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# USE OF FIBER-REINFORCED COMPOSITE FRAMEWORK AND THERMOCHROMIC PIGMENT IN FACIAL PROSTHESES

by

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*Yes, there is goal and meaning in our path,*
*but it´s the way that is the labour´s worth.*

*Karin Boye*

***To my Family***

# ABSTRACT

**Rosita Kantola**

**Use of fiber-reinforced composite framework and thermochromic pigment in maxillofacial prostheses.**

Department of Biomaterials Science, Institute of Dentistry, University of Turku. Annales Universitatis Turkuensis, Turku, Finland 2014

The purpose of this investigation was to evaluate the possibility to enhance certain qualities of facial prostheses. Polymethyl methacrylate is still being used as base material or clip carrier material, but it is hard and heavy, and debonding of the silicone from the acrylic base material is a frequent problem. This thesis aims to evaluate the use of fiber-reinforced composite (FRC) as framework material for maxillofacial silicone prostheses. FRC has been used as reinforcement in removable and fixed partial dentures since the 1990s. This material is lightweight and can be fabricated to compress the margins of the prosthesis slightly, to keep it tightly against the skin during jaw movements and facial expressions. Additionally, the use of a thermochromic pigment, colorless in room temperature and red in a cold environment, was studied in order to evaluate the possibility of using this color changing pigment in facial prostheses to mimic the color change of facial skin in cold weather.

The tensile bond strength between pre-impregnated, unidirectional FRC and maxillofacial silicone elastomer was studied. Three different bonding agents or primers were compared. Bond strength was improved by one of the primers and by roughening the surface. The effect of a skin compressing glass fiber-reinforced composite framework on facial skin blood flow was studied by using a face mask, constructed with a compression pad corresponding to the outer margin of a glass fiber-reinforced framework beam of a facial prosthesis. The skin blood flow of ten healthy volunteers, aged 23-25 years, was measured during touch, light, and moderate compression of the skin, by using laser Doppler imaging technique. None of the compressions showed any marked effects on local skin blood flow. There were no significant differences between blood flow during compression and at baseline.

Maxillofacial silicone elastomer was colored intrinsically with conventional color pigments: a control group containing only conventional pigments was compared to two test groups with 0.2 wt% and 0.6 wt% thermochromic pigment added. The color of the material was measured with a spectrophotometer in room temperature and after storage in a freezer. The color stability of the maxillofacial silicone elastomer colored with thermochromic pigment was evaluated by artificial aging. The color difference of the L* (lightness) and a* values (redness), comparing color after the samples were stored at room temperature and in a freezer (-19°C), was statistically significant for both 0.2 wt% and 0.6 wt% thermochromic pigment groups. The differences in the b* values (yellowness) were statistically significant for the 0.6 wt% group. Exposure to ultraviolet (UV) radiation led to visually noticeable and statistically significant color changes ($\Delta E$) in all color values in both test groups. The specimens containing thermochromic pigment were very sensitive to UV radiation.

In conclusion, a framework of fiber-reinforced composite can successfully be bonded to maxillofacial silicone elastomer, and a framework beam, compressing the facial skin, did not remarkably alter the skin blood flow on healthy, young adults. The thermochromic pigment showed color change in maxillofacial silicone elastomer. However, artificial aging showed that it was too sensitive to UV radiation to be used, as such, in maxillofacial prostheses.

**Key words:** facial prostheses, glass fiber-reinforced composite framework, maxillofacial silicone elastomer, tensile bond strength, facial skin blood flow, thermochromic pigment.

# TIIVISTELMÄ

**Rosita Kantola**

**Lasikuitukomposiittirungon ja termokromisen pigmentin käyttö kasvoproteeseissa**

Biomateriaalitiede, Hammaslääketieteen laitos, Turun yliopisto.
Annales Universitatis Turkuensis, Turku, Suomi 2014

Tämän väitöskirjatyön tarkoitus oli selvittää, onko mahdollista parantaa kasvoproteesien tiettyjä ominaisuuksia. Lasikuiduilla vahvistettua komposiittimuovia on käytetty vahvistamaan siltoja ja irrotettavia proteeseja 1990-luvulta saakka, ja tämä materiaali voisi olla huomattavasti miellyttävämpi, kevyempi ja teknisesti helppokäyttöisempi kasvoproteesirunkomateriaali kuin tähän asti käytetty polymetyylimetakrylaatti. Lasikuiturunkoa voidaan muotoilla siten, että se kevyesti painaa proteesin ulkoreunoja kasvojen ihoa vasten, jolloin proteesin reuna pysyy tiiviisti kasvojen ihossa kiinni leuan ja kasvolihasten liikkeiden aikana, mikä parantaa kasvo-proteesin käyttövarmuutta ja -mukavuutta. Tutkimuksessa selvitettiin myös mahdollisuutta käyttää termokromista - huoneenlämmössä läpinäkyvää ja kylmässä punaista – reversiibelisti väriä muuttavaa pigmenttiä kasvoproteesisilikonissa. Keinotekoisella vanhenemisella tutkittiin, soveltuisiko tämä pigmentti kliiniseen käyttöön.

Työssä testattiin kolmen eri primerin ja kahden eri pintaominaisuuden (sileä ja karhennettu) vaikutusta kasvoproteesisilikonin ja lasikuiduilla vahvistetun komposiittimuovin väliseen sidoslujuuteen. Sekä primeri että lasikuidulla vahvistetun komposiittimuovin makroskooppinen pintarakenne vaikutti sidoslujuuteen. Karhennetulla lasikuitupinnalla ja yhdellä primerillä saavutettiin paras sidoslujuus.

Lasikuiturungon aiheuttaman paineen vaikutusta kasvojen ihon verenkiertoon tutkittiin kasvomaskilla, joka oli valmistettu vastaamaan kasvoproteesin lasikuiturungon ihoa komprimoivaa uloketta. Laser Doppler Imaging (LDI) tekniikkaa käyttäen tutkittiin kevyen kosketuksen, kevyen ja keskinkertaisen paineen aiheuttamaa mahdollista muutosta kasvojen ihon verenkiertoon terveillä, 23-25 vuotiailla koehenkilöillä. Kasvomaskin aiheuttama kompressio ei merkittävästi vaikuttanut kasvojen ihon verenkiertoon.

Termokromista pigmenttiä sekoitettiin ihonväriseen kasvoproteesisilikoniin pitoisuuksissa 0,2 ja 0,6 paino%. Kontrolliryhmänä toimi ihonvärinen silikoni ilman termokromista pigmenttiä. Silikonin väri mitattiin spektrofotometrillä huoneenlämmössä ja kylmäsäilytyksen (-19°C) jälkeen. Väriarvoissa L*(vaaleus) ja a* (punaisuus) todettiin merkitsevä ero molemmissa ryhmissä jotka sisälsivät termokromista pigmenttiä, ja b* -arvossa (keltaisuus) ainoastaan 0,6% ryhmässä. Keinotekoinen vanheneminen ultravioletti (UV) -sädetystä ja inkubaattorisäilytystä käyttäen osoitti että termokrominen pigmentti on erittäin herkkä UV valolle.

Yteenvetona voidaan todeta, että lasikuiturungon ja kasvoproteesisilikonin sidoslujuus on riittävän hyvä kliiniseen käyttöön kasvoproteeseissa. Kasvoproteesirungon lasikuitu-ulokkeet eivät vähennä ihon verenkiertoa terveillä aikuisilla. UV säteilyherkkyyden vuoksi termokrominen pigmentti ei sellaisenaan sovellu kliiniseen käyttöön kasvoproteeseissa.

**Avainsanat:** kasvoproteesit, lasikuiturunko, kasvoproteesisilikoni, sidoslujuus, kasvojen ihon verenkierto, termokrominen pigmentti.

# SAMMANFATTNING

Rosita Kantola

**Användning av glasfiberkompositstomme och termokromiskt pigment i ansiktsproteser**

Odontologiska institutionen, Åbo universitet, Finland. Annales Universitatis Turkuensis 2014

Studiens syfte var att utvärdera möjligheten att förbättra särskilda egenskaper hos ansiktsproteser. Glasfiberförstärkt komposit har använts som förstärkning i intraorala avtagbara proteser och broar sedan 1990-talet, och kunde vara ett avsevärt lättare och bekvämare material än polymetylmetakrylat, som hittills använts. En stomme tillverkad av glasfiberförstärkt komposit kan formas så att den till en viss grad blir elastisk och den kan med ett lätt tryck komprimera proteskanterna mot huden för att få bättre kantanslutning under käkrörelser och mimiska rörelser. Man ville även utreda om ett termokromiskt pigment, färglöst i rumstemperatur och rött i kyla, kunde användas i ansiktsprotessilikon och om detta även kunde fungera i kliniskt bruk, där materialet utsätts för fukt, värme och solljus.

Bindningen mellan silikon och preimpregnerad glasfiberkomposit undersöktes genom att testa bindningens draghållfasthet. Tre olika primers och två olika ytegenskaper jämfördes. Bindningsstyrkan förbättrades med en primer samt genom att preparera glasfiberkompositens yta.

Med hjälp av en ansiktsmask, motsvarande perifera extensionen av en ansiktsprotesstomme tillverkad av fiberförstärkt komposit, undersöktes om stommens tryck mot ansiktets hud kunde hämma hudens blodcirkulation. Inverkan av lätt beröring samt lätt och moderat kompression av huden undersöktes på friska, unga personer med hjälp LDI (Laser Doppler Imaging) teknik. Kompressionen hade ingen signifikant inverkan på blodcirkulationen.

Termokromiskt pigment i koncentrationen 0,2 respektive 0,6 vikt% blandades i hudfärgad ansiktsprotessilikon och jämfördes med konventionellt pigmenterad, hudfärgad silikon. Färgen mättes med en spektrofotometer i rumstemperatur samt efter förvaring i -19°C. En statistiskt signifikant förändring i L*(ljushet) och a*(rödhet) värdena kunde iakttas i båda grupperna innehållande termokromiskt pigment, medan förändringen i b* värdet (gulhet) var statistiskt signifikant endast i gruppen innehållande 0,6% termokromiskt pigment. Bestrålning med ultraviolett (UV) ljus visade att silikonet som innehöll termokromiskt pigment var mycket känsligt för UV strålning.

Sammanfattningsvis kan konstateras att bindningen mellan en glasfiberkompositstomme och ansiktsprotessilikon är tillräckligt stark för kliniskt bruk i ansiktsproteser. Stommens perifera fiberextensioner reducerar inte hudens blodcirkulation hos unga, friska individer. Det termokromiska pigmentet är alltför känsligt för UV ljus för att användas i ansiktsproteser.

**Nyckelord:** ansiktsproteser, glasfiberförstärkt kompositstomme, ansiktsprotessilikon, bindningsstyrka, hudens blodcirkulation i ansiktet, termokromiskt pigment.

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# ABBREVIATIONS

| | |
|---|---|
| ASTM | American Standard for Testing and Materials |
| AVA | arteriovenous anastomoses |
| FRC | fiber-reinforced composite |
| HTV | heat temperature vulcanized |
| IPN | interpenetrating polymer network |
| LC | liquid crystals |
| LD | leuco dyes |
| LDF | laser Doppler flowmetry |
| LDI | laser Doppler imaging |
| LSCI | laser speckle contrast imaging |
| OPS | orthogonal polarization spectral imaging |
| PMMA | polymethyl methacrylate |
| RTV | room temperature vulcanized |
| SEM | scanning electron microscopy |
| SDF | sidestream dark field imaging |

# LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following original publications, which are referred to in the text by the Roman numerals *I – V*.

I. **Kurunmäki H, Kantola R, Hatamleh MM, Watts DC, Vallittu PK.** A fiber-reinforced composite prosthesis restoring a lateral midfacial defect. A clinical report. *J Prosthet Dent 2008;100:348-352.*

II. **Kantola R, Lassila L, Vallittu P.** Adhesion of maxillofacial silicone elastomer to a fiber-reinforced composite resin framework. *Int J Prosthodont 2011;24:582-588.*

III. **Kantola RM, Kurunmäki H, Vallittu PK, Lassila LVJ.** Use of thermochromic pigment in maxillofacial silicone elastomer. *J Prosthet Dent 2013;110:320-325.*

IV. **Kantola R, Lassila LVJ, Tolvanen M, Vallittu PK.** Color stability of thermochromic pigment in maxillofacial silicone. *J Adv Prosthodont 2013;5:75-83.*

V. **Kantola R, Sivén M, Kurunmäki H, Tolvanen M, Vallittu PK, Kemppainen P.** Laser Doppler imaging of skin microcirculation under fiber-reinforced composite framework of facial prosthesis. *Acta Odont Scand 2013; Jul 4 Epub ahead of print.*

# 1. INTRODUCTION

The face is the most visible and noticeable part of the body. It plays a crucial part in communication, expresses emotions, and provides vital access routes to the respiratory and gastrointestinal systems. The facial region also contains the source of senses like taste, smell, vision and hearing. Therefore, it is understandable that any facial disfigurement can lead to both physical and psychosocial problems. Missing portions of the face, such as loss of an eye, ear, the nose, full or partial loss of the jaw bone or other head and neck structures, need to be rehabilitated in order to restore appearance and function, and to enhance patient´s quality of life. As patients with facial disfigurements or injuries are a challenge to rehabilitate, a multidisciplinary team is required for optimal treatment and functional outcome (van Oort et al. 1994, Lemon et al. 2005, Hubalkova 2010).

The development of materials used to fabricate facial prostheses has emerged from historical materials like leather, wood, waxes and metals to polymers, such as acrylates and silicone elastomers. Currently, silicone elastomers are still the most commonly used materials, also in combination with polymethyl methacrylate as the base or clip carrier material (Heller and McKinstry 1995, Lai et al. 2002, Aziz et al. 2003, Beumer et al. 2011). In clinical service, the life span of a facial prosthesis is still very short, on average 1,5 to 2 years, which is an extremely short time period, considering the costs and amount of clinical work the fabrication of a facial prosthesis requires. The most common reasons for remaking a facial prosthesis are discoloration of the silicone elastomer and debonding of the silicone from the acrylic base material (Visser et al. 2008).

