 was used. The stimulating electrode (13L 36, DANTEC, Skovlunde, Denmark) was attached to the palmar surface of the wrist of the treated limb to stimulate the median nerve. An earthing electrode was applied to the opposite wrist. The skin was cleaned with alcohol. Beckman's surface disc electrodes were covered with electrode gel and attached to the skin: at the centre of the distal phalanx (recording electrode) and on the dorsum of the same hand (reference electrode) bilaterally. A single square electrical impulse of 80–150 V amplitude and 0.2 ms duration was delivered near the end of inspiration to evoke the SSR.

Skin temperature in all patients was kept above 31°C. The measurements were taken simultaneously on both hands. At each site four consecutive responses were recorded to ensure reproducibility. The latency, peak-to-peak amplitude and area (integrated surface below and above the baseline) of each response were measured. Left-to-right ratios of the areas of the responses were calculated and expressed as percentages.

### Table 2: Toe-to-hand transfers

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age (years)</th>
<th>Sex</th>
<th>Year of injury</th>
<th>Time from injury to transfer</th>
<th>Follow-up interval (years)</th>
<th>Mechanism of injury</th>
<th>Toe-to-hand transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. SE</td>
<td>37</td>
<td>M</td>
<td>1981</td>
<td>14 months</td>
<td>12</td>
<td>Hot cutter</td>
<td>Great toe</td>
</tr>
<tr>
<td>2. KR</td>
<td>18</td>
<td>F</td>
<td>1982</td>
<td>10 years</td>
<td>3</td>
<td>Lawn mower</td>
<td>2nd toe</td>
</tr>
<tr>
<td>3. RI</td>
<td>26</td>
<td>M</td>
<td>1984</td>
<td>10 months</td>
<td>9</td>
<td>Conveyor Belt</td>
<td>Great toe</td>
</tr>
<tr>
<td>4. KS</td>
<td>44</td>
<td>F</td>
<td>1988</td>
<td>Primary</td>
<td>6</td>
<td>Borer</td>
<td>Great toe</td>
</tr>
<tr>
<td>5. KA</td>
<td>37</td>
<td>M</td>
<td>1989</td>
<td>9 months</td>
<td>5</td>
<td>Punch press</td>
<td>Great toe</td>
</tr>
<tr>
<td>6. DR</td>
<td>21</td>
<td>M</td>
<td>1989</td>
<td>17 months</td>
<td>4</td>
<td>Explosion</td>
<td>Great toe</td>
</tr>
<tr>
<td>7. HO</td>
<td>14</td>
<td>M</td>
<td>1989</td>
<td>22 months</td>
<td>3</td>
<td>Electrical current</td>
<td>2nd toe</td>
</tr>
<tr>
<td>8. PO</td>
<td>23</td>
<td>M</td>
<td>1990</td>
<td>4 months</td>
<td>4</td>
<td>Conveyor belt</td>
<td>Great toe</td>
</tr>
<tr>
<td>9. ZU</td>
<td>45</td>
<td>M</td>
<td>1990</td>
<td>9 months</td>
<td>4</td>
<td>Lawn mower</td>
<td>2nd toe</td>
</tr>
<tr>
<td>10. CV</td>
<td>19</td>
<td>M</td>
<td>1991</td>
<td>5 months</td>
<td>3</td>
<td>Cutter</td>
<td>2nd toe</td>
</tr>
<tr>
<td>11. ZI</td>
<td>24</td>
<td>F</td>
<td>1991</td>
<td>4 months</td>
<td>3</td>
<td>Corn crusher</td>
<td>Great toe</td>
</tr>
<tr>
<td>12. KT</td>
<td>13</td>
<td>F</td>
<td>1997</td>
<td>17 months</td>
<td>3</td>
<td>Combine harvester</td>
<td>Great toe</td>
</tr>
</tbody>
</table>

All patients were asked about post-traumatic cold intolerance.

