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Macro- and microcirculatory assessment of cold sensitivity after traumatic finger amputation and microsurgical replantation

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Abstract
Introduction Finger replantations after traumatic amputation are associated with good prognosis and acceptable functional results. However, cold sensitivity is a common and sometimes disabling sequelae after digital replantation. The exact causes of cold intolerance are still unclear; neural as well as vascular mechanisms have been discussed. We examined the macro- and microvascular performance of replanted fingers using high-resolution color-coded sonography for the assessment of skin vessel density of the fingertips as well as nailfold capillary microscopy and laser Doppler anemometry. Subsequently, we correlated these findings with the presence of cold sensitivity of the replanted digits.
Patients and methods Thirty-seven patients (mean age 45 years; range 19–72) with 40 traumatic finger amputations and microsurgical replantations were studied. The mean time interval between amputation and examination was 57.7 months (range 13–95). Macro- and microvascular examination consisted of electronic oscillograms of both arms, photoplethysmograms of all fingers before and after cold test, duplex ultrasound of the finger arteries, high-resolution color-coded sonography of the fingertips and nailfold capillary microscopy with laser Doppler anemometry.
Results Cold sensitivity was present in 33 (83%) of the 40 replanted fingers. Peripheral arterial disease of the upper extremity could be excluded as all oscillograms showed normal findings. A vasospastic reaction after cold test was documented in 74% (30 of 38) of the replanted fingers, compared to 24% (9 of 38) of the contralateral uninjured fingers. Raynaud's phenomenon was restricted to replanted fingers and occurred in 10 of 40 patients (25%). Compared with the contralateral fingertips, reduced skin vessel density was found in 27 of 36 (75%) replants. Nailfold capillary microscopy revealed uncharacteristic morphologic patterns. The capillary flow velocity was 0.28 ± 0.12 mm/s in the replanted fingers and 0.48 ± 0.23 mm/s in their unaffected counterparts ($P < 0.001$). Correlating these findings with the presence of cold intolerance, reduced skin vessel density in the fingertips was significantly different between cold-sensitive replants and those without cold sensitivity ($P = 0.05$). Reduced skin vessel density was not related to the extent of reconstruction of nerves (P = n.s.), arteries (P = n.s.) and veins (P = n.s.).
Conclusions Our results do not confirm hypotheses that cold sensitivity after finger replantations is caused

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by macrovascular problems nor do they support assumptions of a primary capillary microcirculatory failure. Our findings of reduced vessel density point towards diminished thermoregulatory capacities in the fingertips of cold-sensitive replanted digits.

Keywords Finger amputation · Finger replantation · Cold sensitivity · Raynaud's phenomenon · Vasospasm · Thermoregulation · Microcirculation

Introduction

Despite good prognosis and acceptable return of motor function after finger amputation and replantation [1, 4, 5, 8, 10, 21], patients often suffer from cold intolerance of the replanted fingers [2, 6]. However, the exact physiological mechanisms of cold sensitivity are still unclear [14, 17, 18]. Besides neuronal malfunction, macro- and microcirculatory failures have been suggested to play a crucial role [9, 16, 22]. Studies focusing on vascular aspects of the problem usually concentrate on digital arterial anastomoses or cold-induced vasospasm in the replanted fingers [2, 3, 7, 13, 14, 17, 23]. Until now, a holistic study on macro- and microcirculatory aspects including nailfold capillary microscopy and capillary flow velocity measurements has not been reported. The aim of our study was to examine the macro- and microvascular performance of microsurgically replanted fingers and to correlate these findings with the presence of cold sensitivity at the replanted digits.