Coloration of a facial prosthesis is done either intrinsically or extrinsically, or both. The early prosthetic materials required external coloration and characterisation with paints, but the introduction of polymers, along with their fabrication process, made it possible to use intrinsic coloration techniques with different color pigments and pigment suspensions (Gary and Smith 1998, Seelaus and Troppmann 2000). Skin color is dependent on both individual, genetic factors, and environmental factors, such as temperature. This is due to the thermoregulation of the skin, which regulates the temperature of the skin by vasodilatation and vasoconstriction of the blood vessels. When the arteriovenous anastomoses (AVAs) of the ear lobes and the nose vasodilate, the skin color changes to red as the AVAs warm up the skin in a cold external environment

(Midttun and Sejrsen 1996, Braverman 2000). Thermochromic (color changing) pigments are used in everyday products, such as thermometers, indicators of overheating machine parts, and in the food industry (Ogrodnik 2008, Seeboth and Lötzsch 2008). A reversible, thermochromic pigment would enhance the natural appearance of a facial prosthesis, mimicking the color change of the ears and nose in cold weather, provided that the pigment is suitable for intrinsic coloring of the maxillofacial silicone.

The use of osseointegrated implants in the facial region provided a vast improvement for the retention and stability of facial prostheses. The stability enhances both the functional and the aesthetic qualities of the prosthesis (Eckert and Desjardins 1998, Leonardi et al. 2008). However, the thin edge of the silicone margin of the prosthesis is susceptible to ruptures and does not always lie tightly against the skin during facial expressions and jaw movements and, therefore, it is still not aesthetically ideal.

Since the 1990s, glass fiber-reinforced composites (FRCs) have been in clinical use in dental appliances, such as intraoral removable and fixed prostheses and recently also as reinforcement in composite filling material (Vallittu 1999, Rantala et al. 2003, Garoushi et al. 2007a,b, van Heumen et al. 2010).

Preimpregnated glass FRC fibers are commercially available in different modifications, and could possibly provide an alternative to polymethyl methacrylate as a base or framework of facial prostheses. Polymethyl methacrylate is stiff, heavy, and uncomfortable against the skin (Andreapoulos and Theopanides 1993). An FRC framework can be constructed with extensions, which are used to support the thin edges of the silicone at the margins of the prosthesis. It can also be designed to compress the skin slightly at the margins of the prosthesis, in order to enhance the marginal fit during facial expressions and jaw movements. However, because the chemical nature of the maxillofacial silicone elastomer and glass FRC is different, bonding of a glass fiber-reinforced framework to the silicone elastomer might be problematic. Also, the compression of the FRC framework extensions on facial skin might impair the microcirculation of the facial skin and can, therefore, be a risk factor for the development of pressure ulcers.

The aim of this series of studies was to evaluate the possibility of using glass fiber-reinforced composite frameworks to support the silicone of facial prostheses and, additionally, to evaluate the suitability of a thermochromic pigment to be used in a maxillofacial silicone elastomer.

# 2. LITERATURE REVIEW

## 2.1 Extraoral maxillofacial prostheses

### *2.1.1 Indications for maxillofacial prostheses*

Acquired conditions, such as defects due to tumor surgery of head and neck cancer, trauma or burn injury, and congenital defects are the most common reasons for maxillofacial rehabilitation. Examples of congenital conditions include underdeveloped or missing outer ear/ears, and hemifacial microsomia.

Depending on the location and size of the defect, the defect can be restored either surgically or prosthetically. Reconstructive and microvascular surgery are the preferred treatments for many cancer and trauma patients, but the availability of tissues and radiation–induced changes of the tissue may limit the surgical procedures. Surgical reconstructions of facial defects are technically demanding and the reconstruction of a nose or an ear usually requires several operations to achieve an aesthetically pleasing result (Ariani et al. 2013). There will always be a need for extraoral maxillofacial prostheses. In cases when reconstructive surgery is not possible, a maxillofacial prosthesis is used as a substitute for missing biologic structures, in order to rehabilitate the facial structure to restore normal appearance. As the prosthesis restores the normal anatomy, it also protects the tissue of the defect and provides psychological benefits for the patient (Flood and Russell 1998, Huber and Studer 2002, Wallace and Wei 2008, Beumer et al. 2011, Mantri and Khan 2012).

### *2.1.2 Retention of maxillofacial prostheses*

The retention method for the maxillofacial prostheses depends on the individual case requirements, with respect to the location and size of the defect, resilience and possible undercuts of adjacent tissue, and the weight of the fabricated maxillofacial prosthesis (Chalian et al. 1972 a,b).

Anatomical factors, such as undercuts and concavities, may be used as retention. The interior of the surgical defect may be used to retain the prosthesis. Caution should be taken with irradiated tissue, as the abrasion of the prosthesis may cause ulceration. Traditionally, mechanical retention by attaching maxillofacial prosthesis to eyeglasses, headbands or straps, has been used. Adhesives are

used, in some cases, to retain the prosthesis. They are simple to use, and they are available in two common forms: liquid (silicone or acrylic based) or as double sided tape. The adhesive retention methods are limited as movement of the surrounding skin, oily skin or humidity might loosen the margins from the adjacent tissue. Good prosthesis hygiene is required, and still, the adhesive may irritate the skin or cause allergic reactions. The adhesives also require special removers (Lemon et al. 2005, Mantri and Khan 2012).

Osseointegrated implants are used to improve the retention and stability of facial prostheses (Parel and Tjellström 1991, Watson et al. 1995, Arcuri and Rubinstein 1998, Wolfaardt et al. 1998, Hooper et al. 2005, Leonardi et al. 2008, Ethunandan et al. 2010). The first titanium implants were placed for fixation of prosthetic ears, noses and eyes in 1979 (Leonardi et al. 2008). They provide the most reliable form of retention for maxillofacial prostheses and function as a stable platform for fixation of the prosthesis. Good retention enhances the function of the prosthesis, as good marginal fit makes the thin margins less visible, improves the accuracy and enhances the aesthetic qualities of the prosthesis. Most implants used as retention for maxillofacial prostheses are cylindrical titanium implants, which are mechanically anchored in the bone. A two-step surgery is usually required. During the first surgery, the implants are inserted into the bone. After 4-6 months of osseointegration, the abutments are attached to the implants. The prosthesis can be "clipped" to precision attachments, such as bars or magnets, used as retentive elements (Mantri and Khan 2012).

Usually, three or four implants are required for defects of the midface, while one or two implants are used for auricular prostheses. There are specially designed craniofacial implants for the mastoid temporal bone (Jakobsson et al. 1992, Jensen et al. 1992, Heller and McKinstry 1995, Eckert and Desjardins 2000, Wolfaardt et al. 2003, Goiato et al. 2012). For a nasal prosthesis, the preferred site for placement of implants is the maxilla region and the anterior floor of the nose (Carr 1998). A simple ocular prosthesis replaces only the contents of the orbita, when the eyelids are still intact, while an orbital excenteration defect is more challenging to restore. The implants for rehabilitation of a larger defect are generally placed at the supraorbital rim or at the lateral rim of the orbit, because of the poorer bone quality and quantity medially (Nishimura et al. 1998).

## 2.2 Materials used for maxillofacial prostheses

A successful facial prosthesis should simultaneously possess many different qualities: it should be durable, biocompatible, flexible, lightweight, and have

a natural appearance by remaining unnoticed and recreating the lost facial structures. The material must have good processing characteristics, as well as good mechanical and performance characteristics, and it should ensure good patient-accommodation properties. This means, it should be soft enough to adapt to facial structures, but still have high tear strength, high durability and dimensional stability. It should also be resistant to chemicals and environmental factors, be light in weight, have a skin-like texture and feel lifelike, but still be hygienic in use. The material should be non-toxic and non-allergenic. No material has all of these ideal properties, although several materials possess many good qualities (Chalian et al. 1972a, Sweeney et al. 1972, Lontz 1990).

### *2.2.1 Historical materials*

Various materials have been used to reconstruct missing facial parts. Historically, extraoral prostheses were fabricated of cloth or leather. Auricular, nasal and ocular prostheses have been found in Egyptian mummies. Chinese are said to have used natural waxes and resins to fabricate nasal and auricular prostheses (Bulbullian 1945). The first described facial prostheses in the medical literature are presented in a textbook from 1575 by the French surgeon Ambrose Pare´. He described nasal prostheses made of silver, auricular prostheses made of papier-mache´or leather, and ocular prostheses retained by a metal band passing around the patient´s head (Heller and McKinstry 1995, Beumer et al. 2011).

In the 19$^{th}$ century, metals such as gold and silver, as well as ceramic materials and wood, were used to create prostheses (Chalian 1979, Heller and McKinstry 1995). The case of a 22 year old soldier, Monsieur Alphonse Louis, who received severe facial trauma during the siege of Antwerp in 1832, is well documented. Monsieur Louis lost almost the entire mandible when he was hit by shrapnel from an exploding shell. The French dental surgeon Dr Forget fabricated a silver mask with the help of a plaster cast. The mask was painted with oils and a moustache and side-whiskers were added (Kaufman et al. 1997). In a report by Upham (1901), the fabrication of nasal and auricular prostheses from vulcanite rubber was described. This material was, at that time, widely used for intraoral prostheses (Beumer et al. 2011).

During World War I, the French government organized caring for the wounded soldiers in cooperation with the American Red Cross. An American sculptress named Anna Coleman Ladd, working at “The Red Cross Studio for Portrait Masks” in Paris, created facial masks for facially mutilated soldiers. With the help of photographs, taken before the injury, and by making a mold of the face,

she created portrait masks of pure copper, covered with silver. The portrait mask covered the deformity, and was fixed to glasses or with a ribbon behind the head (Romm and Zacher 1982). During World War I, a material based on gelatin and glycerine, called elastine, was used to fabricate facial prostheses for patients injured in the war. Because of water absorption, this material lasted only for seven or eight days, and the patients themselves were taught to make their own prostheses (Romm and Zacher 1982, Heller and McKinstry 1995).

Prevulcanized latex was introduced as material for maxillofacial prostheses between World War I and World War II. This material was lightweight and easy to process. However, in the early 1940s, acrylic resin replaced vulcanized rubber, due to better processing and physical properties (Heller and McKinstry 1995). As an attempt towards more flexible materials, polyvinylchloride was used for a period starting from the mid-1940s. This stiff polymer had to be plasticized for use in maxillofacial applications. The processing procedure was difficult and the material yellowed as a result of exposure to ultraviolet light (Craig et al. 1980, Heller and McKinstry 1995).

The currently available facial prosthetic materials are divided into methacrylate or acrylic resins, polyurethane elastomers, and silicone elastomers. Today most maxillofacial prostheses are made of medical grade silicone elastomer (silicone rubber) (Heller and McKinstry 1995, Beumer et al. 2011).

### *2.2.2 Methacrylates (acrylic resins)*

Acrylic resins have been used in dental practice for artificial, removable dentures since the 1930s. They replaced the use of vulcanite in both intraoral and extraoral prostheses because of their better properties. Acrylic resin is translucent and easy to color both intrinsically and extrinsically. It is also easy to process and is relatively hard, but durable (Lemon et al. 2005).

Oils or other plasticizers can be added to produce copolymers, which are used as flexible polymethacrylates in maxillofacial prosthodontics (Huber and Studer 2002). Soft polyacrylates are used as soft liners or tissue conditioners on removable dentures, but they are mechanically weak and harden in a short time and are not suited to be used as permanent material in maxillofacial prostheses. Polymethyl methacrylate (Fig 1) can be plasticized with butylacrylate and methyl methacrylamide, to be used as synthetic latex (acrylic latex). However, because of the time-consuming fabrication and the short durability of the material (3-4 months) this material is not suitable for facial prostheses (Lontz 1990).

Hard polymethacrylates are still commonly used in dentures and in orthodontic appliances. In facial prostheses, acrylic resins are used for fabrication of prosthetic eyes in ocular or orbital prostheses, and for frameworks, as a base material or clip carrier material in silicone maxillofacial prostheses (Lemon et al. 2005). Provisional facial prostheses can be fabricated of acrylic resin, as this is easy to modify after tissue changes, such as those due to repetitive surgery. After surgery, the acrylic prosthesis can be temporarily lined with soft tissue liners. Heat-polymerized acrylic is more tissue-friendly, containing no unpolymerized tertiary amines, and, therefore, it is preferred over autopolymerized acrylic (Lontz 1990).

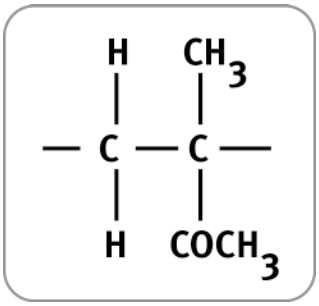


**Fig 1.** Repeat units of polymethyl methacrylate.

### 2.2.3 *Silicone elastomers*

Silicone rubber was introduced in the 1940s (Abdelnnabi et al. 1984, Andres 1992). It is easy to process, and it possesses many good qualities. Medical use of silicone elastomer began in 1953 and it was first used for external prostheses in 1960 by Barnhart (Begum et al. 2011). A great variety of maxillofacial silicone products has been developed since the 1960s. It is still the most commonly used material for fabricating the surface of, or entire, facial prostheses (Heller and McKinstry 1995, Huber and Studer 2002, Montgomery and Kiat-amnuay 2010, Beumer et al. 2011).

Silicones used for maxillofacial prostheses are room-temperature vulcanizing polymers based on polydimethylsiloxane (Fig 2). The maxillofacial silicone elastomer additionally contains surface-treated silica powder as a filler material, a functional polymer as a crosslinker, a catalyst and pigments. The viscosity of the silicone elastomer is determined by the length of the polymer. In *condensation-type polysiloxanes*, the cross-linking is carried out by condensation of hydroxyl groups (Si-OH), using stannous octoate as the catalyst. In *addition-type polysiloxanes*, the addition of silane groups (Si-H) (hydro-methylsiloxane) to silicone vinyl-units leads to compounds which process lower shrinkage and

better dimensional stability. In this reaction, platinum compounds (chloroplatinic acid) serve as catalysts (Andreapoulos and Theopanides 1993).

