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ORIGINAL ARTICLE

Laser Doppler imaging of skin microcirculation under fiber-reinforced composite framework of facial prosthesis

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Abstract

Objective. Glass-fiber reinforced composite has been suggested to be used as framework material in silicone elastomer facial prostheses. The glass-fiber reinforced framework makes it possible to make the margin of the prosthesis very tight, so that it will lean tightly against the skin even during facial expressions and jaw movements. The purpose of this study was to study how the compression of the glass-fiber reinforced framework would affect the microcirculation of the facial skin. ***Materials and methods.*** A face mask, with a compression pad corresponding to the outer margin of a glass fiber-reinforced composite framework beam of a facial prosthesis, was used to apply pressure on the facial skin of healthy volunteers. The skin blood flow during touch, light and moderate compression of the skin was measured by laser Doppler imaging technique. ***Results.*** None of the compressions had any marked effects on local skin blood flow. No significant differences between the blood flow of the compressed skin, compared to the baseline values, were found. ***Conclusions.*** The pressure applied to the skin by the tight margins of a facial prosthesis, fabricated with a framework of glass-fiber reinforced composite, does not remarkably alter the skin blood flow.

Key Words: *Facial prosthesis, blood flow, compression*

Introduction

Developmental anomalies (or disfigurements of the facial structures due to tumor surgery) are often rehabilitated by facial prostheses [1–3]. The purpose of the prosthetic rehabilitation is to, as naturally as possible; replace the missing tissue and organ. With a naturally looking, retentive and comfortable facial prosthesis, the patient has the possibility to live a normal, social life and the quality-of-life is enhanced [4,5]. The conventional materials used in facial prostheses are polymethylmetacrylate, as a base, and skin-like maxillofacial silicone elastomer as surface-material [6–10]. The base material, polymethylmetacrylate, makes the prosthesis rather heavy and it is stiff and hard against the resected facial tissues [11,12]. The stiffness leads to an inadequate fit of the margins of the prosthesis, especially during facial expressions and jaw movements.

Glass fiber-reinforced composite has, since the late 1990s, been used in fixed dental prostheses, as reinforcement of the acrylic baseplate of removable dentures, as endodontic posts and recently also as reinforcement in dental composite filling-material [13–18]. Glass fiber-reinforced composite has also been suggested to be used as a framework-reinforcement of the silicone elastomer in facial prostheses. The glass fiber-framework is light in weight, it is flexible—to a certain extent—and it is easy to repair when the margins of the prosthesis have to be tightened [19].

If the margins of the facial prostheses lean tight—even with a light pressure—against the soft tissue of

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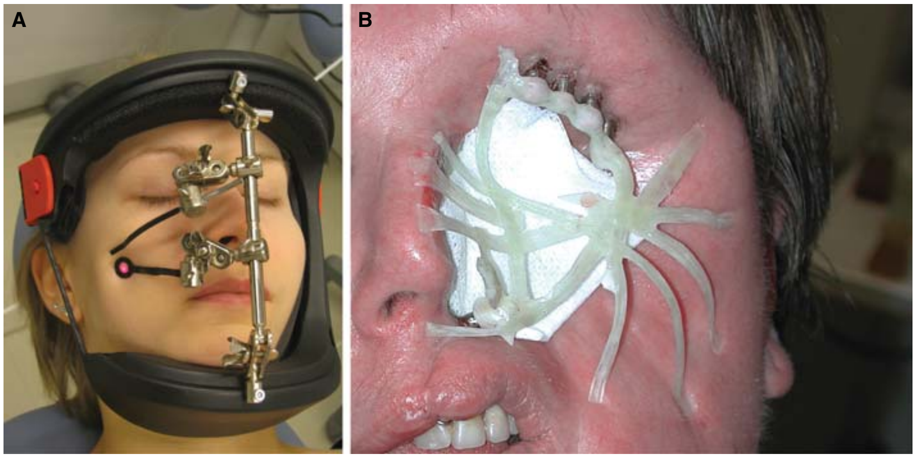

Figure 1. (A) Face mask used to measure the blood flow during different amounts of compression of the skin. (B) Corresponding glass fiber-reinforced composite framework for facial prosthesis.

the face, it is possible that the prosthesis will affect the blood microcirculation of the skin surface. In acute, long-term and home-care populations pressure ulcers (also called decubitus ulcers, bedsores, pressure sores) are a general and frequent problem. Pressure ulcers range from a reddening of the skin to severe, deep crater ulcers with exposed muscle or bone. A pressure ulcer usually develops over a bony prominence as a result of prolonged, localized pressure combined with frictional and shear forces [20]. The etiology of pressure ulcers is considered as multifactorial, of which the main factors seem to be the intensity and duration of applied pressure on the skin; high pressure over a short period or less pressure over a longer period [21,22].