Patients and methods

Between September 2000 and June 2001, 37 patients with 40 traumatic finger amputations and microsurgical replantations were studied during their follow-up examinations at the Department of Vascular Surgery and Plastic and Reconstructive Surgery, Innsbruck Medical University. The mean age of the study group was 45 years with a range from 19 to 72 years. All finger amputations resulted from accidents while working with saws or woodchoppers. The mean time interval between the operation and the examination was 57.7 months (range 13–95 months). All replantations were performed at the Department of Plastic and Reconstructive Surgery using classical microsurgical techniques. Shortening of the bones during debridement was usually 1–2 mm on each side. Bone fixation was achieved by two crossed K-wires and a wire suture. In the cases of transarticular amputation, arthrodesis was performed. Both the flexor and the extensor tendons were repaired primarily. One or two arteries and 1 to 3 veins were anastomosed directly. If venous reconstruction was impossible, leach therapy was performed postoperatively. Whenever possible, both nerves were coapted (see Table 1). Perioperative antibiotics were given intravenously and low-dose heparin was administered subcutaneously.

Examinations

During the follow-up, all patients were first investigated by the plastic surgeon and asked about cold sensitivity of the replanted fingers. Thereafter, patients were examined by an angiologist blinded to the questionnaire recorded before.

Pulse status, acral lesions and the occurrence of Raynaud's phenomenon were documented. Oscillograms of both arms (Gutmann Medizin-Elektronik, Germany) were recorded in all patients, followed by photoplethysmograms (ULP 85, Gutmann Medizin-Elektronik, Germany) derived from all fingertips. Subsequently, a cold test was performed by bathing the hands in 15°C water for 2 min. Thereafter, acral photoplethysmography was repeated. A cold-induced vasospastic reaction was assumed if there was vasospastic deformity of the pulse waves and the signal amplitudes were reduced by >50% compared to the recordings before cooling. These findings had to be completely reversible after bathing the hands in 40°C water for 5 min.

After a resting period of 15 min duplex ultrasound studies (HDI 5000, 5–12 MHz linear transducers, ATL-Philips) of both hands was performed with special attention to the anastomoses and the arterial supply of the replanted fingers. In addition, the assessment of the fingertips of the replanted fingers and their contralateral counterparts were carried out with high-resolution sonography. Adequate zooming was performed and the color-gain was reduced just below the noise level. Skin vessel density of the fingertip in the replanted finger was semiquantitatively expressed in relation to the contralateral uninjured finger as increased, identical, reduced or completely missing.

After another resting period of 15 min, nailfold capillary microscopy (magnification ×200) with laser Doppler anemometry was performed (KK-Research Technology LTD, UK). Capillary morphology was assessed according to the recommendations of the Microcirculatory Section of the German Society of Angiology (DGA) [20]. Capillary flow velocities were determined in the afferent capillary loops near the apex of five adjacent capillaries of each finger and were expressed as mean.