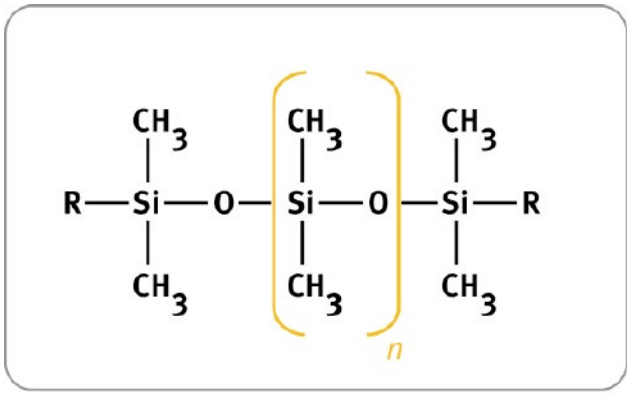


**Fig 2.** Polydimethylsiloxane-chain. A long chain makes the material elastic.

A network is formed when the polymer chains are cross-linked at various points. The network makes it difficult to separate the chains mechanically and makes it less likely to degrade from aging and environmental factors (Huber and Studer 2002). Room temperature vulcanizing (RTV) silicones have been preferred because of their easy fabricating process. Stone molds can be used, and even if the polymerization reaction occurs at room temperature, the process can be accelerated at higher temperatures (Lewis and Castleberry 1980). Heat temperature vulcanizing (HTV) silicones are generally stronger, tougher and stiffer, but the fabrication is more complicated as the material requires a milling machine and metal molds during fabrication (Bell 1985, Lewis and Castleberry 1980, Lontz 1990).

During the 1970s, several attempts were made to develop both the maxillofacial products based on silicone elastomers, and to create methods to test the properties of the maxillofacial materials (Sweeney et al. 1972, Moore et al. 1977). In 1987, Udagama suggested the combination of a thin polyurethane sheet bonded to silicone, in order to improve the strength of the margin of the prosthesis (Udagama 1982).

Commercially available maxillofacial silicone elastomers, examples presented in Table 1, have been widely studied with respect to mechanical properties such as tensile strength, tear strength, tensile modulus (elasticity), hardness and elongation (Moore et al. 1977, Yu and Koran 1979, Yu et al. 1980, Abdelnabi et al. 1984, Bell et al. 1985, Wolfaardt 1985, Farah et al. 1987, Polyzois et al. 1992, Sanchez et al. 1992, Mohite et al. 1994, Polyzois et al. 2000, Lai et al. 2002, Aziz et al. 2003, Hatamleh and Watts 2010a, Begum et al. 2011). Different testing methods and conditions have been used to investigate the physical properties of

the silicone elastomers and this makes it difficult to compare the studies to each other. The properties of the maxillofacial silicone elastomers have improved. However, none of the commercially available maxillofacial silicones possess ideal properties, but their mechanical properties are considered adequate.

The color stability with respect to aging and environmental factors, such as ultraviolet light, has also been thoroughly studied (Craig et al. 1978, Andres et al. 1992, Haug et al.1992, Mohite et al. 1994, Beatty et al. 1995, Lemon et al. 1995, Haug et al. 1999b, Hulterström and Ruyter 1999). A silicone facial prosthesis has to be remade every 1.5 – 2 years, most often due to discoloration (Visser et al. 2008, Hatamleh et al. 2010).

**Table 1.** Examples of brands of maxillofacial silicone elastomers.

| Maxillofacial silicone | Manufacturer | Type of silicone | Ingredients: elastomer/curing agent | Fabrication | Coloration |
|---|---|---|---|---|---|
| Silastic MDX4-4210 | Dow Corning Corp., Midland, Mich | Pourable, two-component, RTV, addition silicone | Polydimethylsiloxane, silica, platinum catalyst/ dimethylsiloxane polymer, inhibitor, crosslinker | In stone molds at room temperature; curing can be acceleratedat higher temperatures | Intrinsic and extrinsic |
| A-2186 | Factor II Inc., Lakeside, Ariz | - " - | - " - | - " - | - " - |
| Medical Adhesive Type A | Dow Corning | The silane molecules are hydrolyzed by water; requires moisture to cure. RTV | Hydroxyl-terminated polydimethylsiloxane which is being pre-mixed with crosslinker triacetoxysilane. | Requires no mold, has a long curing time. | Only extrinsic coloration of the surface. |
| Cosmesil Standard M511 (1982- ) | Principality Medical, Newport, UK | Two-component, RTV, addittion silicone | Polydimethylsiloxane, silica, platinum catalyst/ dimethylsiloxane polymer, crosslinker. | 24 hrs at room temperature or 1 h at 100°C. | Intrinsic and extrinsic |
| Cosmesil High Compliance (1993- ) | - " - | Two-component, RTV, addition silicone | Polydimethylsiloxanes are crosslinked via an addition reaction: silyl groups (SiH-) to vinyl groups. | 24 hrs at room temperature or 1 h at 100°C. | |
| Premium Facial and Body Elastomer | Prestige Dental, Bradford, UK. | Two-component addition silicone. | | 2 hrs at 100°C. | |
| TechSil S25 | Principality Medical | | Platinum-cure silicone. | | |

Attempts to enhance certain properties often result in a decrease of other desirable properties (Andreopoulos and Theopanides 1993, Huber and Studer 2002, Hooper et al. 2005). One still non-desired property is that silicone rubber is unmodifiable, which means that the whole prosthesis has to be remade due to possible changes of the underlying tissue, which may occur due to the results of healing, radiation therapy or further surgery. Silica or other fillers are added to increase the tensile strength, but the fillers may give rise to a loss of translucency. Other main disadvantages of silicone elastomers are low tear and edge strength, relatively low elongation, problems with color stability (Craig et al. 1978, Koran et al. 1979, Lemon et al. 1995, Beatty et al. 1999, Haug et al. 1999b, Hulterström and Ruyter 1999, Polyzois 1999, Kiat-amnuay et al. 2002, Huber and Studer 2002, Kiat-amnuay et al. 2006, Visser et al. 2008, Hatamleh and Watts 2011a) and the potential to support bacterial or fungal growth (Heller and McKinstry 1995, Beumer et al. 2011, Ariani et al. 2012). The discoloration and degradation of the maxillofacial silicone may be associated with a microbial biofilm, consisting of yeast and bacteria species, on the skin opposing surface of the facial prosthesis (Pigno et al. 1994, Donlan 2001, Heller and McKinstry 1995, Beumer et al. 1996, Ariani et al. 2012). According to a study by Ariani et al. (2012), degradation of the surface of facial prostheses was present at the areas of the prostheses which were in contact with the facial tissues. Pores within the maxillofacial silicone may serve as colonization sites on the prosthesis surface in contact with the skin, and pore entrapment may reduce the color stability of the prosthesis (Hatamleh and Watts 2011a).

### 2.2.4 *Polyurethane and chlorinated polyethylene*

Polymers, such as polyurethane and chlorinated polyethylene (CPE), have been studied and suggested as materials for facial prostheses as they have many useful properties. They are commonly used in several everyday products.

*Polyurethane* consists of a hard segment of an extended di-isocyanate and a soft segment of polyols, and the polymerization process is performed at room temperature with an organotin catalyst. The proportion of these segments determines the softness of the end-product. The elastomer type of polyurethane has been used as material in maxillofacial prostheses (Gonzalez 1978). The iso-cyanate component is toxic and it is very sensitive to moisture during the fabricating process. The presence of moisture can lead to bubbles and incomplete curing of the material (Chalian 1979). Cured polyurethane contains isocyanate in a bound and nontoxic form, but it is possible that remnants of the free, toxic isocyanate component may also be present in cured material. The polyurethane composition used in maxillofacial prosthetics has been found

to be toxic to human tissue cells (Huber and Studer 2002). As the material is also more susceptible to degradation both in the presence of ultraviolet light and environmental metabolites, when compared to silicone, it has not been as popular for facial prostheses (Andres 1992, Andreapoulos and Theophanides 1993, Mohite et al. 1994).

*Chlorinated polyethylene* has some advantages compared to silicone elastomer: it is possible to repair, reline or recondition - factors which may extend the lifetime of the prosthesis. It is also much less expensive than silicone rubber, has greater edge strength and does not support fungus growth. However, the fabrication of CPE prostheses requires high temperatures and metal molds, which complicates the fabrication process (Gettleman et al. 1989 and 2008, Gettleman 1992, Lemon et al. 2005, Kiat-amnuay et al. 2010). The coloration has to be done with oil-soluble dyes by using a laminating technique, with layers of pigmented and unpigmented material. To enhance color stability, the colored external layer of the prosthesis is protected by an unpigmented layer (Gettleman 1992). According to Gettleman et al. (1989), chlorinated polyethylene is suitable for making thin feather edges of the prosthesis, or to simulate cartilage while silicone elastomer is more suitable for fabricating soft facial prostheses. More recent studies have shown that aging, due to exposure to ultraviolet radiation, sebum and perspiration, leads to considerable changes in the physical properties of chlorinated polyethylene, probably due to cross-linking reactions within the material (Eleni et al. 2009).

### *2.2.5 Fiber-reinforced composite (FRC)*

Glass fibers were introduced by Smith in the 1960s for use as reinforcement of polymethyl methacrylate denture base material (Smith 1962). At that time, appropriate and clinically usable resin systems for dental use were not available (Smith 1962, Vallittu 2013). Other suggested fibers for reinforcement of dental materials have been Kevlar fibers (Berrong et al. 1990), carbon fibers (Bowman and Manley 1984) and plasma-etched ultra-high-modulus polyethylene fibers (Braden et a1. 1988, Gutteridge 1992, Ladizesky et al. 1992, Vallittu 1997) or polyethylene woven fabric (Cheng and Chow 1999). Carbon/graphite fibers are limited in use because of their black color, and polyethylene fibers don´t have the ability to bond to the resin matrix as strongly as glass fibers (Schreiber 1971, Gutteridge 1992, Braden et al. 1998).

Glass fiber-reinforced composite (glass-FRC) has been used as reinforcement in removable intraoral prostheses, either as reinforcement of the entire prosthesis

base or only at the weakest part of the prosthesis (Vallittu 1999, Narva et al. 2005), in orthodontic retainers and periodontal splints (Sewón et al. 2000, Rantala et al. 2003, Kirzioglu and Erturk 2004, Ohtonen et al. 2013), in endodontic posts (Lassila et al. 2004), in fixed dental prostheses (bridges) (Meiers et al. 1998, Rosentritt et al. 2000, Meiers and Freilich 2001, Behr et al. 2003, van Heumen et al. 2010), in implant-supported removable and fixed prostheses (Duncan et al. 2000, Behr et al. 2001, Freilich et al. 2002) and in reconstruction of bone defects (Vallittu et al. 1999, Brown 2000, Tuusa et al. 2007). Composite restorative filling material has been reinforced with short glass fibers (Garoushi et al. 2007a,b, and 2011, Jie et al. 2013). Some recent studies suggest the use of FRCs as implants (Ballo et al. 2009, Zhao et al. 2009, Aitasalo et al. 2013).

FRCs consist of reinforcing fibers embedded in a polymer matrix. FRCs are a heterogeneous group of materials where the components vary greatly, i.e. the nature of the fibers, the geometrical arrangement of them, and the polymer matrix. As the purpose of the fibers is to enhance the physical properties of the material, it is important that the fibers are well bonded to the resin matrix. Glass fibers are clinically accepted because of their ability to be silanized and adhered to the resin matrix. The most suitable fibers for this purpose are E- or S-glass fibers, which are durable and chemically stable (Vallittu 1993, Vallittu et al. 1994, Brown 2000, Norström et al. 2001, Vallittu 2013). The polymer matrix of the FRC protects and fixes the fibers at a certain geometrical arrangement; the fibers within the matrix may be oriented as rovings (continuous unidirectional), weaves (continuous bidirectional), mats (continuous random oriented) or as short, random oriented fibers (Butterworth et al. 2003, Vallittu 2013). The direction of the fibers influences the strength of the FRC. Continuous unidirectional FRCs is the most suitable fiber-orientation for dental appliances as it provides the highest strength and modulus of elasticity. Water absorption of the polymer matrix may reduce these properties (Lassila et al. 2002).

The surface of the commercially available glass fibers used in dentistry is either non-impregnated or pre-impregnated by the manufacturer. The pre-impregnated fibers are ready to be bonded to composite resin while the non-impregnated fibers require chairside impregnation. The wetting of the fibers is important to create a strong bond to the overlying resin. When resins are used to impregnate the fibers, a cross-linked, linear or multiphased polymer matrix is formed. The FRC used in dentistry has the structure of an interpenetrating polymer network (IPN) (Fig 3). It is a combination of two or more polymers in a network form: one cross-linked polymer and one linear polymer mixed together (Sperling 1994, Lastumäki et al. 2003). Dimethacrylate or multifunctional

monomers are functioning as cross-linkers while the non-cross-linked part of the polymer system consists of monofunctional MMA (Vallittu 2009). The different kinds of polymer matrices possess different properties: for example, a FRC with a cross-linked polymer matrix has a high modulus of elasticity while the linear (=thermoplastic) and semi-IPN polymer matrices are tougher and show good handling properties in clinical use, such as bonding the FRC to luting cements or composites (Vallittu 2013).

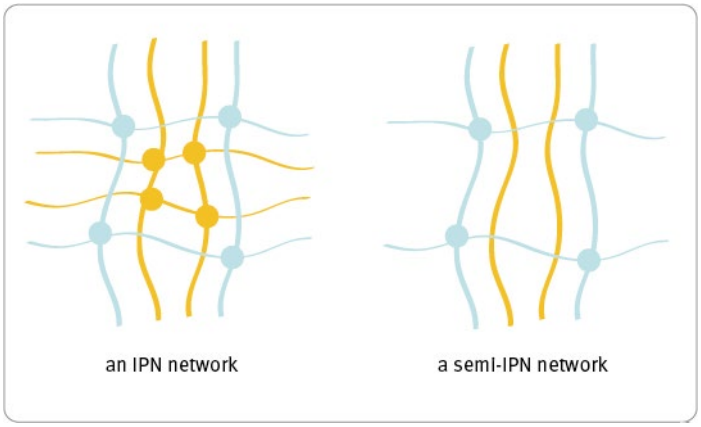


**Fig 3.** Schematic structure of IPN and semi-IPN polymer network.

### 2.2.6 *Coloring agents and pigments*

A maxillofacial prosthesis is characterized and colored with dry pigments, pigment suspensions, dyes or pastes to match the color of adjacent facial structures. The prosthesis should also possess a certain translucency to obtain a lifelike appearance. Rayon flock, thread or yarn, can be added to achieve a realistic skin appearance and texture. Most maxillofacial silicones can be colored easily using different coloring techniques. The maxillofacial prosthesis is colored either internally or externally (Lontz 1990, Andres et al. 1992, Heller and McKinstry 1995, Seelaus and Troppmann 2000, Leow et al. 2002). It is important that the silicone elastomer accepts and retains the coloration, and that potential environmental factors do not change the appearance or strength of the prosthesis (Lewis and Castleberry 1980).