In this study, the microcirculation of the facial skin is registered by laser Doppler imaging (LDI) technique, which has been commonly used for the assessment of tissue blood flow perfusion in a number of studies. Experimental studies in humans have shown that LDI is a valid and non-traumatic method for monitoring blood flow perfusion of the healthy skin [23–31] and oral mucosa [32]. Additionally, LDI has been used to study the vascular aspects of rheumatologic disease, as in systemic sclerosis and Raynaud's phenomenon [33–35]. Clinical applications of the LDI technique have been used in monitoring blood flow in surgical flaps [31,36,37] and to assess blood perfusion as a sign of healing in ischemic wounds [38,39] and burn wounds [40–44].

The purpose of this study was to investigate the bio-physiological suitability of a newly developed glass fiber-reinforced composite framework as reinforcement of the silicone elastomer in facial prostheses. This was done by monitoring the possible changes in the local facial skin blood flow levels due to compression forces, large enough to maintain a good margin accuracy of our new facial prostheses. A face mask was fabricated to resemble the compressive margins of a tightly fitting facial prosthesis. The hypothesis was that the face mask does not significantly alter the local skin blood flow perfusion.

Materials and methods

Subjects

Ten healthy, non-smoking and medication-free young students were enrolled in the study (age range 23–25 years). Each subject provided written consent prior to the experiments, in accordance with the ethics guidelines of the World Medical Association Declaration of Helsinki (version 2005). The ethics committee of the Hospital District of Southwest Finland approved the study protocol (26/180/2011).

Face mask

A face mask (Figure 1A) mimicking the outer margin of the glass fiber-reinforced composite framework of a silicone elastomer facial prosthesis was fabricated of dimethacrylate resin impregnated glass fiber-rovings (everStick C&B; StickTech, Turku, Finland). The face mask was designed to enable the use of the laser Doppler imaging technique for measuring the skin microcirculation close to a pad and it was designed to correspond to one of the peripheral endings of the skin compressing fiber-extensions that are used in fiber-reinforced composite frameworks supporting the silicone elastomer in facial prostheses (Figure 1B). The polymer matrix of the fiber-reinforced composite consisted of a semi-interpenetrating polymer network of pBisGMA-pTEGDMA-PMMA polymers with a fiber loading of 60 wt%. The fiber rovings were attached to each other using StickResin resin (StickTech, Turku) and polymerized using a light curing device (Optilux 180; Kerr Corp, Orange, CA). A continuous unidirectional fiber-reinforced composite cantilever beam with the span length of 43.0 mm and a

Figure 2. Scanning areas of the skin, with respect to the position of the pad.

cross-sectional size of 1.0 × 4.0 mm^2 was used to compress the skin by a maximal deflection of 4–5 mm, causing a load of 0.45–0.47 N at the outer extension pad. The fiber-reinforced composite extension beam was painted black in order not to reflect the laser beam of the LDI. The outer extension pad was made as a ring, 12 mm in diameter, with a 6 mm hole designed to enable the measurement of the skin blood flow within the hole and at the area outside the margins of the extension pad (Figure 1A).

LDI technique

The skin blood flow was measured by a Laser Doppler perfusion Imager (Moor Instruments, Wilmington. DE). A low power (2 mV) He-Ne laser beam/light (wavelength 632 nm) was directed at the subject's cheek through a computer-controlled optical scanner, placed ~ 30 cm above the subject's face. The skin area was scanned by moving the laser beam step by step over a 3.9 × 3.9 cm area (100 × 100 pixels) at a selected region of the subject's cheek. The moving red blood cells in the microvessels of the skin were detected as a fraction of the Doppler-shifted light (a shift in frequency of the light waves) and converted into an electrical signal. The software program of the LDI (Moor Instruments Software version 5.1) processed an output signal, which was linearly related to the tissue perfusion. The perfusion values were generated and presented as color-coded images on a monitor. The actual applied compression forces used in this study were measured with the Lloyd XLC Loadcell-device (Lloyd LR30K Plus; Metek inc., Largo, FL). The compression force was calculated from three measurements. The mean compression force at a moderate compression of the skin (C measurement) was 0.45 N (4 mm compression)–0.47 N (5 mm compression), corresponding to a force of ~ 5.5 kPa.