**R Evaluation of sensory nerve fibre regeneration**

**Recording of sensory nerve action potentials.** Antidromic sensory nerve action potentials (SNAPs) were recorded from the replanted digit or transferred toe and from the corresponding digit of the uninjured hand. A pair of standard ring electrodes (Digital ring electrodes 16639, MEDELEC, UK) was placed around the proximal and distal interphalangeal joints (distal to the site of replantation). A stimulating electrode (Bipolar stimulating electrode 16893, MEDELEC, UK) was attached to the wrist 3 cm proximal to the distal crease of the wrist longitudinally along the white chromatographic paper and pressed gently. We traced the outline of the fingers with a pencil. The paper was passed several times through a 1% ninhydrin solution in acetone, to which a drop of glacial acetic acid was added. The sheet was then heat-dried in an incubator at 110 °C. The results on the injured side were compared to those on the normal side. They were classified by the intensity of the print pattern: normal sweating (+++), diminished sweating (++), and deficient (+) or absent sweating (−).

In the ninhydrin test, spontaneous sweat secretion was observed and documented by the ninhydrin test. Each patient placed their clean and dry fingers on a sheet of white chromatographic paper and pressed gently. We traced the outline of the fingers with a pencil. The paper was passed several times through a 1% ninhydrin solution in acetone, to which a drop of glacial acetic acid was added. The sheet was then heat-dried in an incubator at 110 °C. The results on the injured side were compared to those on the normal side. They were classified by the intensity of the print pattern: normal sweating (+++), diminished sweating (++), and deficient (+) or absent sweating (−).

All patients were asked about post-traumatic cold intolerance.
Nerve regeneration

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course of the median or ulnar nerve, respectively. The
ground electrode was attached to the same wrist
close to the site of stimulation. SNAPs elicited by
stimulation of the ulnar nerve at the wrist were
recorded from the little finger and SNAPs evoked by
median nerve stimulation at the wrist were recorded
on the thumb, index and middle fingers. Ten responses
were averaged during each stimulation procedure.
These recordings were made in a standard way on
the same EMG machine as used for the SSRs. The
stimulus pulse duration was 0.1 ms and the stimulus
frequency 0.5 Hz. The stimulation strength was slightly
above the one producing maximum response.
The skin temperature was kept above 31°C. The
latency and the amplitude of the response were
measured. The results on the replanted finger or
transferred toe were compared to the normal finger.
The left-to-right SNAP amplitude ratios were calcu-
lated and expressed as percentages.

Clinical testing of sensation

The patients were tested for the Hoffmann-Tinel sign,
ligh touch, pain and static and dynamic two-point
discrimination using standard techniques. The results
were interpreted following criteria suggested by the
British Medical Research Council and Seddon. 14,15
All studies were repeated on the corresponding
nerves of the contralateral normal finger so that each
parameter could be matched with a control value
obtained from the same subject.

Results

Replanted digits

In 7 of the 22 replanted digits the sudomotor function
was complete (Table 3, Fig. 1). These patients had a
normal ninhydrin print (Fig. 2). The SSR area on the
replanted digit reached 80% or more when compared
to the uninjured site in 13 replanted digits (Fig. 1). In 5
replanted digits the SSR area did not reach 20% when
compared to the uninjured site. Sweating was deficient
in only 3 digits. In 6 patients, post-traumatic cold
intolerance was a major cause for disability after
digital replantation.

SNAPs could be recorded in 12 of the 22 replanted
digits (Fig. 3). In 15 replanted digits sensation reached
a high degree of recovery: S3+ or S4 according to the
criteria suggested by the British Medical Research
Council and Seddon.

In 4 patients (DE, KO, KP, MA) the index finger
was replanted onto the thumb site with excellent
results (notably in terms of sudomotor regeneration).

Toe-to-hand transfers

The degree of end-stage recovery of sudomotor and
sensory function after microneurovascular toe-to-hand
transfer was worse than that in the replanted fingers
(Table 4). The SSR area on the transferred toe reached
80% or more in only 2 patients. In 9 patients the SSR
area was 30% or less compared to the uninjured hand
(Fig. 4). None of the patients had a normal ninhydrin
test (Fig. 5). Eight patients complained of post-
traumatic cold intolerance.

SNAPs could be recorded in only 4 of the 14 trans-
ferred toes (Fig. 6). In the majority of the transferred
toes, sensation was S3 or less (Table 4).