A color pigment acts as a solid filler, which does not bond to the silicone. It is a finely divided colored substance that does not dissolve, but remains dispersed, when mixed or ground in a liquid vehicle. Dyes dissolve in liquid and give their color effect by staining the material (McLaren 1986). Inorganic pigments are usually metal oxides while organic pigments are carbon hydrogen derivates of

animal, vegetable or synthetic origin. The term *inorganic* may also indicate that the pigment is of mineral origin. The pigments are usually classified according to their major component element (Mayer 1991). Some pigments are almost chemically pure, simple compounds, while others contain minor elements added during manufacturing, to modify the color, or as natural impurities (McLaren 1986).

Silicone elastomers, as used in maxillofacial prostheses, are transparent to UV radiation and are also permeable to moisture and many gases. This means that any pigment, although the silicone is intrinsically colored, is exposed and susceptible to degradation. External pigments may also dissolve during cleaning the prostheses (Gary and Smith 1998). The ASTM (American Society for Testing and Materials) has created standards intended to identify materials and their degree of purity and permanence. There are different standardised test methods for testing the lightfastness of pigments, and the pigments are classified in lightfastness categories I-IV. ASTM has developed a list of pigments according to their color index names (ASTM, Standard terminology of appearance). According to studies on pigments used in maxillofacial elastomers, it is concluded that RTV silicone elastomers and pigments show color changes and that the color change of a maxillofacial prosthesis is to be expected due to the outdoor atmosphere, solar radiation, humidity, temperature, cleaning agents and disinfectants (Craig et al. 1978, Koran et al. 1979, Haug et al. 1992, Beatty et al. 1995 and 1999, Lemon et al. 1995, Hulterström and Ruyter 1999, Polyzois 1999, Gary et al. 2001, Leow et al. 2002, Kiat-amnuay et al. 2002 and 2006, Dos Santos et al. 2010, Goiato et al. 2011). Especially in silicone hand prostheses and maxillofacial prostheses, the color stability of the pigments is crucial. Over time, a change towards a darker and more yellowish shade of the silicone is common (Leow et al. 2002). Generally, pure inorganic pigments are more color stable than impure inorganic pigments, organic pigments and dyes. According to several studies, certain red, orange-yellow and yellow pigments seem to be the least color stable among the dry pigments (Koran et al. 1979, Beatty et al. 1995, Kiat-amnuay et al. 2002). It has also been found that non-pigmented, clear silicone elastomer itself changes color during the ageing process (Beatty et al. 1995, Polyzois 1999, Gary 2001). UV absorbers, such as opacifiers and certain nano-oxides, can be used to enhance the color stability of maxillofacial silicone elastomer and may be a future solution to enhance color stability (Li et al. 2002, Kiat-amnuay et al. 2009, Han et al. 2010). The addition of nano-oxides of titanium, zinc and cesium may also enhance the mechanical properties of maxillofacial silicone elastomer (Han et al. 2008).

## 2.3 Bonding of the silicone elastomer to the substrate of the framework

Polymers adhere to each other through mechanical interlocking (micromechanical retention), chemical bonding (ionic or covalent bonds), interaction of dispersion forces (van der Waals forces) or the formation of an interpenetrating polymer network (IPN) at their interface. Micromechanical retention is made by roughening the surface by air-borne-particle abrasion (sandblasting) or etching the surface in order to enlarge the surface to be bonded. This is used when it is not possible to bond two substrates by chemical adhesion. The strongest chemical bonds between atoms are ionic or covalent bonds. Ionic bonds are formed between atoms with different electronegativity while covalent bonds form between non-metallic atoms, such as carbon atoms. Molecules of the substrate and the adhesive adhere to each other with weak dispersion forces if the molecules are non-polar. Polar molecules are held together with dipole-dipole bonds. The strongest chemical bond between molecules is the hydrogen bridge, which is formed between a hydrogen atom and an electronegative non-metal atom (Marshall et al. 2010).

The chemical affinity between two substrates depends on the composition of the materials. In maxillofacial prosthodontics, adhesive primers act as a "chemical intermediate component" between the silicone elastomer and the base material. The primer contains both hydrophilic and hydrophobic groups which react with the functional groups of the bonding substrates. The primer also increases the wettability of the substrate surface as it impregnates the surface layer. A solvent may enhance this property of the primer. When two polymers are to be bonded to each other, a monomer (solvent) is needed to dissolve the surface of the polymer. An example of this type of adhesion is the bonding of IPNs to each other (Mutluay and Ruyter 2007, Hatamleh and Watts 2011b).

### *2.3.1 Polymethyl methacrylate*

Bonding of a silicone elastomer to polymethyl methacrylate (PMMA) means bonding of two materials with basic molecular differences to each other. To achieve sufficient bond strength for clinical use, the surfaces have to be prepared. For this purpose, primers have been developed (Polyzois et al. 1991, McMordie and King 1989). For the best result, the primer should be compatible to the respective silicone (Frangou et al. 2003). Studies concerning the bonding of maxillofacial silicone to acrylic resin have shown that mechanical surface treatment, such as airborne-particle abrasion, may improve the adhesion between the silicone and acrylic resin (Usumez et al. 2004, Li and Zhao 2008).

There are several studies concerning the bonding of soft prosthetic lining materials to denture base materials, usually PMMA. The bond strength has been tested by using peel bond strength, shear bond strength and tensile bond strength. The results of all performed studies are not fully comparable, due to different test methods and the different designs of the samples (Emmer et al. 1995, Aydin et al. 1999, McCabe et al. 2002, Mutluay and Ruyter 2007). Generally, resilient acrylic-based lining materials create stronger bonds to the acrylic resin denture base than the silicone-based resilient lining materials. This is explained by differences in the chemical structure of the silicone elastomer as compared to PMMA (Wood et al. 1993). The bond strength between one soft lining and different acrylic denture resins can vary. The most durable bonds occurred when the acrylic resin surfaces were cured, roughened and treated with an adhesive (Kutay et al. 1994). Different bond strengths between the maxillofacial silicone elastomer and acrylic resin have been registered for primers with different chemical compositions. It is important that the primer possesses a good compatibility and affinity with the silicone elastomer and also bond well to the acrylic resin substrate (Frangou et al. 2003).

In a study by Haddad et al. (2012), bonding between auto-polymerized acrylic resin and facial silicone MDX4-4210 was investigated. The highest peel bond strength values were recorded for the samples prepared with Sofreliner Primer. Comparing the peel and shear-bond strengths of three maxillofacial silicone elastomers bonded to acrylic base materials using three different adhesive primers, both before and after accelerated artificial light-aging, maxillofacial silicone elastomer Cosmesil Z004 used with primer A330-G proved to be the best silicone/primer combination (Hatamleh and Watts 2010b). According to Polyzois and Frangou (2002), a condensation-type maxillofacial silicone showed higher bond strength when compared to an addition-type silicone, tested with three different acrylic resins.

### *2.3.2 Fiber-reinforced composite (FRC)*

FRC contains inorganic glass fibers, polymers (the resin matrix) and fillers. Both the fibers and the polymer matrix of the FRC participate in the bonding process. To bond an IPN, which consists of two or more polymers in network form, a solvent (monomer) is needed to dissolve the polymer. The glass and silica fibers have OH groups which can be silanized with methacrylate silanes. Silanes are bonding agents used to optimize the adhesion by improving the wettability between two materials. A silane usually contains two functioning parts: an

organic group which can attach to the resin and groups which are able to bond to the inorganic substrate (Sperling 1986, Vallittu 2009).

When a new resin or resin composite (resin luting cement or restorative composite) is being bonded to FRC during an ongoing polymerization process of the FRC matrix soon after curing, the adhesion of the polymer matrix to the filler is enhanced. The other main adhesion mechanism between FRC and another polymer is mechanical interlocking. The adhesional qualities of the fibers will be greater if the fibers are exposed on the bonding surface. Additionally, possible non-cross-linked polymer phases of the FRC matrix can adhere to monomers which diffuse from the resin which is to be bonded (Kallio et al. 2001, Lastumäki et al. 2003).

There are only a few studies concerning the adhesion of maxillofacial silicone to FRC. They show, however, that the adhesion between the maxillofacial silicone and FRC might be even stronger than the adhesion between the maxillofacial silicone and PMMA. In a study by Hatamleh and Watts, glass fiber-reinforcement in an acrylic matrix was found to have a stronger bond to a soft lining (Molloplast B) than non-reinforced smooth or rough acrylic surfaces. The mean bond strength between fiber-reinforced acrylic surface and soft silicone liner was 0.70 MPa (Hatamleh and Watts 2008a). In another study, Hatamleh and Watts reported that resin-impregnated glass fiber-bundles showed high bonding strength (pull out strength) to a maxillofacial silicone elastomer, when the fiber-bundles were embedded into the maxillofacial silicone elastomer. They drew the conclusion that the bond strength should be sufficient for clinical use in maxillofacial prostheses (Hatamleh and Watts 2008b).

## 2.4 Measurement of color

### *2.4.1 What is color?*

Light is a type of electromagnetic radiation. Visible light is in the wavelength range 380-780 nm- the wavelength detectable by the human eye and the brain. The perception of color consists of three elements: the illuminating light, the eye and the reflectance properties of the object. We perceive color with our visual nerves; it is what we see as a result of physical modification of light, observed by the eye and interpreted in the brain. The surface of the object absorbs or disperses part of the wavelengths of the light that strikes it, and the reflected wavelengths correspond to the perceived colors. Our perception of color is a result of the combination of the dominant wavelength of the color (the hue),

the intensity or saturation of the color (chroma), and its brightness or lightness (Fullerton et al. 1996, Billmeyer and Saltzman 1981).

The visual nerves register color in terms of its attributes: the amount of green or red, the amount of blue or yellow, and the brightness. These are the three dimensions which form the foundation for the brain to perceive color. The color attributes are opposites, like hot and cold; color nerves sense green or red and blue or yellow, but never both. The light-sensitive cells of the retina, called rods and cones, function as photoreceptors. There are approximately 6 million cones and 125 million rods in the retina of the human eye. They convert the light (photons) into electro-chemical signals, which are processed and transmitted via the ganglion cells to the brain. The cones are sensitive to brightness and different colors, while the rods are monochromatic- they perceive only black and white and are used only in dim light. There are three different kinds of cones, sensitive to short, medium and long wavelengths. They are active at high light levels and do not work well in low light. The retinal ganglion cells receive signals from many cones and by comparing the amount of response from different cones, the ganglion cell determines the color. The visible part of the spectrum consists of wavelengths between 380 and 750 nm (Table 2). Blue lies below 480 nm; green is roughly between 480 and 560 nm; yellow lies between 560 and 590 nm, orange between 590 and 630 nm and red lies over 630 nm (Billmeyer and Saltzman 1981, Wyszecki and Stiles 1982).

**Table 2.** The colors of the spectrum. Wavelengths between 380 and 700 (750) nm are visible for human eye.

| Color | Wavelength interval (nm) |
|---|---|
| Infrared | >1000 |
| **Red** | 635 - 700 |
| **Orange** | 590 - 630 |
| **Yellow** | 560 - 590 |
| **Green** | 480 - 560 |
| **Blue** | <480 |
| **Violet** | 420 |
| Near ultraviolet | 300 |
| Far ultraviolet | <200 |

As light strikes a material, it leads to reflection, transmission and absorption of the rays (Fig 4). The reflection of light can be regular, diffuse, or retro. Transmission can be regular or diffuse. The light that is neither reflected nor transmitted is absorbed. Theoretically, an absolute white object reflects every type of light while a black object absorbs every type of light. A red object

reflects only red light and absorbs all other colors. If a material is colorless and translucent, all the light, except for a small amount that is reflected, is transmitted through the material. Scattering of the light occurs when the object (material) has another refractive index than air; the refractive index describes how much light is slowed down in the material. A small amount of the light is reflected and the beam changes direction. Color pigments act as light scatterers within the material. If the refractive index of the pigment is different from that of the matrix, the pigment gives rise to scattering. Pigments of small particle size make the material look transparent as the amount of scattered light is small (Billmeyer and Saltzman 1981).

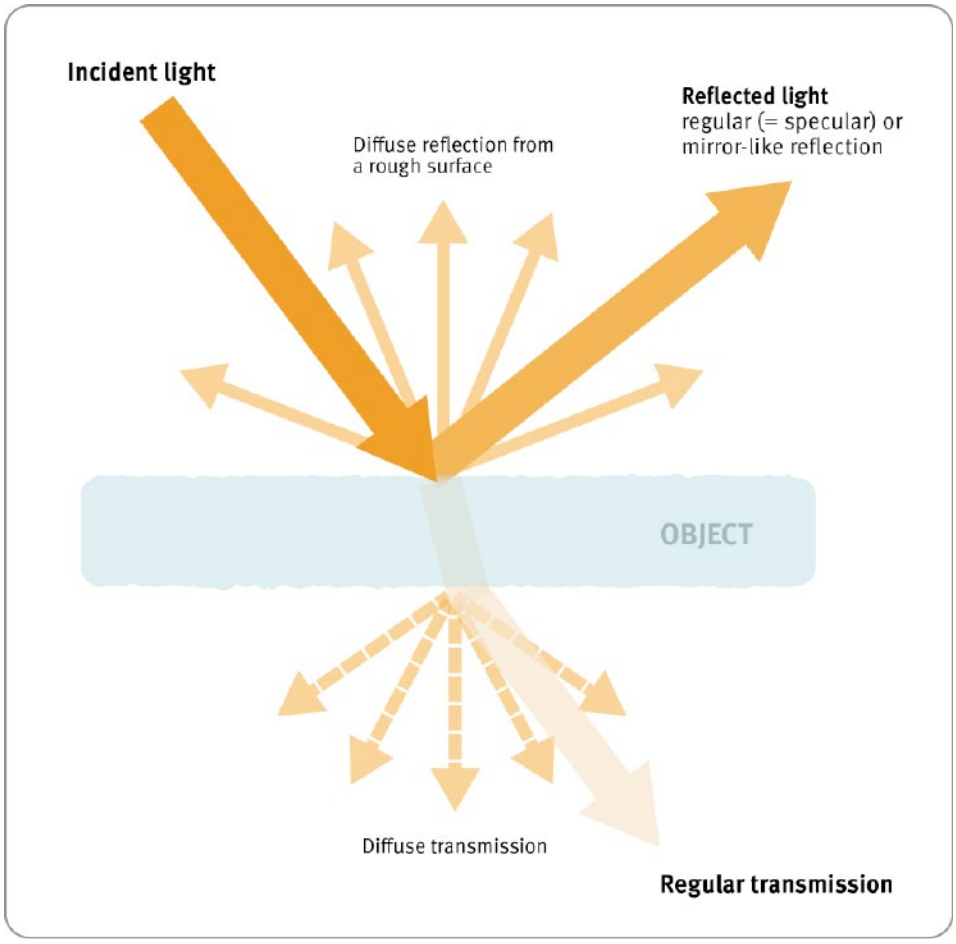


**Fig 4.** When light strikes an object, it is reflected, absorbed and transmitted. If the surface of the object is rough, the light is diffusely reflected and the reflected light is soft. If the object is transparent, with a clear surface, the light goes through the object without change in the quality or direction. When light goes through a transparent object with a textured surface, the light is redirected to many directions (diffuse transmission) (Modified from Billmeyer and Saltzmann 1981).