Course of the study

Before starting the measurements, each subject was resting in a supine position in a dental chair for 10 min, to acclimatize to the situation and to the room temperature of 23°C. The experimental session lasted 45 min for each subject. All measurements were done with the subject lying in the dental unit chair. The LDI blood flow determination session consisted of 12 scans, ~ 1 min each, and was performed as follows: before the positioning of the face mask, six baseline LDI measurements were performed, each measurement lasted ~ 1 min, followed by a 2 min break. With the face mask, three scans were done with the extension pad: the first scan (A) as the pad was touching the subject's skin without compression, the second (B) with a light compression of the skin and the third one (C) with a moderate compression of the skin (compressing the skin 4–5 mm). Immediately after this last compression, the compression extension pad was released from the skin and three more scans were done. The heart rate (HR) and blood pressure (BP) of each subject were measured (Omron digital blood pressure monitor, HEM-705C; Osaka, Japan) and registered from the left upper arm between every second LDI measurement.

Data analysis and statistics

A mean value of the six baseline measurements, performed before the application of the face mask, was calculated and used as a baseline value. The perfusion values were calculated inside the ring and at three different areas (100 × 100 pixels) outside the ring (Figure 2). The differences between the six baseline measurements, performed before the application of the face mask, were examined with the Friedman test for several related samples. Since there were no statistically significant differences between the baseline measurements, a mean value of those values was calculated for each subject and used as a baseline value. The perfusion values during 'touch' (A), light compression (B) and moderate compression (C) of the skin were all separately compared to the baseline value of the corresponding area.

Likewise, after the compression pad was removed, the return of the perfusion was compared to the baseline value. The statistical significances between the perfusion values determined before, during and after the compression, were calculated by means of paired samples *t*-test using statistical software (SPSS 19.0; SPSS Inc., Chicago, IL).

Table I. Mean values (SD) of the baseline perfusion values inside the ring (R) and at areas 1, 2 and 3 ($n = 10$) (p-values based on Friedman test for several related samples).

Area	Measurement 1	Measurement 2	Measurement 3	Measurement 4	Measurement 5	Measurement 6	p
R	163.6 (75.0)	185.3 (86.3)	178.0 (89.8)	175.0 (87.4)	169.9 (79.2)	179.8 (89.3)	0.232
1	174.7 (91.7)	179.1 (78.1)	188.4 (97.9)	181.1 (80.2)	173.4 (73.5)	170.9 (72.2)	0.782
2	171.1 (91.5)	187.5 (88.2)	189.5 (106.4)	188.6 (95.8)	189.3 (93.0)	179.9 (83.8)	0.874
3	154.0 (78.1)	171.0 (68.0)	157.0 (86.5)	156.1 (82.3)	143.7 (87.3)	128.3 (52.9)	0.092

Results

There were no statistically significant differences between the six baseline measurements in any of the measurement sites. The mean (n = 10) values of skin blood perfusion at the baseline are presented in Table I. Figure 3 shows a typical example of the blood perfusion response to the pressure: a short lasting tendency to blood flow increase inside the skin compressive ring and a slight tendency to blood flow decrease outside the ring was detected. When the compression ceased, the blood flow returned to the baseline values very quickly—that means, no reperfusion reactions, such as post-vasodilatation or post-vasoconstriction were seen. None of the compressions (touch, light or moderate compression) had any marked effects on the local skin blood flow in any of the measurement sites. No significant differences between the blood flow of the compressed skin, comparing to the baseline values, were found. However, inside the ring of the 'pad', (R), the perfusion tended to increase during compression; the greater the compression was, the greater was the perfusion. Outside the ring, the compression seemed to have the opposite effect: the perfusion tended to be smaller during compression than at the baseline (Table II).

Discussion

The current results show that the compression forces mimicking the compression of the tight fitting margin of the glass fiber-reinforced composite framework of a novel facial prostheses did not induce marked blood flow changes in the healthy facial skin, as documented by Laser Doppler imaging (LDI) in healthy human subjects.

Although, being an indirect measure, LDI has earlier proved to be a reliable method for documentation of orofacial blood flow changes [32,45]. The skin blood flow of different sites of the human body varies greatly, for example, the skin microcirculation of the face, fingers, palms and ears is significantly higher than the perfusion of the trunk and extremities [46,47]. In the present study the LDI technique was applied to investigate the effect of different compression forces on facial skin blood flow in healthy human volunteers. The current results showed that the spatial differences between separate orofacial measurement sites were small and that facial skin compression caused a short lasting blood flow decrease only in the close vicinity of the compressed area. These results emphasize the usefulness and validity of LDI technique also in clarifying spatial and temporal