Discussion

The functional outcome following suture of divided
nerves depends on the number of nerve fibres that
have regenerated across the site of the nerve repair and

<table>
<thead>
<tr>
<th>Patient</th>
<th>Digit</th>
<th>Ninhydrin test</th>
<th>SSR (%)</th>
<th>Post-traumatic cold intolerance</th>
<th>Sensation recovery</th>
<th>SNAP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. DE</td>
<td>Pollicization</td>
<td>+++</td>
<td>80</td>
<td>Absent</td>
<td>S3</td>
<td>Absent</td>
</tr>
<tr>
<td>2. FI</td>
<td>Thumb</td>
<td>+++</td>
<td>100</td>
<td>Absent</td>
<td>S4</td>
<td>Absent</td>
</tr>
<tr>
<td>3. KO</td>
<td>Pollicization</td>
<td>/</td>
<td>100</td>
<td>Absent</td>
<td>S3+</td>
<td>35</td>
</tr>
<tr>
<td>4. UR</td>
<td>Index</td>
<td>+</td>
<td>10</td>
<td>Present</td>
<td>S3+</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>++</td>
<td>60</td>
<td>Present</td>
<td>S4</td>
<td>60</td>
</tr>
<tr>
<td>5. RU</td>
<td>Ring</td>
<td>++</td>
<td>100</td>
<td>Present</td>
<td>S3+</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Little</td>
<td>++</td>
<td>100</td>
<td>Present</td>
<td>S3+</td>
<td>20</td>
</tr>
<tr>
<td>6. MU</td>
<td>Index</td>
<td>/</td>
<td>90</td>
<td>S3+</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>/</td>
<td>50</td>
<td>S3+</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>7. JA</td>
<td>Index</td>
<td>++</td>
<td>100</td>
<td>S3</td>
<td>S4</td>
<td>80</td>
</tr>
<tr>
<td>8. JB</td>
<td>Thumb</td>
<td>+++</td>
<td>75</td>
<td>Absent</td>
<td>S3+</td>
<td>25</td>
</tr>
<tr>
<td>9. ZU</td>
<td>Index</td>
<td>++</td>
<td>60</td>
<td>Present</td>
<td>S3+</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Little</td>
<td>++</td>
<td>70</td>
<td>Present</td>
<td>S3+</td>
<td>30</td>
</tr>
<tr>
<td>10. LE</td>
<td>Thumb</td>
<td>+++</td>
<td>100</td>
<td>Absent</td>
<td>S3+</td>
<td>80</td>
</tr>
<tr>
<td>11. HR</td>
<td>Thumb</td>
<td>+++</td>
<td>100</td>
<td>Absent</td>
<td>S3+</td>
<td>15</td>
</tr>
<tr>
<td>12. KP</td>
<td>Pollicization</td>
<td>+++</td>
<td>100</td>
<td>Absent</td>
<td>S4</td>
<td>100</td>
</tr>
<tr>
<td>13. MA</td>
<td>Pollicization</td>
<td>++</td>
<td>80</td>
<td>Absent</td>
<td>S3+</td>
<td>100</td>
</tr>
</tbody>
</table>

/: no measurement or test. Pollicization: Replantation of index finger onto thumb site.
Figure 1—SSRs in patient LE, registered from the centres of the hypothenar eminences, show a typical SSR left-right asymmetry (upper traces). Minimal asymmetry between replanted and uninjured thumbs (lower traces) mirrors excellent sudomotor nerve regeneration. (Horizontal lines: isoelectric base lines).

Figure 2—Ninhydrin test sweat patterns of uninjured thumb (left) and replanted thumb (right). Appearance of normal sweating has returned.

Figure 3—SNAPs in patient LE, 3 years after thumb replantation. Small SNAPs asymmetry between replanted thumb (upper trace) and uninjured thumb (lower trace) shows excellent sensory nerve regeneration. (Horizontal lines: isoelectric base lines). Sensory recovery in this patient was almost complete.
Table 4 Results after toe-to-hand transfer