### 2.4.2 Color atlases

In color science, black, grey and white are said to be achromatic. The attribute of *hue* describes color sensations in their own right; such as red, blue, green, yellow, etc. These are chromatic colors. The *lightness* is the quality which describes how large fraction of light the area or object reflects. The term *saturation* means the same as the *intensity* or *purity* of the color. As early as 1611 a logical ordering of colors was discovered by Swedish monk and astrologer Forsius, who made a three-dimensional color order system. It was based on a central axis with black at the bottom and white at the top, with the hues arranged around this axis in a complete circle (McLaren 1986).

Later developed *color order systems* were built according to the same principle with a central, vertical achromatic axis while the other two variables are organized differently. The color order systems were developed for use in color science and color technology. Different color-order systems have usually been developed for specific purposes. One of the most well known color-order systems is the Munsell Color System, first published in 1915, which is based on principles of color perception. In the Munsell Color Tree material standards, painted color chips, are selected to represent hue, saturation, and lightness, spaced three dimensionally, in cylindrical coordinates, according to perceptions of an observer with normal color vision (Wyszecki and Stiles 1982, McLaren 1986).

### 2.4.3 The CIE system

Colors can be classified and specified according to a certain order, numerical values and color matching equations. The basis of this modern color measurement method emerged from studies on human color vision. As early as 1942, the CIE system was modified by Adams, as a consequence of studies on the color-vision theory. Later, this modification formed the basis for the 1976 CIE Lab-space, which gave the color space similar components as those of the human vision.

In 1976, the CIE (Commission Internationale de l´Eclairage) introduced the CIE color space ("CIELAB" or CIE 1976 $L^*a^*b^*$). The CIELAB color space is based on three dimensional coordinates with numerical values. $L^*$ stands for the lightness (brightness) of the color, where absolute black is given the numerical value 0 and white is 100. The chromaticity coordinate $a^*$ describes redness vs. greenness: a high + $a^*$ means redness while a high - $a^*$ means greenness. The chromaticity coordinate $b^*$ describes yellowness vs. blueness: a high + $b$ means yellowness, a high $-b^*$ means blueness (Fig 5).

The L*a*b* coordinates can be used to calculate color differences or color changes, by using the CIELAB color-difference equation: $\Delta E^* = [ (\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$ (Robertson 1977, CIE 2004). A trained human eye can detect a color change or color difference of $\Delta E$ greater than 1.0 (ASTM Int. Std practice for calcul. 2011).

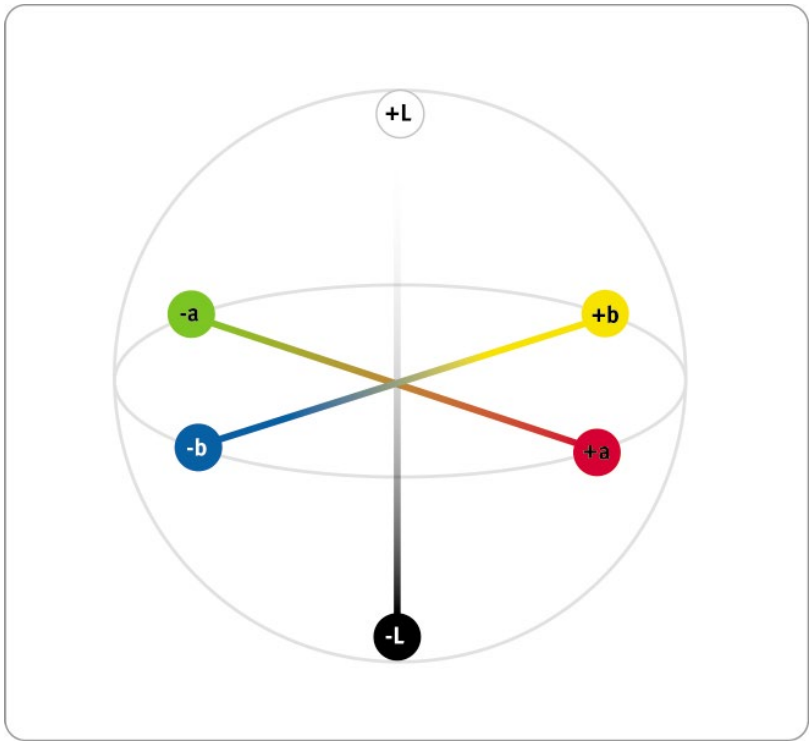


**Fig 5.** The three-dimensional Lab color space.

The CIELAB system is widely used in color science, where exact color measurement and matching is essential. It is used in many instruments for color measurements (Billmeyer and Saltzmann 1981, Wyszecki and Stiles 1982, McLaren 1986).

Additionally to the standard trichromatic system for the expression of color measurements, the CIE also defines how, and under which circumstances color should be measured. Standardized illuminants and standardized conditions for color measuring are described: the stimulus for color has to be provided by a certain, standardized source of light (Standard illuminant A, B, C or $D_{65}$), an object and a standard observer. Illuminant $D_{65}$, which represents average daylight with a correlated color temperature of 6500 K, has been widely used. According to the recommendation of CIE in 1931, the CIE Standard Observer should be representative of the average vision of the human population having normal color vision; the experiments were performed only using the fovea, which

covers only about a 2° angle of vision. In 1964, the CIE introduced the use of a recommended 10° standard observer. That means that the observer should use a 10° area of the retina of the eye. From the information of the object in question, using a CIE standard illuminant and one of the CIE standard observers, the CIE tristimulus values are calculated, giving the color an exact numerical value (Wright 1969, Billmeyer and Saltzmann 1981).

### *2.4.4 The spectrophotometer*

Color can be measured both visually and instrumentally. Visually, color is measured by examination and comparison of colored materials or objects, comparing the sample against a certain standard and under standardized lighting conditions.

There are three essential factors for perception and measurement:
- the spectral power distribution of the light source,
- the reflectance curve of the object,
- the response curve of the human observer or instrumental detector.

These factors explain the function of the *spectrophotometer,* which is the instrument used in studies dealing with color or color-changes (Billmeyer and Saltzmann 1981).

Spectrophotometry is the measurement of the spectral reflectance or transmittance curves of materials. The three fundamental components of the spectrophotometer are a radiation source, a monochromatic or polychromatic light and a photoelectric detector. Light from the source (a xenon arc or filtered tungsten-filament lamp which simulates daylight) illuminates the sample and the reflected light passes through a monochromator and falls on the detector. Alternatively, monochromatic radiation illuminates the sample directly, and the reflected light is collected and falls on the detector. The CIE recommends certain illumination and viewing directions of the sample, as well as certain light sources. "The spectrophotometer measures the amount of light reflected from the surface of an opaque specimen at a number of wavelengths throughout the visible spectrum as a fraction of that reflected by a white standard identically illuminated. This fraction is termed *the reflectance factor* (CIE definition)." The absolute standard is the perfect reflecting diffuser, whose reflectance at every wavelength is 100% (McLaren 1986).

Modern spectrophotometers usually have a hollow, white painted metal sphere, an *integrating sphere* which collects all the light reflected from the sample placed against an opening in its side. The light reflected from a glossy sample (a "mirror")

is either included or excluded ("specular component" included or excluded). The detector or the light source is being placed to view or illuminate the inside of the spheres as the sample is either viewed or illuminated through a second port. For translucent samples, the integrating sphere is the only suitable option**.** A microprocessor collects, stores, and processes the obtained data. It multiplies, wavelength by wavelength, the spectral reflectance of the sample, the relative spectral power of the illuminant and the tristimulus values of the spectrum colors which define the CIE standard observer. The microprocessor uses the acquired data and converts it into desired color spaces, such as the *L*a*b** color space. The spectrophotometers possess a very high precision: repeated measurements give the same results with high statistical precision. The spectrophotometer should always be calibrated according to the manufacturer´s instructions before conducting color measurements (Billmeyer and Saltzmann 1981, McLaren 1986).

Today, spectrophotometry can be used in combination with computerized color formulation technology (Seelaus et al. 2010).

## 2.5 Chromism and thermochromism

*Chromism* is a process that leads to a change in the colors of certain compounds. The change is usually reversible. External stimuli, which transfer energy, give rise to an alteration in the density of the electron state of the molecules. The energy is selectively absorbed, and the subsequent reflection of light in different wavelengths is seen as a color change. Temperature, light irradiation, polarity of solvents, gain or loss of electrons, ion exchange, mechanical pressure or friction, and moisture are examples of energy transferring stimuli. *Thermochromism* is defined as the ability of a substance to change color due to a change in temperature. There are different kinds of thermochromic pigments: liquid crystals, metal oxides or polymer based pigments. Thermochromic materials most commonly used for commercial purposes are liquid crystals (LC) and leuco dyes (LD) (Ogrodnik 2008).

Due to their cost and the fact that they are difficult to process, thermochromic LCs are used in small quantities and limited applications, mostly in devices that require very precise readings of temperature, such as forehead thermometers and vaccine vials. Most thermochromic LDs include the leuco dye, a weak acid, and a solvent. LDs are usually colored in a cool state, and the color disappears - it transforms to translucent - when the temperature rises. The typical range of color change temperatures can be as low as -25º C to as high as +65ºC. LDs can be fabricated in almost any color. LDs are relatively inexpensive and are easier to process and apply than LCs. They can be mixed with other LDs with

different clearing temperatures, with polymers or with other color pigments, which makes different cold and hot colors possible. As used in polymers, the material is opaque (colored) when cold and loses its color (becomes nearly translucent) when the temperature trigger point of the LD ("clearing point") is reached (Fig 6). Thermochromic polymer materials are used in the industry for self-monitoring of machine parts to prevent overheating and to identify thermal leaks. During storage or transportation of drugs or food articles, smart packages with irreversible color change can be used to control required temperature conditions. Thermochromic surfaces on heating plates or other appliances can function as non-touch warnings of hot surfaces (Seeboth and Lötzsch 2003, 2008).

LDs are susceptible to degradation and are sensitive to UV light and certain chemicals. Both LCs and LDs have to be microencapsulated before usage. A microcapsule is a small sphere, surrounded by a shell. A protective membrane, which functions as a stabilizing and protecting barrier, is formed around the coloring agent and solvent by an interfacial polymerization process. Microencapsulation makes the dye more stable, protects the coloring agent from the environment, enhances color control and makes it easier to use. Different microencapsulation techniques are available and new techniques are under development. It is also possible to process UV additives into the shell layer of the microcapsule (Hallcrest 1991).

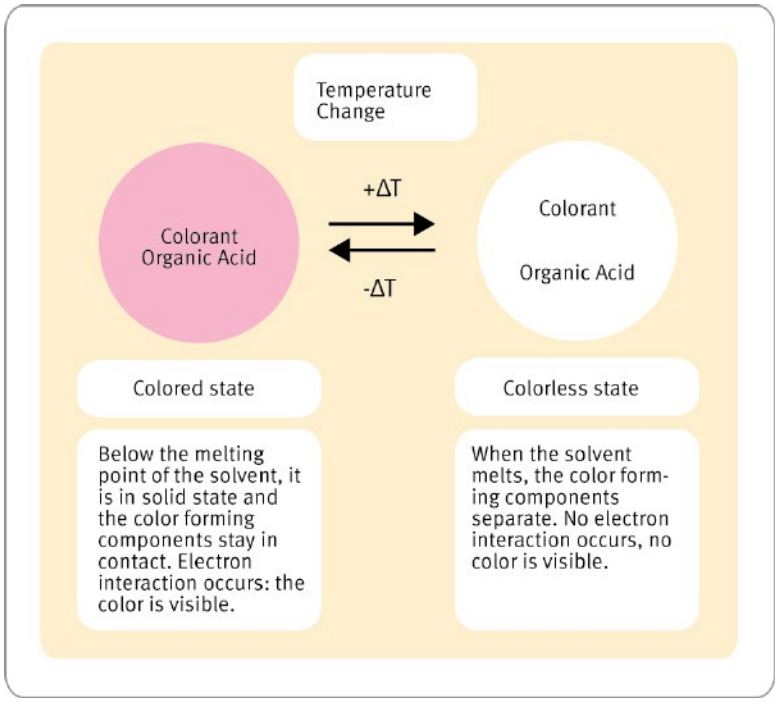


**Fig 6.** The principle of thermochromism, represented by microcapsules of a thermochromic colorant. (Modified from Ogrodnik 2008).

## 2.6 The human skin

The skin is the largest organ of the human body. The skin of an adult man has an area of, on average, about 1.74 $m^2$ and it weighs about 4-5 kg. Microscopically, the skin consists of three layers: epidermis, dermis and subcutis, containing vasculature, neural elements and appendices. It is an outer covering that provides protection against pathogens, physical and chemical injury, as well as against radiation from the sun. The skin takes part in the thermal and fluid homeostasis, protecting the body against water loss with the help of the eccrine sweat glands, and it both absorbs heat from the environment and loses heat to the environment, maintaining a constant body temperature. Under normal conditions, over 90 % of the total heat loss occurs through or on the surface of the skin. The skin has an essential role in the perception of the environment. Nerve receptors of the skin provide information about outer stimuli, such as touch, pain, and temperature, and make the body respond to them (Swain and Grant 1989, Elias and Jackson 1996).