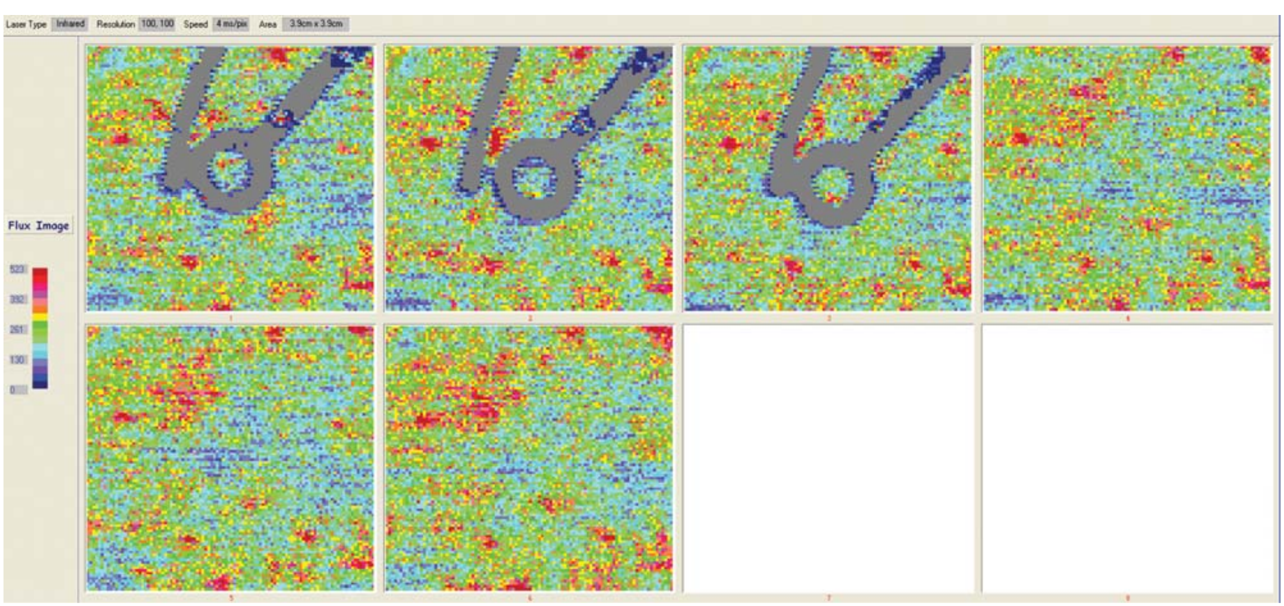

Figure 3. LDI scans of one subject. Blood flow is seen as color coded images. Blue color means a low perfusion, green-to-yellow indicates a mid-range perfusion and red indicates a high blood flow.

Table II. Return perfusion mean values (SD) over all subjects (*n* = 10), compared to baseline, after compression of the skin.

Area	Baseline Perfusion	Touch (A)	Light Compression (B)	Compression (C)	Return 1	Return 2	Return 3
R	175.3 (81.6)	182.8 (95.6)	195.9 (146.8)	208.8 (46.5)	174.7 (61.8)	164.7 (55.8)	168.1 (63.5)
1	179.4 (79.4)	167.7 (75.2)	165.7 (73.7)	161.7 (53.6)	171.8 (68.4)	169.8 (62.0)	170.8 (72.1)
2	185.8 (91.3)	183.2 (82.7)	172.7 (80.6)	173.7 (69.0)	172.6 (84.4)	175.2 (72.1)	173.6 (86.5)
3	155.7 (78.7)	158.7 (68.7)	144.7 (69.8)	146.4 (68.1)	154.7 (70.9)	175.3 (81.3)	169.7 (92.8)

features of compression-evoked vasoactive blood flow changes on the facial skin.