<table>
<thead>
<tr>
<th>Patient</th>
<th>Ninhydrin test</th>
<th>SSR (%)</th>
<th>Post-traumatic cold intolerance</th>
<th>Sensation recovery</th>
<th>SNAP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. SE</td>
<td>+</td>
<td>15</td>
<td>Present</td>
<td>S 2</td>
<td>Absent</td>
</tr>
<tr>
<td>2. KR</td>
<td>+</td>
<td>10</td>
<td>Present</td>
<td>S 3</td>
<td>30</td>
</tr>
<tr>
<td>3. RI</td>
<td>++</td>
<td>80</td>
<td>Absent</td>
<td>S 3+</td>
<td>Below 10</td>
</tr>
<tr>
<td>4. KS</td>
<td>+</td>
<td>20</td>
<td>Absent</td>
<td>S 2</td>
<td>Absent</td>
</tr>
<tr>
<td>5. KA</td>
<td>++</td>
<td>100</td>
<td>Absent</td>
<td>S 3+</td>
<td>Below 10</td>
</tr>
<tr>
<td>6. DR</td>
<td>Great toe +</td>
<td>30</td>
<td>Present</td>
<td>S 2+</td>
<td>Absent</td>
</tr>
<tr>
<td></td>
<td>Second toe +</td>
<td></td>
<td>Present</td>
<td>S 2+</td>
<td>Absent</td>
</tr>
<tr>
<td>7. HO</td>
<td>++</td>
<td>10</td>
<td>Present</td>
<td>S 3+</td>
<td>Absent</td>
</tr>
<tr>
<td>8. PO</td>
<td>++</td>
<td>35</td>
<td>Present</td>
<td>S 3</td>
<td>/</td>
</tr>
<tr>
<td>9. ZU</td>
<td>++</td>
<td>60</td>
<td>Absent</td>
<td>S 3</td>
<td>Absent</td>
</tr>
<tr>
<td>10. CV</td>
<td>+</td>
<td>35</td>
<td>Present</td>
<td>S 3</td>
<td>20</td>
</tr>
<tr>
<td>11. ZI</td>
<td>+</td>
<td>20</td>
<td>Present</td>
<td>S 3</td>
<td>Absent</td>
</tr>
<tr>
<td>12. KT</td>
<td>Great toe -</td>
<td>5</td>
<td>Present</td>
<td>S 3</td>
<td>Absent</td>
</tr>
<tr>
<td></td>
<td>Second toe +</td>
<td>30</td>
<td>Present</td>
<td>S 3</td>
<td>Absent</td>
</tr>
</tbody>
</table>

/ : no measurement.

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**Figure 4**—SSRs in patient SE, registered from the centres of the hypothenar eminences, show a typical SSR left-right asymmetry (upper traces). End-stage recovery of SSR (lower traces) in transferred toe with a low amplitude shows bad sudomotor nerve regeneration. (Horizontal lines: isoelectric base lines).

**Figure 5**—Ninhydrin test sweat patterns of transferred toe (left) and uninjured thumb (right). Sweating in the transferred toe was deficient.

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**Fig. 4**

**Fig. 5**
Regenerating nerve fibres initially have no myelin sheath. This and their smaller diameter readily explain the very slow conduction velocities. Conduction in the unmyelinated growing ends of the regenerating fibres is non-saltatory and saltatory conduction follows later, when a myelin sheath has developed.19

The threshold of such immature fibres to electrical stimulation may be very high and exceed the threshold of uninjured fibres by 20–100 times.18 Such axons cannot be electrically stimulated through the skin.

Postganglionic lesions cause degeneration of the sensory axons and loss of sensory nerve action potentials (SNAPS) within a few days.30 Maturation of the regenerating fibres is accompanied by an increase in the number of myelin lamellae and progressive increases in the diameters of the axons. These maturational changes explain the progressive reduction of threshold of the regenerating fibres to electrical stimulation as well as the accompanying increase in their conduction velocity.