### *2.6.1 Skin anatomy and blood flow*

The blood circulation of the skin represents 8.5% of total body blood flow. Skin blood flow comprises both thermoregulatory and nutritional blood flow. At room temperature, blood circulation in the skin is about 450 ml/min (260 ml/min $m^2$ of body surface area). This is about ten times as much needed for the nutrition of the skin (Elias and Jackson 1996). That means that the primary function of skin circulation is keeping the thermal balance. However, even though the nutritional blood flow component is small, when compared to whole maximum blood flow capacity of the skin, the nutritional blood flow is clinically very important; it has to be maintained above a certain critical level otherwise ischemia will occur (Swain and Grant 1989).

The dermis has an extensive vascular network, the purpose of which is to provide nutrition and to participate in the immune response, heat exchange and thermoregulation. The arrangement of the blood vessels is designed for the heat regulation. The dermis provides nutrition to the epidermis by passive diffusion. Terminal arterioles, arterial precapillaries and arterial loops provide the blood flow to the dermis while venous loops, postcapillaries and venules, which terminate in the veins of skin, care for the drainage. There are two horizontal, netlike plexuses, one in the upper and one in the lower dermis, which are connected to each other via arterio-venous anastomoses and vertical capillaries. Loops from the superficial capillary beds reach up into the dermal papillae, and there is a dense network around appendages (Benfeldt 1999, Braverman 2000).

The purpose of thermoregulation is to maintain a constant body core temperature in spite of different environmental conditions. The release of metabolic heat is controlled by both the autonomic and central nervous system, by controlling the vascular and muscular tone. In cold environments, thermal loss is regulated by vasculatory changes in the extremities and the skin. Emotional stimuli, ocular stimuli, sounds, orthostatic position relative to the heart level and gravity, nutrients, smoking and medicines may also affect the vascular tone. Under normal resting circumstances, the vasculature is in a relatively constricted state. Under different physiologic conditions, blood flow can be reduced to less than a half of its basal resting value, and it can increase up to 20-fold to reach maximum capacity. Local blood perfusion of the skin is also enhanced in inflammation-associated skin disorders (Fullerton et al. 2002). In extreme vasoconstriction, skin blood flow may decrease to almost zero (30 ml/min) (Elias and Jackson 1996). Comparing the blood flow of different body parts, the skin blood flow is the highest in the fingers, palms, the face and the ears (Tur et al. 1983).

Physiologically, man copes best in a warm climate and a temperature between + 20° - +30°C. The subcutis, with its fat layer, has a passive thermal isolative function. The skin can function, without cellular damage, over a temperature range from 20°C to 40°C, but the vital, inner organs of the body require the narrow temperature range between 36.2°C and 37.8°C (Elias and Jackson 1996).

Active thermal regulation of skin is managed by the vascular responses of the skin. The blood vessels in the skin are ideally arranged to either dissipate or converge heat. There is a subpapillar plexus in the upper dermis and deeper plexuses in the reticular dermis and subcutis, which are connected to each other via communicating vessels (Fig 7). The superficial plexus supplies each papilla with an ascending arterial and a descending venous limb. In addition to these, there are plexuses around the hair follicles and sweat glands in the border of the subcutis and dermis (Benfelt 1999).

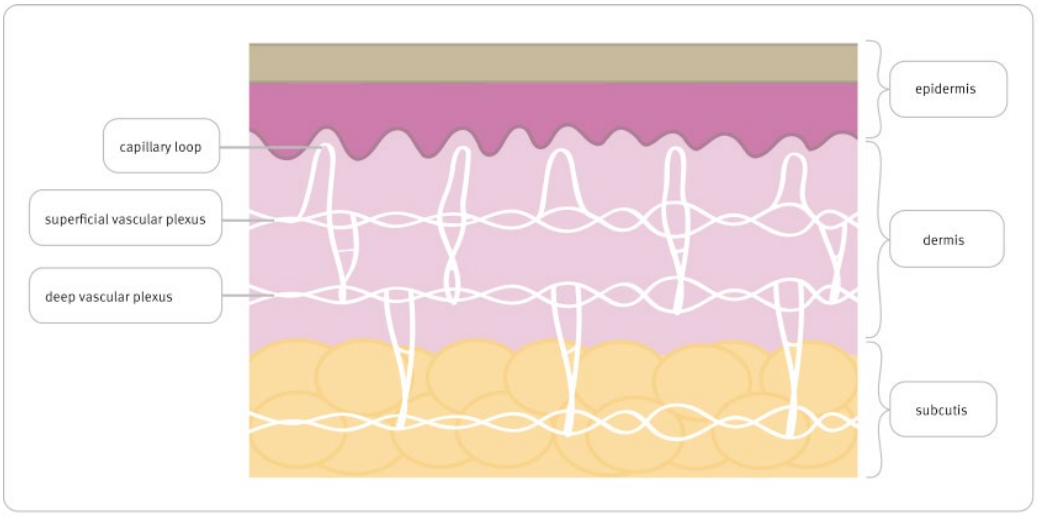


**Fig 7.** Blood vessels of the skin, according to Benfelt 1999 and Braverman 2000.

Between the arterial and venous network in the skin, there are also other vascular connections connecting the subcutaneous plexuses with the feeding arteries: the adjustable *arteriovenous anastomoses (AVAs)*. AVAs are present in toes and fingers, in the pads, in the ear lobes and in the skin of the tip of the nose. The AVAs have a larger diameter (20 – 70 μm, on average 35 μm) than capillaries (5-10 μm). During vasodilatation, a large amount of blood can pass through the vessels. Sympathetic activation leads to active vasoconstriction, and adversely, as the sympathetic activation decreases, the AVAs vasodilate passively (Braverman 2000). The AVAs also participate in the thermoregulation of the skin. They are open in a moderately warm environment and almost closed in a slightly cold environment. As the skin temperature sinks below +10°C, the AVAs lose their vasoconstriction, leading to increased blood circulation, warming up fingers and toes by 5-10° C. Rythmical waves of vasoconstriction, followed by vasodilatation of the AVAs (*rhythmical cold-induced vasodilatation)* protect the peripheral extremities, the ear lobes and the nose from suffering damage in a cold environment (Midttun and Sejrsen 1996, Braverman 2000).

The head has a very constant skin temperature at different environment temperatures, even in the cold. However, there are differences of skin temperature between different regions of the head when there are no garments to protect it. The ears, nose and the chin behave in the same way as the cold, acral parts of the extremities, participating in stabilizing the body core temperature. The skin temperature of the uncovered head in cold is lowest in the rims of the auricles, the nose and the chin. The skin of the head has most of the AVAs in the tip of the nose and in the ear lobes (Bergersen 1993). The color change of the facial

skin, especially at the tip of the nose and the ear lobes, can be explained by this vasodilatation of the AVAs in a cold environment (Fig 8).

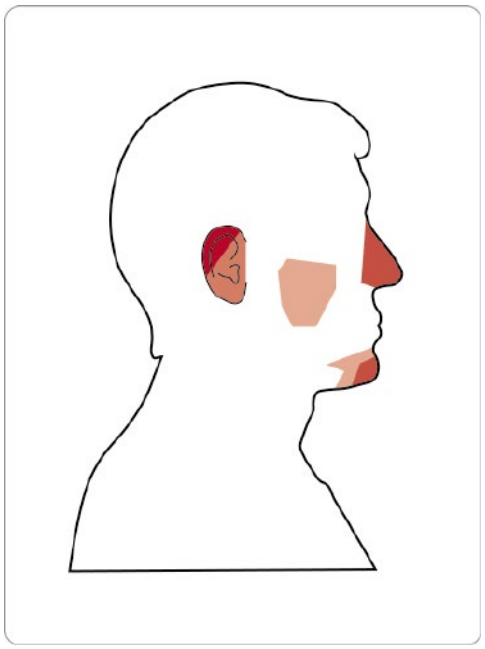

**Fig 8.** The coldest areas of uncovered head at 0°C. (Modified from Edwards and Burton 1960 and Steegmann 1979).

### 2.6.2 *Impaired skin blood flow and development of pressure ulcers*

Studies have shown associations between microvascular dysfunction and vascular diseases; patients who suffer from impaired coronary microvascular function are also found to have an impaired peripheral microvascular function (Sax et al. 1987). In diabetic patients, correlated findings of abnormal microvasculature in the skin and in the retina have been reported (Chang et al. 1997). Because of these findings, and because skin microcirculation can be measured with a non-invasive and accessible method, it has been suggested that human skin microcirculation could be used as a diagnostic tool to assess possible systemic microvascular function in certain diseases (Roustit and Cracowski 2011).

It is also known that aging alters skin blood flow: the perfusion decreases, the capillaries become more fragile, and the number of dermal nutritional vessels is reduced (Kelly et al. 1995, Chang et al. 2002, Li et al. 2006). As a result of exposure to sunlight, the UV radiation of the sunlight may lead to photoaging of the skin. This is seen as a gradual decrease in the number and size of the blood vessels in the skin exposed to the sun (Chung et al. 2002).

Especially among older patients in long-term care, pressure ulcers are a significant problem. A pressure ulcer (decubitus ulcer, bedsore) is an injury to the skin or underlying muscle tissue that develops as a result of unrelieved pressure. They usually develop over a bony prominence, such as the sacrum, heels, and buttocks. The pressure ulcers are divided into different stages depending on the severity, Stages I - IV. The highest prevalence has been documented in long-term acute care settings (Bluestein and Javaheri 2008, VanGilder et al. 2008).

The pathogenesis of pressure-evoked harmful effects and pressure ulcers is considered to be multifactorial. Local ischemia and tissue damage are among the main etiologic factors. A pressure ulcer can develop as a result of great, unrelieved pressure over a short period, or due to smaller applied pressure over a long period of time (Gawlitta et al. 2007, Bluestein and Javaheri 2008, VanGilder et al. 2008). In sites with underlying bony prominences, the pressure effect is enhanced. If the external pressure on the tissue is greater than the arterial pressure of the capillaries, it leads to impaired blood supply to the capillary network and deprives the tissues of oxygen and nutrients. This can lead to local ischemia and tissue damage. Deep pressure ulcers may develop in the muscle layers, adjacent to bony prominences. This is a serious type of pressure ulcer, as it starts in the deeper tissue layers and becomes visible when it has reached an advanced state. It has been suggested that this kind of deep ulcer is a result of tissue deformation, which has led to rapid tissue damage. Ischemia leads to a more gradual damage, due to hypoxia, glucose depletion and tissue acidification. Both pathways lead to cell necrosis (Stekelenburg et al. 2008).

### *2.6.3 Skin color*

Several individual and environmental variables determine the color of the skin. Individual variables are such as race, age, gender and anatomical site on the body. Skin color has been one of the primary features in most systems of racial classification. Environmental factors, which can affect skin color, are physical or mental activity, food, drugs, nicotine, alcohol, orthostatic change, ambient light (Fullerton et al 1996), the surrounding temperature and adjustments of skin perfusion and vascular tone (Fullerton et al. 2002). Expanded blood vessels, as in inflammation or during thermoregulation, result in redness of the skin (Angelopoulou 2001).

There are multiple genes involved in determining skin color. The basic color of the skin is mainly determined by the chromophores melanin and hemoglobin. The amount, density and distribution of melanin are the primary determinant

of skin color. Dense compaction of the melanin granules in the upper layers of the skin cells intensifies the darkness of the skin color. Melanin exists as two types of pigment: eumelanin, which is black-brown, and pheomelanin, which is reddish. Pheomelanin is present only in the skin of those individuals who carry the corresponding genetic trait. The skin of different individuals contains varying degrees of eumelanin. As a result of exposure to UV-A, UV-B and visible light, the skin tans. It is a response during which photo-oxidation of existing melanin, enlargement and increase in dendrite density of melanocytes, and an increased number of melanosomes occurs. The redness of the skin is due to the protein of the red blood cells, haemoglobin, which is responsible for the oxygen transportation from the lungs to the tissues. When oxygenated, haemoglobin has a reddish hue, and as deoxygenated it has a purplish color (Angelopoulou 2001). Carotene may be present as a result of over-consumption of carotene containing foods, like carrots. It results in a yellowing of skin (Karthik et al. 2006).

Since the reflectance spectrophotometer was introduced in the 1950s, measurement of skin color is usually done with a spectrophotometer. In medical science, skin color measurements are performed to compare the color of the skin of different body parts in order to find suitable, color matching skin for skin grafts to other parts of the body (Geishauser et al. 2000), and to diagnose erythema, as in assessment of contact dermatitis or irritant and allergic patch test reactions (Fullerton et al. 1996).

## 2.7 Measurement of skin blood flow

In studies on the cutaneous blood circulation, different aspects of the skin blood flow have been measured: physical movement, heat transport and oxygen content. As blood flows through the skin it transports oxygen and heat. Most methods used for measuring blood flow look at small volumes of tissue, in different body areas, and to different depths (Swain and Grant 1989). The three main non-invasive methods for studying the microcirculation of skin have, since the 1990s, been based on optical microscopy (capillaroscopy), laser Doppler techniques (laser Doppler flowmetry and laser Doppler imaging), or the evaluation of tissue oxygenation (Roustit and Cracowski 2011).

Skin microcirculation consists of two different networks: the superficial and the deeper vascular bed. The superficial network has a nutritive function while the deeper network mainly has a thermoregulatory function. Capillary microscopy is suitable for examining the superficial microcirculation while laser Doppler imaging technique is suitable for measuring both the superficial and the deeper

microcirculation networks (Hoffman et al. 1992). A further developed technique, the laser speckle contrast imaging technique (LSCI), can be used over wide areas continuously to assess skin perfusion. The skin penetration depth with this technique is about 300 μm while it is up to 1 – 1.5 mm with conventional laser Doppler techniques (O´Doherty et al. 2009). Both LDI and LSCI provide an index of the perfusion, which is proportional to the concentration and mean velocity of the red blood cells in the tissue (Thompson and Andrews 2010).

### *2.7.1 Optical microscopy-based techniques*

*Capillaroscopy* allows direct visualization of superficial microvessels of the skin. It is an optical technique, used *in vivo*, which mostly has been used to study rheumatic diseases which affect the digital skin microcirculation, as in *nailfold videocapillaroscopy*. OPS (orthogonal polarization spectral) imaging and SDF (sidestream dark field) imaging techniques have been developed, further improving the capillaroscopy technique. In OPS imaging the tissue is illuminated with linearly polarized green light, and in SDF imaging the light which illuminates the object is placed concentrically (Groner et al. 1999, Goedhart et al. 2007). These techniques provide a better contrast, are safer and non-invasive, and can be used during surgery of certain organs such as the brain, the kidney, and the liver, to assess the microcirculation of the organs during surgery (Perez-Barcena et al. 2011, Schmitz et al. 2008, Puhl et al. 2003). The OPS and SDF imaging techniques can both be used as bedside techniques to study the microvessels of thin epithelial layers. The microcirculation of burn wounds and venous insufficiency of the lower limbs can be evaluated by using OPS imaging. In critical medicine, the OPS imaging technique is used intraorally, in the sublingual region, to study the density of perfused capillaries. The disadvantages of the optical microscopy-derived techniques are that they mainly provide morphological information of the blood vessels and the OPS or SDF probe will result in a pressure, which might affect the flow velocity in the vessels (Virgini-Magalhaes et al. 2006, Treu et al. 2011).