Table 1 Clinical data of the replanted cases

Case no.	Age	Sex	Trauma digit	Site	Replantation digit	Level of trauma	Arterial anastomoses	Venous anastomoses	Nerve coaptation
1	25	M	D II	Left	D II	GP	2	2	2
			D IV						
2	35	F	D I	Right	D I	IP	1	2	1
3	27	M	D I	Left	D I	IP	1	3	2
4	31	M	D IV	Left	D IV	MP	1	1	2
			D V						
5	21	M	D II	Right	D II	GP	2	1	2
6	73	M	D I	Left	D I	GP	1	2	2
7	45	M	D I	Right	D I	GP	1	2	2
8	55	M	D I	Left	D I	IP	1	2	0
9	54	M	D II	Left	D II	MP	2	2	2
10	19	M	D III	Left	D III	GP	2	2	1
11	48	M	D III	Right	D III	DP	1	1	1
12	24	M	D II	Right	D II	GP	2	3	2
13	70	M	D I	Left	D I	IP	1	3	2
14	40	M	D III	Left	D III	GP	1	2	1
			D IV		D IV	GP	1	1	2
15	35	M	D I	Left	D I	TMC	2	2	2
			D II[a]		D II[a]	MP[a]	2	2	2
			D III[a]		D III[a]	GP[a]	2	2	1
16	57	M	D II	Left	D II	GP	1	0	1
17	23	M	D I	Right	D I	IP	2	2	2
18	23	M	D I	Left	D I	DP	1	0	0
19	41	M	D I	Left	D I	GP	2	3	2
20	69	M	D I	Left	D I	DP	2	2	1
21	35	M	D III	Right	D III	GP	1	2	2
22	74	M	D II	Left	D II	MP	2	2	2
23	61	M	D I	Right	D I	MP	1	2	2
24	57	M	D I	Right	D I	GP	2	2	1
25	45	M	D I	Right	D I	GP	1	2	2
26	53	M	D I	Right	D I	GP	1	2	2
27	29	M	D II	Left	D II	MP	1	1	1
			D III						
			D IV						
			D V						
28	67	M	D I	Left	D I	GP	1	3	1
29	62	F	D III	Right	D III	DIP	1	2	2
30	56	M	D I	Right	D I	DIP	2	3	2
31	51	M	D I	Left	D I	GP	1	1	2
32	43	M	D I	Right	D I	GP	1	2	2
33	61	M	D I	Right	D I	GP	1	2	2
34	51	M	D I	Left	D I	DIP	1	2	1
35	27	M	D II	Right	D II	MP	2	2	2
			D III		D III	MP	2	2	2
			D IV		D IV	MP	2	2	2
36	19	M	D IV	Left	D IV	DIP	2	2	2
37	72	M	D V	Left	D V	MP	2	2	1

M male, *F* female, *D I–V* affected fingers, *GP* proximal phalanx, *MP* middle phalanx, *DP* distal phalanx, *TMC* transmetacarpal, *IP/PIP* (proximal) interphalangeal joint, *DIP* distal interphalangeal joint

[a] Not examined

Statistics

Statistical analysis was performed with the SPSS for windows 10.0. Univariate comparisons of continuous variables between the groups of patients were done by unpaired *t* test or Mann–Whitney *U* test. Dichotomized variables were compared using Fisher's exact test. A *P* value ≤ 0.05 was considered statistically significant.

Results

Table 1 shows the clinical characteristics of the patients. There is a clear predominance of men.

Table 2 demonstrates the distribution of the traumatic amputations. The most affected finger was DI. Left-sided lesions ($n = 21$) were more common than right sided ($n = 16$). This pattern seems to be strongly

Table 2 Distribution of traumatic finger amputations ($n = 40$)

Localization	Number	%
Proximal phalanx	18	45
Middle phalanx	9	22.5
Distal phalanx	3	7.5
Proximal interphalangeal joint	5	12.5
Distal interphalangeal joint	4	10
Transmetacarpal	1	2.5

Table 3 Capillary morphologic pattern in finger replantations ($n = 32$)

Morphology	
Reduced capillary density	22 (69%)
Capillary torsions	31 (97%)
Capillary elongations	18 (56%)
Pericapillary edema	8 (25%)

influenced by the hand dominance as well as the causes of the traumata.

Thirty-three (83%) patients complained of cold sensitivity in the replanted fingers. There were no acral lesions or perniones.

In all patients, pulses of the upper extremities and electronic oscillograms were normal, thus excluding arterial occlusive disease as a possible cause of acral cold sensitivity.

Photoplethysmography could be performed in 38 (95%) of the replanted fingers. Reduced signal amplitudes at room temperature were recorded in 28 of 38 (74%) patients. A vasospastic reaction after cold test was documented in 30 (79%) of the replants and 9 (24%) of the contralateral non-injured fingers. Raynaud's phenomenon with white or cyanotic skin discolorations was restricted to cold sensitive fingers and occurred in 10 of 40 (25%) replants.

Duplex ultrasound was performed in 36 (90%) of the replanted digits. There were four (11%) digital artery occlusions; two (5.5%) were caused by failure of the arterial anastomoses and the other two arteries had not been reconstructed during replantation.