Pressure-evoked harmful effects on tissue health or even pressure ulcers are a frequent problem, especially among older patients in long-term care. Although the pathogenesis is multifactorial and complicated, local ischemia and tissue damage are most likely the major etiologic factors for these detrimental pressure effects [48–50]. The exact critical amount of pressure to develop tissue damage is still not known, but the external pressure must be greater than the arterial capillary pressure to lead to inflow impairment. In early findings it was proposed that 'critical compressive pressure' might be 4.27 kPa (32 mmHg) [51]. Later studies have indicated that experimentally applied pressure of 5.3 kPa [52] and 6.47 kPa [53] can lead to significant skin blood flow decrease of the sacral area and on top of the ankle-bone, respectively. It is known, that the effect of external pressure on skin is highest on bony prominences, where the underlying, hard bone naturally enhances the pressure effect. The highest compression force tested in this study was calculated to be 5.5 kPa, which did not induce any marked flow decrease on the compressed or neighbouring facial skin area, as documented by LDI. This is understandable, as in this study the compression was targeted on soft, resilient facial skin on young individuals with only partly directly underlying bone. In fact, when compared to a clinical situation, a pressure compressing the skin 4–5 mm corresponds to an extremely tight, fiber-reinforced framework extension at the margin of a silicone elastomer facial prosthesis and, correspondingly, the applied 'light' compression in this study resembles the clinical situation of a more natural and tightly fitting prosthesis' margin. As the peripheral end of the fiber-bundle is designed to 'actively' compress the skin, in order to keep the margins of the prosthesis tightly in place during jaw movements and facial expressions, the compression is the highest at these end points (beams) of the fiber-reinforced composite framework. This compression could be estimated to be ~ 2–3 kPa. Because the rest of the margins of the prosthesis are made of soft, resilient maxillofacial silicone elastomer, the pressure of these silicone margins will be much smaller than that of the harder end points of the fiber-reinforced composite framework. Also, if the margins of the prosthesis are made to slightly compress the skin in the outer regions of the defect and the prosthesis is retained by implants in this kind of facial prosthesis the rest of the prosthesis' surface does not have to apply pressure to the rest of the tissue surface in order to be stable and to possess well-fitting margins.

Interestingly, in a recent study Van-Buendia et al. [54] used the same LDI technique as in this study, studying facial skin blood flow through a transparent face mask to diminish burn scar development. In their study the pressure of the mask was applied for a long period of time and with compression forces that were high enough to give a blanched appearance to the skin area susceptible for scar formation. The mask reduced scar development without any harmful after effects [54]. In our study even the strongest compression force did not induce marked skin blood flow changes or reperfusion neither under the compression pad nor at any of the other skin areas near the compression site. In the light of these findings it seems that the bio-suitability of our new lightweight fiber-reinforced composite framework is good and could be safely used in facial prostheses in long-term use.

It is known that aging alters skin blood flow. For example, it has been documented that cellular aging influences the microvasculature and leads to decreased perfusion, increased capillary fragility and reduction of dermal nutritional vessels [55–57]. Also photoaging or aging as a result of exposure to UV radiation over a prolonged period may lead to a gradual decrease in number and size of dermal vessels [58]. Radiation treatment usually leads to acute increases in skin blood flow, but the long-term effects of radiotherapy on skin microcirculation are not very well known [59–61].

Silicone elastomer facial prostheses with acrylic base material are often considered to be uncomfortable, heavy and with 'unsecure' margins. The main advantages of this novel glass fiber-reinforced composite framework are that it is light in weight (~ $^1/_4$ of the weight of a prosthesis made with acrylic base), which means that the friction and the compression on the underlying tissue surface is considerably smaller than with a rigid acrylic baseplate and that it can be designed with tight, more 'secure' margins, as it is possible to design the margins of the silicone elastomer prosthesis to slightly compress the surrounding tissue. It is also easier to repair, in case the silicone margins have to be tightened or loosened: the beams of the fiber-reinforced composite framework can be cut off and new parts of fiber-bundles can be attached to the old ones. Since patients who are using facial prostheses usually are of an older age and often have received radiation therapy, it is important that the prosthesis itself is as non-irritating as possible and has a minimal effect on tissue blood flow perfusion. The results of the present study suggest that our novel facial prosthesis could very well meet these needs.

The test subjects in the present study were healthy, young adults. This means that the subjects do not quite correspond to the clinical situation, as most of the patients who need facial prostheses, due to resective surgery, are older persons. Also, the compression time of the skin was rather short. The face mask was designed to enable the use of laser Doppler imaging technique for measuring the skin microcirculation close to a pad and it was designed to correspond to the peripheral endings of those skin compressing fiber-extensions used in fiber-reinforced composite frameworks supporting the silicone elastomer in facial prostheses. The mask did not, of course, completely correspond to an actual facial prosthesis. Our purpose was to study the effect of moderate compression, which resembles the pressure of a tightly fitting prosthesis margin, on the local facial skin blood flow. The results of this study do show that further similar studies on older subjects, with tissue blood flow compromising factors and with longer compression periods, should be carried out and could be safely performed.

This study shows that the pressure applied to the skin by a face mask, corresponding to a prostheses fabricated with a glass fiber-reinforced composite framework with margins laying very tight against the skin, did not give rise to any considerable changes in the blood circulation of facial skin. That means, while it does not alter the perfusion of the skin, there should not be a risk of developing pressure ulcers. However, caution should still be taken in older subjects, especially those who have received high doses of radiation as cancer treatment.

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Declaration of interest: Pekka Vallittu consults Stick Tech Ltd, and he is a member of GC group in training and research. The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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