### *2.7.2 Laser Doppler techniques*

The most commonly used techniques for studying cutaneous blood flow in the field of microvascular function research today are the laser Doppler techniques.

Laser Doppler techniques do not directly measure skin blood flow, but the laser Doppler signals give values corresponding to the average speed and concentration of the moving red blood cells, as an index of skin blood flow,

or flux. As the laser beam, directed at the tissue, hits the moving blood cells, it undergoes wavelength changes (Doppler shift) which are registered from the backscattered light (Stern 1975).

#### *2.7.2.1 Laser Doppler Flowmetry (LDF)*

Laser Doppler flowmetry (LDF), or laser Doppler perfusion monitoring (LDPM) was the first developed laser Doppler technique, introduced by Stern in 1975 for measuring of skin microcirculation (Stern 1975). With this method, the blood flow is not measured directly, but flux values are quoted in volts. The LDF probe has a measuring volume of approximately 1 $mm^3$ with a high sampling frequency. Rapid changes in blood flow can be detected with high accuracy, which makes this method suitable for quantifying relative changes in skin microcirculation as a response to an external stimulus. However, as the tissue perfusion is very heterogeneous, the probe can show different values only millimetres apart (Harrison et al. 1994).

#### *2.7.2.2 Laser Doppler Imaging (LDI) technique*

A further development based on the laser Doppler technique was introduced in the early 1990s: the laser Doppler imaging technique (Essex and Byrne 1991). In this technique, the physical principle is the same as in the LDF technique, but the advantage is that it does not need to be in direct contact with the tissue. With the LDI technique, a wide area of tissue can be studied, which means that a more representative sample of the tissue blood flow is obtained (Seifalian et al. 1994).

A low energy He-Ne laser beam, consisting of different wavelengths penetrating the skin, is directed at the skin via a moving, computer-driven mirror. The laser beam is moved step by step in a rectangular pattern over the surface of the tissue. As the laser light interacts with the skin, the microvasculature, and the moving red blood cells, the wavelength of the light changes due to the Doppler effect. A part of this light is backscattered. The information provided from the qualities of the fraction of the backscattered light is detected by a photodetector in the scanner head. The processor of the LDI equipment converts the light into an electrical signal. This output value is linearly related to tissue perfusion, the *flux*, which is defined as the product of average blood cell speed and the concentration of blood cells (Fig 9).

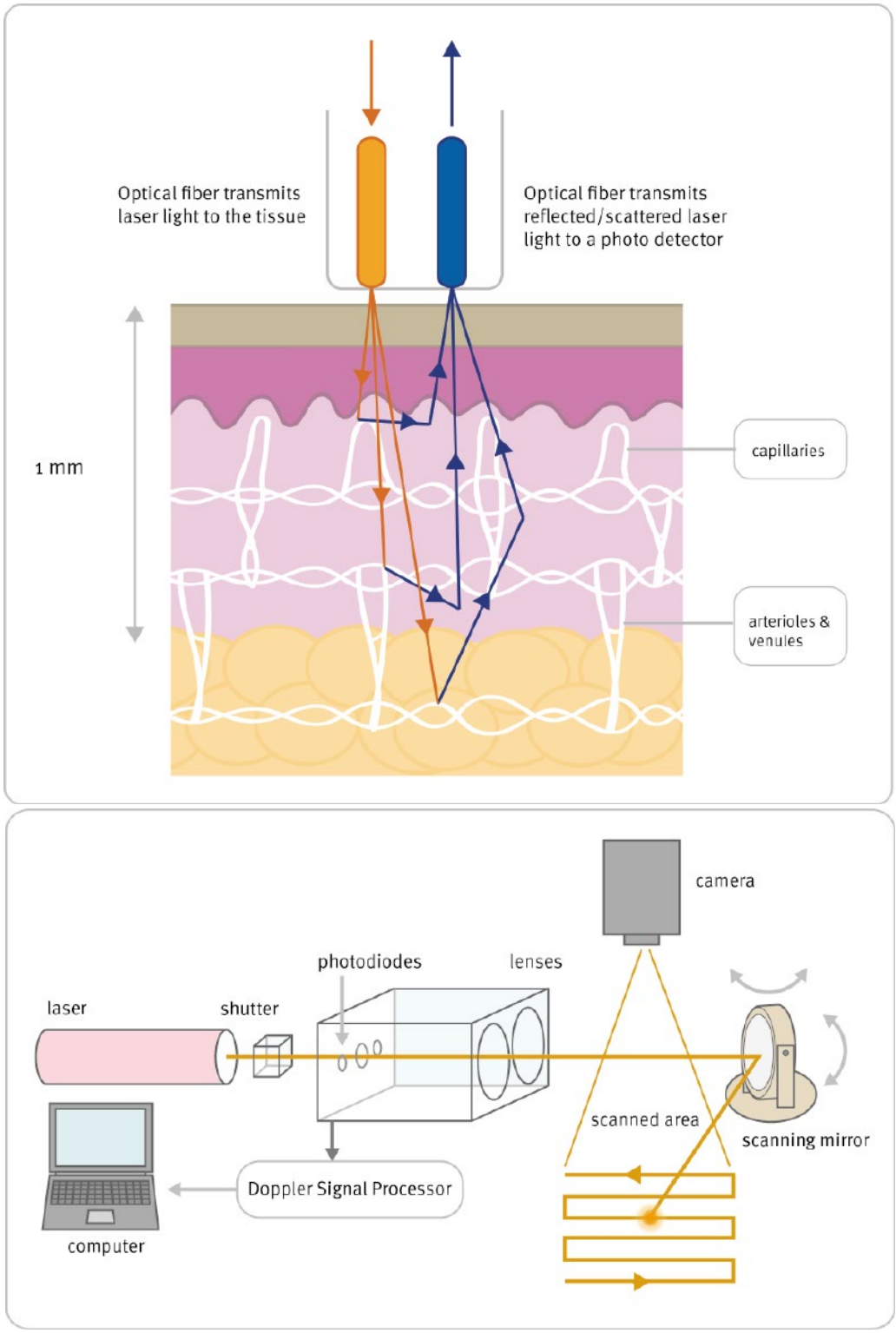


**Fig 9.** The principles of Laser Doppler Imaging (LDI).

The perfusion values are presented as a two-dimensional, color-coded image of the flux, where each pixel represents a certain perfusion value. Further, the perfusion values of each measuring point can be stored for further processing and data analysis (Wårdell et al. 1993, Nilsson et al. 2003, Wårdell 2006).

The LDI technique does not provide exact values of the blood flow (ml/min), but, in spite of that, it is considered to be a valid and non-traumatic method for assessment of skin blood flow, and has been used in a number of studies concerning skin blood flow (Wårdell et al. 1993, Seifalian et al. 1994, Svedman et al. 1998, Kemppainen et al. 2001, Fullerton et al. 2002, Nilsson et al. 2003, Wårdell 2006, Schlosser et al. 2010).

Laser Doppler imaging technique has also been used in studies concerning vascular aspects in rheumatological diseases, studying Raunaud´s phenomenon and vascular changes in systemic sclerosis (Seifalian et al. 1993, Picart et al. 1998, Murray et al. 2004).

As this technique does not require contact with the studied tissue, it is a suitable method for assessing burn depth and wound healing in skin burn (Droog et al. 2001, Kloppenberg et al. 2001, Chatterjee 2006, van Herpt et al. 2010) and for studying blood flow in pressure ulcers (Gschwandtner et al. 1999 and 2001). In studies by Kemppainen and coworkers, the LDI technique was used for studying blood flow in the extraoral orofacial area (Kemppainen et al. 2001a,b) and in the oral mucosa (Kemppainen et al. 2003).

# 3. AIMS OF THE PRESENT STUDY

1. To clinically test the use of a fiber-reinforced framework in a silicone elastomer facial prosthesis.

2. To investigate different bonding agents for bonding maxillofacial silicone elastomer to a fiber-reinforced composite framework.

3. To evaluate the use of thermochromic pigment in maxillofacial silicone elastomer.

4. To study the effect of artificial aging on maxillofacial silicone elastomer colored with thermochromic pigment.

5. To investigate the effect of a compressive facial mask, mimicking the fiber-reinforced composite framework of a facial prosthesis, on facial skin blood flow.

# 4. MATERIALS AND METHODS

## 4.1 Materials

The materials used in studies I – V are presented in Table 3.

**Table 3.** Materials used in studies I – V.

| Study | Brand name | Composition | Manufacturer |
|---|---|---|---|
| II | Palapress | PMMA polymer powder, MMA monomer liquid | Heraeus Kulzer, Werheim, Germany |
| I, II, V | Stick Resin | Light cured adhesive of bis-GMA and TEGDMA | Stick Tech Ltd, Turku, Finland |
| I, II, V | everStick C & B | Continuous unidirectional silanized E-glass fibers embedded in a resin matrix of bis-GMA-TEGMA and PMMA | Stick Tech Ltd, Turku, Finland |
| I, II, III, IV | SILASTIC MDX4-4210 | Room temperature-vulcanized addition cure silicone:<br>- elastomer component: dimethylsiloxane polymer, reinforcing silica, and platinum catalyst<br>- curing agent: dimethylsiloxane polymer, inhibitor and siloxane cross-linker | Dow Corning Corp., Midland MI, USA |
| II | Sofreliner Primer | 99.5% methylene chloride, 0.5% PMMA polyorganosiloxane | Tokyuama Dental, Tokyo, Japan |
| I, II | Gold Platinum Primer A-330-G | Modified polyacrylates in methyl ethyl ketone and trichlorometane | Factor II Inc., Lakeside, AR, USA |
| I | ESPE Sil | silane coupling agent | 3M ESPE, Seefeld, Germany |
| II | VMS Primer | 2% vinyltrimethoxysilane, ethylacetate-based | Fluca Chemie, Buchs, Switzerland |
| I, III, IV | Thixo A-300-1 | unknown | Factor II Inc., Lakeside, AR, USA |
| I, III, IV | Color pigments Functional Intrinsic Silicone Coloration II: white, flesh ferro, yellow, blue, buff, redbrown, red, tan | unknown | Factor II Inc., Lakeside, AR, USA |
| I, III, IV | Rayon fiber flocking | | Factor II Inc., Lakeside, AR, USA |
| III, IV | Chromazone Free Flowing Powder, pigment red 15C | unknown | Thermographic Measurements Co. Ltd, Honiton, UK |

### *4.1.1 Materials and fabrication of facial prosthesis (study I)*

Study I is a clinical report of the prosthetic rehabilitation of a 48-year old female, suffering from a lateral midfacial defect, acquired after cancer surgery of an adenocarcinoma of the left nasal cavity and maxillary sinus. No radiation therapy was provided.

An impression of the defect was made by using a vinyl polysiloxane impression material (Coltex; Colténe/Whaledent AB, Altstätten, Switzerland). A glass fiber-reinforced composite substructure, designed as a framework with radiating extensions of unidirectional, continuous fiber-reinforced fiber bundles (everStick C&B Fibre; Stick Tech Ltd, Turku, Finland) was fabricated to support the maxillofacial silicone elastomer (MDX4-4210; Dow Corning Corp., Midland, MI, USA) of a facial prosthesis. The prosthesis was attached to the face by osseointegrated implants (Brånemark Mk II self-tap fixture; Nobel Biocare AB, Gothenburg, Sweden) and magnet precision attachments (Mini and Maxi Magnacap; Technovent Ltd, Leeds, UK). The magnets were attached to the fiber-reinforced composite framework after preparing the surface of the framework and the surface of the magnets with airborne-particle abrasion (Rocatec Junior; 3M ESPE, Seefeld, Germany). The FRC framework was stiffened using resin (Stick Resin; StickTech Ltd) and composite (Sinfony; 3M ESPE). A silane coupling agent (ESPE Sil; ESPE) was applied on the surface of the magnets and the FRC surface. The FRC framework was incorporated into the silicone on a stone mold (GC Fujirock EP; GC Europe) and polymerized according to the manufacturer´s instructions.

### *4.1.2 Materials and preparation of specimens in study II*

Baseplates for test substrates, sized 12 x 12 x 3 $mm^3$, were fabricated using PMMA resin (Palapress; Heraeus Kulzer, Wehrheim, Germany) in silicone molds (Lab-Putty; Colténe-Whaledent AG, Switzerland). The PMMA resin baseplates were heat cured at 60°C for 15 minutes at 600 kPa pressure (Ivomat Typ IPZ; Ivoclar Ag, Shaan, Lichtenstein). To get a roughened surface, the bonding surfaces of the PMMA baseplates were ground with grinding paper (320-grit FEPA SiC paper; Struers, Denmark). Then, unidirectional, resin-impregnated E-glass fiber rovings (everStick; Stick Tech, Turku, Finland) were attached to the PMMA baseplate with monomer resin (Stick Resin; Stick Tech, Turku, Finland) to cover the entire baseplate surface. The resin and the resin-impregnated E-glass fiber rowings were polymerized with a light-curing device (Kerr Demi; Kerr corp., USA) for 40 seconds.

The baseplates with attached E-glass fiber rovings were divided into two groups: half of the baseplates were ground (1000 grit FEPA Waterproof SiC paper; Struers, Denmark) in order to expose the glass fibers of the resin-impregnated fiber rowings. Half of the baseplates were left with an intact surface, meaning that the fibers were covered with a thin layer of bis-GMA-TEGDMA-PMMA polymer (bisphenyl glycidyl methacrylate-triethylene glycol dimethacrylate-PMMA).

The FRC substrate specimens were divided into 6 groups, each group consisting of 10 specimens, according to surface quality and type of primer used (Table 4).

**Table 4.** Groups of specimens in study II.

| Group | Surface type | Primer |
|---|---|---|
| 1 | intact (=not ground) | A-330-G |
| 2 | intact | Sofreliner |
| 3 | intact | VMS |
| 4 | ground | A-330-G |
| 5 | ground | Sofreliner |
| 6 | ground | VMS |

The respective primer was applied to the surfaces of the specimens according to the manufacturers´ instructions.