Color-coded high-resolution ultrasound (HRUS) of the fingertips identified reduced skin vessel density in 27 of 36 (75%) replants, compared with the contralateral normal fingers. Increased vessel density or avascular fingertips were not observed.

Capillary microscopy could be performed in 32 (80%) of the replanted digits. In the rest of the cases, nailfold quality was either unsuitable or positioning of the distal phalanx under the capillary microscope was impossible due to contractions in the replanted fingers. Table 3 summarizes the morphologic pattern of the replanted digits. Unspecific morphologic features were common. A reduction in capillary density was seen in about two-thirds of the replanted fingers.

Laser Doppler anemometry was technically satisfactory in 21 of 32 cases (66%). Mean capillary flow velocity was 0.28 ± 0.12 mm/s in the replanted fingers and 0.48 ± 0.23 mm/s in their unaffected counterparts ($P < 0.001$).

As shown in Table 4, neither reduced amplitudes in the photoplethysmograms nor the appearance of Raynaud's phenomenon or a vasospastic reaction after cold test differed significantly in replanted fingers as far as cold sensitivity is concerned. Additionally, there was no significant difference in any of the capillary microscopic morphologic features. Capillary flow velocities in cold-sensitive replanted digits were similar to those without cold intolerance. In contrast to these findings, a significant reduction of skin vessel density was found in the fingertips of the cold-sensitive replanted digits ($P = 0.05$). As is shown in Table 5 in fingers with normal skin vessel density complete reconstructions of nerves (P = n.s.) and arteries (P = n.s.) as well as anastomoses of two or more veins (P = n.s.) were not performed. Two-point discrimination was slightly better in replanted finger with normal skin vessel density but differences did not reach statistical significance (P = n.s.). According to the data shown in Table 4, there was no correlation between capillary flow velocity and fingertip skin vessel density (P = n.s.).

Discussion

Cold intolerance is a very common condition after finger replantation occurring in up to 100% of the patients [2, 14, 17]. In our series of 40 replants in 37

Table 4 Distribution of clinical, capillary morphologic and microcirculatory characteristics in replanted fingers with and without cold sensitivity

	Cold sensitivity	Cold insensitivity	P value
Reduced amplitudes in photopletysmography	9 of 32	1 of 6	n.s.[a]
Vasospastic reaction in cold test	25 of 32	5 of 6	n.s.[a]
Raynaud's phenomenon	3 of 33	0 of 7	n.s.[a]
Reduced capillary density	18 of 25	4 of 7	n.s.[a]
Capillary elongations	16 of 25	2 of 7	n.s.[a]
Capillary torsions	24 of 25	7 of 7	n.s.[a]
Pericapillary edema	6 of 25	2 of 7	n.s.[a]
Capillary flow velocity (mm/s)	0.28 ± 0.04	0.28 ± 0.14	n.s.[a]
Reduced skin vessel density	24 of 29	3 of 7	0.05[a]

[a] Fisher's exact test

[b] Unpaired t test

Table 5 Correlation between number of reconstructed nerves, arteries, veins and 2 PD and reduced vessel density ($n = 36$)

		Reduced skin vessel density, $n = 27$	Normal skin vessel density, $n = 9$	P value
Number of nerve coaptation	1	7 (26%)	1 (11%)	n.s.[a]
	2	20 (74%)	8 (89%)	
Number of reconstructed arteries	1	16 (59%)	2 (22%)	n.s.[a]
	2	11 (41%)	7 (78%)	
Number of reconstructed veins	0–1	6 (22%)	1 (11%)	n.s.[a]
	>1	21 (78%)	8 (89%)	
2 PD radial (mean, mm)		6.41	5.22	n.s.[b]
2 PD ulnar (mean, mm)		7.11	5.00	n.s.[b]

[a] Fisher's exact test
[b] Mann–Whitney U test

patients, cold sensitivity was present in 83% of the replants.