In humans, the conduction velocity of regenerated motor and sensory fibres following nerve section may eventually reach 80–100% of normal values.19

The amplitude of SNAPS gives some indication of the number of intact axons.22 It depends on the number of conducting axons and the degree of synchronicity of their responses under the recording electrodes. When the number of conducting axons falls below a certain limit, or their action potentials become dispersed in time because of slowing of conduction, or both, no SNAP may be recorded.23

The SNAP of a regenerated nerve becomes detectable (using a near-nerve recording technique) 4–5 months following division and suture. It subsequently increases in size (amplitude) and area. The near-nerve potential usually has a complex shape with many components, which reflects a considerable temporal dispersion, i.e. a wide range of conduction velocities along the immature regenerated nerve fibres.24

In the absence of marked slowing of conduction and temporal dispersion, the amplitude of the SNAP evoked by stimulation of the regenerated nerve segment is an index of the number of functional regenerated fibres.25

In an electrophysiological study of divided human peripheral nerves 13–53 months after surgical repair, the conduction velocity of the sensory fibres averaged 70–80% of normal nerves and the mean amplitude of the SNAP at the wrist remained depressed at 15% of the control values.30 Only three patients had a median nerve SNAP amplitude above 30%.

In another study,67 ulnar and median nerves sutured after complete division 3.5 months to 24 years previously were evaluated electrophysiologically. Before 10 months, SNAPS were detected in only two nerves, up to 20 months after repair only 13% of nerves had a measurable SNAP, between 20 and 40 months SNAPS were seen in 50% of nerves, and between 40 and 55 months in 75% of nerves.

A high SNAP amplitude therefore indicates a fairly normal conduction in a large number of sensory axons and can be regarded as a sign of an excellent result of surgery. However, peripheral nerves constitute only a part of the somatosensory pathways. Important integrative processes occur at the central synaptic relays and particularly in the somatosensory cortex.26 For this reason, the quality of sensory recovery in the replanted finger is not simply a function of SNAP amplitude. Poor peripheral regeneration can be compensated in part by plasticity of the somatosensory cortex and strengthening or ‘unmasking’ of relatively weak or totally ineffective synaptic connections in cortical somatotopic maps, at the level of the thalamus and the dorsal column nuclei;27,28 so in spite of low amplitudes or unrecordable SNAPS the patient’s sensation may be satisfactory. This may explain good
sensation in children and adolescents after toe-to-hand transfer when no SNAP was recorded.

To our knowledge there are no data in the literature on recovery of SNAPs following replantation or toe-to-hand transfer. In our study we were able to record SNAPs of different amplitudes in more than 50% of patients 2–7 years following finger replantation and in 33% of patients 2–12 years after toe-to-hand transfer. In some of the replanted fingers we recorded SNAPs equalling 100% of normal values. This can be explained by an immediate and technically perfect reconstruction at a very distal point from where the distance for regeneration is short.

All the patients with a high or fair SNAP amplitude, except one, also had a very good recovery of sensation. Nevertheless, recovery of sensitivity that is normal in all respects is unattainable after peripheral nerve injury. Paradoxical clinical consequences of peripheral nerve injury due to anatomical, neurophysiological and psychological mechanisms are possible. Ectopic impulse generation and cross-excitation between neurons in the peripheral nervous system can occur after injury.

Aggravation and problems with insurance are considered to have affected the results of sensory testing in patient RU (Table 3).

When assessing a patient following replantation, usually little attention is paid to regeneration of autonomic nerve fibres, although this is quite significant for the quality of function of the replanted finger as well as of the whole hand. Loss of sweating results in the loss of adhesion which slightly moist skin normally provides. This seriously interferes with grasping of smooth cylindrical objects as well as with fine pinch grip and precision manipulation.

The combination of insensitivity and dry, slippery skin seriously limits the mobility and function of the patient's hand despite good motor control.

End-stage sudomotor recovery (sweating) estimated by an objective neurophysiological test (SSR) and the ninhydrin test was more complete in patients with replanted fingers than in patients with toe-to-hand transfers. Amputation affects all nerve fibres including the vasomotor fibres, which innervate the blood vessels and are probably one of the factors responsible for the very disturbing cold intolerance that so often follows hand and finger replantation or toe-to-hand transfer.

Cold intolerance is likely to decrease during the first two years after replantation but not to disappear completely. It is less pronounced in patients without pathological vasospasm in the replanted digit. The incidence of cold-induced vasospasm after hand injuries has been reported to be as high as 100%, following replanted digital amputation. Patients with moderate symptoms may perceive an improvement with time, probably due to a change of habits, while patients with severe problems may not experience improvement with time.