We tried to shed light on the underlying cause of cold sensitivity by means of non-invasive macro- and microcirculatory assessment. To our knowledge, this is the first study using capillary microscopic techniques in combination with high-resolution color-coded sonography of the fingertips for the determination of skin vessel density in replanted and non-replanted fingers.

As has already been reported by others, failure of the arterial anastomoses is rarely found, indicating good prognosis for replanted digits [15, 21, 23]. All but two arteries remained open in our patients. We found no correlation between the fate of the digital anastomoses and cold sensitivity. These findings are in agreement with those of Nylander et al. [14], who could exclude organic insufficiency of the finger circulation as a reason for cold intolerance. Our results on the measurement of resting blood flow also agree with those of Povlsen et al. [18], who did not observe an improvement of cold sensitivity over the years, although resting blood flow had increased. Irrespective of the arterial reconstruction, Lithell et al. [11] and Isogai et al. [7] suggest that cold intolerance after digital replantation seems to be defined by the initial trauma and not by the subsequent reconstructive surgery. Patients who underwent digital replantation did not show a significant difference in cold sensitivity compared with those patients who underwent stump revision [7, 11].

Besides macrovascular causes, microvascular factors have been proposed. Some studies related the perception of cold intolerance to the presence of cold-induced vasospasm or the persistence of vasoconstrictor patterns in the replanted fingers [2, 7, 14]. Povlsen identified sensitized cold nocireceptors and nerve injuries as possible causes of vasomotor disturbances [19]. Arterial vasospasm with or without accompanying Raynaud's phenomenon was reported in 60% of Backman's series, in 80% of Nylander´s study and in almost all cases in Povlsen's report [3, 14, 17, 18]. In our series, vasospastic reactions were recorded not only in 79% of the examined replants but also in 24% of the uninjured contralateral fingers. These results support Backman and Lithell's view that vasospastic reactions in cold sensitive patients are highly unspecific [2, 11]. Raynaud's phenomenon was seen in 25% of our cases. Neither Raynaud's phenomenon nor experimental vasospastic reactions were more common in cold-sensitive replants compared with cold-insensitive digits in our investigation.

Capillary microscopy revealed unspecific changes in the capillary morphology of replanted fingers. The pattern resembled those often seen in primary Raynaud's syndrome, but there was no difference between cold sensitive and insensitive replants.

Meuli-Simmen et al. [12] found subnormal resting flow conditions and significantly decreased vascular capacity in the replanted fingers using laser Doppler flowmetry and capillary microscopy. Besides capillary microscopy with laser Doppler anemometry, we also performed color-coded HRUS for the microvascular assessment. HRUS is able to visualize av-anastomoses (Hoyer–Grosser organs) in the fingertips, which play a major role in skin thermoregulation. We found a significant reduction in skin vessel density in the fingertips of cold-sensitive replanted fingers compared with non-sensitive replants. As these vessels and their av-anastomoese are important for thermoregulation of the skin, it is likely that reduced skin vessel density reflects a reduction of thermal modulation capacities of the skin in cold-sensitive replants. Reduced skin vessel density was not related to the extent of reconstruction of nerves, arteries and veins.

Our findings correspond with former results of Piza and Lassmann [9, 16]. Neurohistologic investigation of autotransplanted rabbit ears depicted a significant reduction of newly formed nerve plexus, which were hardly attached to the vascular wall [9, 16]. Thus, one might speculate that defects in the restoration of the vascular nerve plexus might reduce the number of functionally active av-anastomoses consecutively inducing cold intolerance of transplanted digits. Unfortunately, only a minority of our patients underwent electrophysiologic examination for exact characterization of nerve function in the replanted fingers not allowing us to correlate electrophysiologic data with vessel density in the replanted fingers.

In conclusion, our results do not confirm the hypothesis that cold sensitivity after finger replantations is caused by macrovascular problems nor do they confirm assumptions of a primary capillary microcirculatory failure. Our findings of diminished skin vessel density suggest reduced thermal modulation capacities in the fingertips of cold-sensitive replanted digits.

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