The exact mechanism of post-traumatic cold intolerance is unknown. However, poor regeneration of autonomic vasomotor fibres, abnormal vasoregulation of the digital vascular tree, and the vasoconstrictor input of the sympathetic nervous system, including humoral control by circulating catecholamines and chemical mediators such as serotonin, histamines and prostaglandins, may play a role. There is local myogenic control related to perfusion pressure which, in the presence of traumatic or chemical denervation, may react directly to cold by vasoconstriction.

Thermal sensitivity of spontaneously active A- and C-fibres in nerve-end neuromas may account for the aggravation of phantom limb and post-traumatic cold intolerance during cold weather.

In some of our patients, post-traumatic cold intolerance develops early following replantation, considerably before clinically manifested sensory regeneration. In a series of patients injured fingertips treated by local Hueston flaps, two-point discrimination averaged 5 mm in cases without cold intolerance and 8 mm in those with significant cold intolerance. Thus it is not clear which nerve fibres convey this type of pain. Furthermore, post-traumatic cold intolerance appeared in some of our patients with very good sensory recovery, recordable SNAPs, normal sweating pattern and normal SSR (patients MU, JA, LE).

The functional outcome in our toe-to-hand transfer group was not as good as in the digit replantation group, although the reverse might be expected considering the lower mean age in the toe-to-hand transfer group. However, the injuries in this group had been particularly bad, owing to their mechanism (electrical, thermal, explosive injuries, avulsions, blunt injuries), and required extensive debridement and later reconstruction by a toe-to-hand transfer (Table 2).

Another factor responsible for the less favourable outcome could be the delay of the reconstruction; the average delay in our toe-to-hand transfer group, excluding the patient KR with a transfer 10 years after injury, was 12.4 months. Immediate replantation ensures synchronicity of regenerating axonal sprouts, neurotrophic factors and contact guidance in terms of time and location, which is important for successful regeneration of injured peripheral nerves. Lack of such synchronicity occurs with delayed healing. In cases of delayed toe-to-hand transfer the innervation of sensory corpuscles at the toe is interrupted, which causes the release of neurotrophic factors; however, the regenerative capacity of the proximal nerve stump on the hand may at that time already be diminished, since the phase of non-guided (random) regeneration is already over.

After years of controversy, it is now generally agreed that primary nerve repair by end-to-end coaptation, whenever feasible, yields better results than secondary procedures.

Differences in tissue, nerve fascicle and end-organ characteristics may be another factor to account for the less good results in the toe-to-hand transfer group. Target-specific nerve regeneration has been documented at various levels of tissue. It is therefore not surprising that the results of primary replantation, where the fascicles from the same nerves are joined, are better than those of toe-to-hand transfers, in which the proximal ends of digital branches of the ulnar or median nerves are sutured to plantar digital nerves originating from the tibial nerve.
A wide variety of clinical measures of sensory performance has been described and recommended for use in hand surgery. They can be divided into timed functional testing of sensibility derived from the work of Moberg and the 'pure' sensory tests of stimulus threshold and discrimination. Some are simple, cheap, and quick to use, some have been frequently and widely reported, and others less so. Some methods developed relatively recently by neurophysiologists are new to peripheral nerve surgery but established in clinical neurophysiology.

On the basis of our data, we consider the recordings of SNAPs and SSRs to be useful additional clinical tests besides the many well-known quantitative tests of sensibility (static and dynamic two-point discrimination, cold perception, ridge detection, vibration threshold, warm perception and cutaneous pressure threshold).

There are various methods of assessing sensory recovery, including the modified Medical Research Council classification. Chassard et al. proposed a further modification, including a new grade, S5. The Medical Research Council classification was used in this study for easier comparison with other studies.

We agree with other authors that comparison with the equivalent area on the contralateral uninjured hand is an accurate way of expressing outcome, when assessing the results of peripheral nerve repair and replantations.

Acknowledgements

We would like to thank Józef Trontek MD, PhD, of the University Institute of Clinical Neurophysiology, for useful discussions during the course of this work. Many thanks to Mrs Józefa Brit and Mrs Ruprecht Ruth for their help with ninhydrin sweat pattern tests and Mr Gregor Cerkvenik and Mr Nacek Zidar for their help with the computer work.

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Paper received 15 August 1996.
Accepted 17 February 1997, after revision.