Maxillofacial silicone elastomer (MDX4-4210; Dow Corning, MI, USA) was mixed according to the manufacturer´s instructions in a ratio of 10:1 in a mechanical speedmixer (Speedmixer model type DAC 150FV2-K; FlackTek). Then, the silicone was applied into a polyethylene ring, with a diameter of 10mm and a height of 3 mm, on top of each FRC substrate specimen. Another FRC substrate plate was placed on top of each silicone-filled ring.

### *4.1.3 Preparation of samples for studies III and IV*

Maxillofacial silicone elastomer (MDX4-4210; Dow Corning Corp, MI, USA) was mixed manually in a ratio 10:1 (base:catalyst). Anti-slump additive, thixotropic agent (Thixo A-300-1), was added to the silicone according to the instructions of the manufacturer. Conventional color pigments (Table 3) were added to make the colorless silicone naturally fair skin colored. All specimens were fabricated at the same time, from the same batch of silicone.

The skin-colored silicone was divided into three parts and two parts had thermochromic pigment added to them (Chromazone Free Flowing Powder

Pigment red 15 C; Thermographic Measurements Co Ltd, Honiton, UK) in different concentrations: 0.2 wt% and 0.6 wt%, respectively.

Disc-shaped silicone elastomer specimens (n=36) were fabricated by using stone molds with round cavities of 7 x 35 mm. After the silicone was poured into the stone molds, it was polymerized at 90°C for 2 hours. The cooled specimens were then cleaned manually by using grinding paper (Struers Waterproof Silicone Carbide Paper FEPA p#1200; Struers, Denmark), and thoroughly rinsed with water.

The groups of fabricated disc-shaped silicone elastomer specimens, sized 7 x 35mm, are presented in Table 5.

**Table 5.** Groups of silicone specimens in study III.

| Control group (n=12) | 0.2 % group (n=12) | 0.6 % group (n=12) |
|---|---|---|
| fair skin-colored silicone | 0.2 wt% thermochromic pigment added to fair skin-colored silicone | 0.6 wt% thermochromic pigment added to fair skin-colored silicone |

In study IV, all the test specimens had half of their surface wrapped with aluminium foil. The specimens were divided into groups regarding pigment concentration and storage in between the UV irradiation cycles (Fig 12). Half of the specimens were stored in the dark at room temperature (RT-group) and the other half was stored in an incubator at 37°C, with 97 % humidity (37°-group). The groups of specimens are presented in Table 6.

**Table 6.** The division of silicone elastomer specimens into groups, according to the pigment concentration and storage. Each group consisted of 6 specimens.

| Group | Color pigments used to color the silicone elastomer specimens | Storage in between the exposures to UV irradiation |
|---|---|---|
| Group 1/RT | Conventional color pigments (Table 3) | In darkness, at room temperature (RT) |
| Group 1/37°C | Conventional color pigments | In an incubator (37°C, 97% humidity) |
| Group 2/RT | Conventional color pigments and 0.2 wt% thermochromic pigment | In darkness, at room temperature |
| Group 2/37°C | Conventional color pigments and 0.2 wt% thermochromic pigment | In an incubator (37°C, 97% humidity) |
| Group 3/RT | Conventional color pigments and 0.6 wt% therochromic pigment | In darkness, at room temperature |
| Group 3/37°C | Conventional color pigments and 0.6 wt% thermochromic pigment | In an incubator (37°C, 97% humidity) |

### 4.1.4 *Test subjects and fabrication of face mask (study V)*

The ten test subjects, enrolled in the study, were healthy, non-smoking and medication-free young adults, aged 23-25 years. According to the ethics guidelines of the World Medical Association Declaration of Helsinki (2005), each subject provided a written consent prior to the experiments. The study protocol was approved by the ethics committee of the Hospital District of Southwestern Finland (26/180/2011).

A face mask was fabricated to mimic the glass fiber-reinforced framework of a facial prosthesis (Fig 10) corresponding to the facial prosthesis in study I (case report). The face mask was fabricated with a stabilizing "halo", or cap, to which a compression arm, fabricated of dimethacrylate resin impregnated E-glass fiber rovings (everStick; Stick Tech, Turku, Finland) was attached. A metal frame enabled movement and adjustment of the FRC beam to compress the skin.

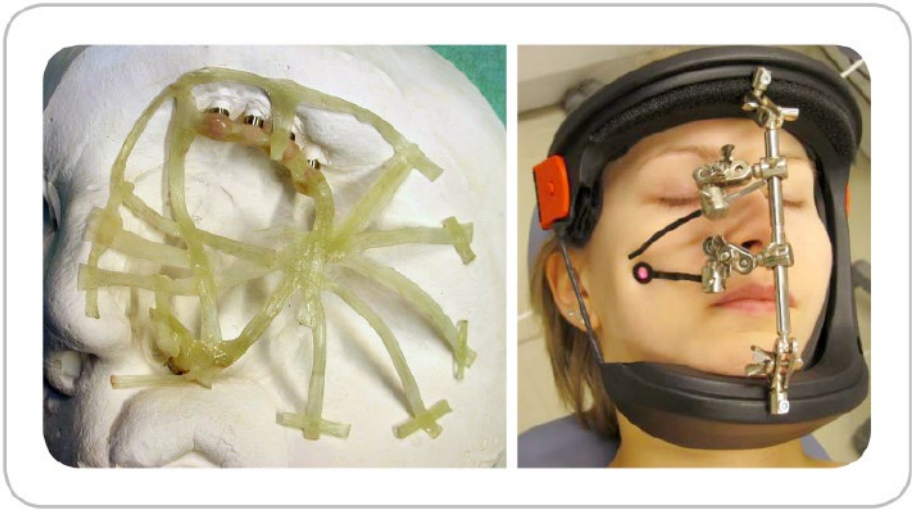

**Fig 10.** Fiber framework for silicone facial prosthesis (study I) and face mask, constructed to compress the facial skin in a similar way as the fber framework, on test subject (study V).

The fiber-reinforced composite of the compression arm contained a polymer matrix consisting of a semi-interpenetrating network (semi IPN) of pBisGMA-pTEGDMA-PMMA polymers with a fiber content of 60%. The fiber rovings were attached to each other with StickResin (Stick Tech) and polymerized by using a light curing device (Optilux 180; Kerr Corp., Orange, Calif., USA). The FRC cantilever beam, with a cross-sectional size of 1 x 4 mm and a length of 43 mm, was used to compress the skin.

The compression pad was constructed as a ring, 12 mm in diameter, at the end of the fiber beam. It was constructed to enable measurement of skin microcirculation close to the pad and within the 6 mm hole of the ring. The FRC beam was painted black in order to prevent reflection of the laser beam. The compression pad corresponded to one of the FRC cantilever beams of a fiber-reinforced composite framework, which is used to support the silicone elastomer in a facial prosthesis. The applied compression forces generated by the compression arms were measured with the Lloyd XLC Loadcell-device (Lloyd LR30K Plus; Metek inc., Largo, FL, USA). The mean compression force of the respective compression was calculated from 3 measurements. The moderate compression, (C), which resulted in a 4 mm induration of the skin, corresponded to a compression force of 0.45N, and a 5 mm induration corresponded to 0.47N (5.5 kPa).

## 4.2 Methods

### *4.2.1 Measurement of tensile bond strength (study II)*

The schematic test-setup for testing the tensile bond strength between silicone elastomer and FRC is shown in Fig 11. The applied test was performed according to ISO 22401 Standard (Standardized testing method) with a universal material testing device (Lloyd LR30K Plus; Metek inc., Largo, FL, USA).

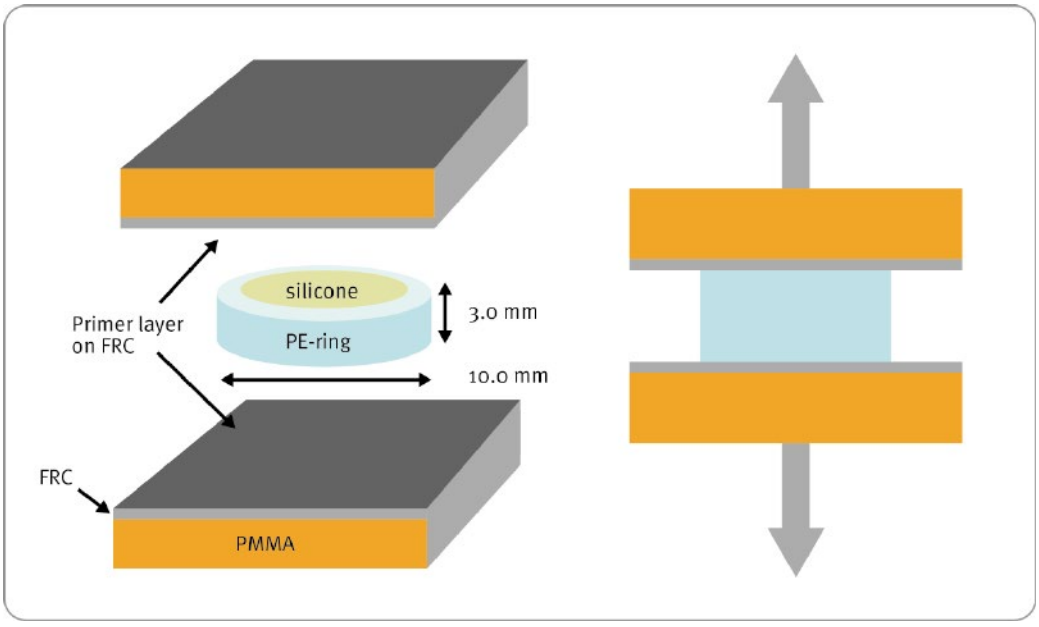


**Fig 11.** Schematic test set-up for testing tensile bond strength (study II).

The tensile bond strength was tested using the testing device to pull the baseplates with the FRC surface from the silicone-filled polyethylene ring at a cross-head speed of 10 mm/min until the bonding failed. The fracture surface was then inspected visually, and the type of fracture was categorized as adhesive, cohesive or mixed.

### *4.2.2 Artificial aging (study IV)*

The maxillofacial silicone elastomer specimens, which had half of their surface covered with aluminium foil, were divided into two main groups: half of the specimen were stored at room temperature, in darkness, and the other half were stored at 37°C, in 97% humidity (in an incubator) (Fig 12).

All specimens were exposed to UV irradiation in 6 h cycles, one cycle per day every day, except for the weekends. A UV lamp (UVA lamp Blacklight, F 15W/350 BL-T8; Sylvania, Havells-Sylvania India Ltd) was used as the UV radiation (315-400nm) source. The color measurements were performed at room temperature as follows: at baseline (day 1), which was 20 days after fabrication of the specimens, and at day 2, 3, 4, 8, 24, 38 and 46.

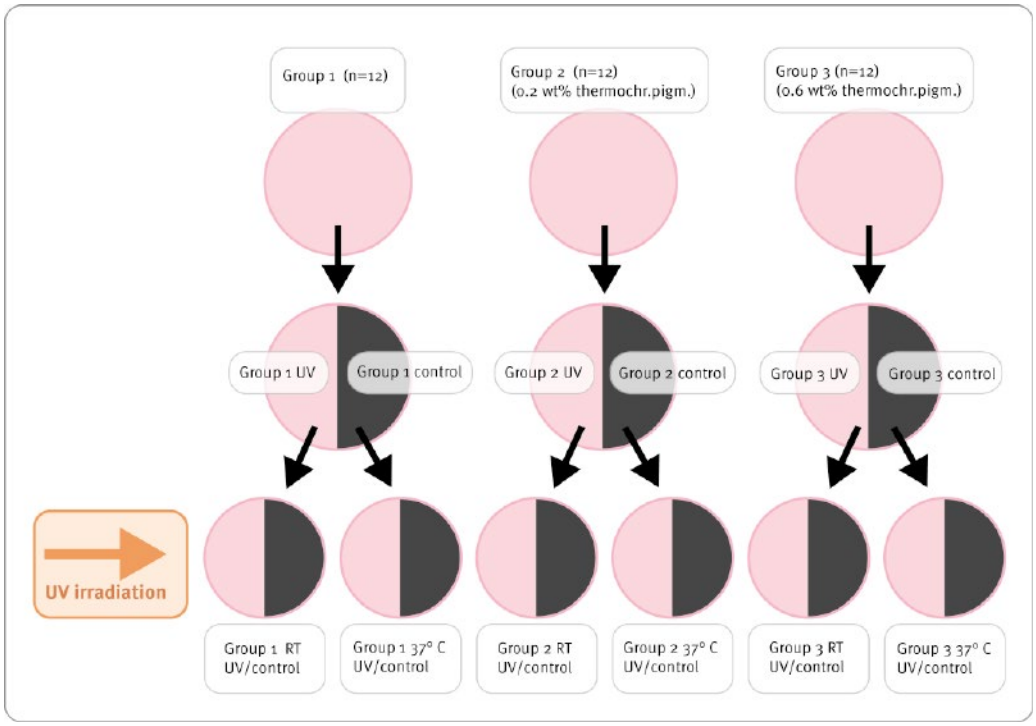


**Fig 12.** Division of specimens into groups prior to artificial aging (study IV). Each group consisted of 12 specimens, half of the surface was wrapped with aluminium foil to protect the surface from UV radiation (study IV).

### 4.2.3 Measurement of color (studies III and IV)

The color measurements of the maxillofacial silicone elastomer specimens in studies III and IV were performed with a spectrophotometer (Konica Minolta M-700d; Konica Minolta Sensing Inc., Tokyo, Japan). The measuring area of the spectrophotometer was 3mm in diameter, and the measurements were performed by using illuminant D65 with 8 degree diffused illumination and 8 degree viewing angle, the specular component included. The measured spectrum ranged from 400 – 700 nm, with a 10 nm wavelength pitch.

The measurements were completed with a white background plate. In order to test the transparency of the 7 mm thick silicone specimens, the color of three of the specimens was measured with both a white and a black background. The color difference ΔE of the same specimen with a white and black background was found to be slightly below 1. As a color difference of $\Delta E < 1$ is considered as not detectable by the human eye, the specimens were classified as non-translucent.

In study III, the color of the specimens was measured at baseline, in room temperature (23°C) 24 hours after fabrication of the specimens, and after storage in a freezer at -19°C.

In study IV, the first color measurements were performed 20 days after preparation of the specimens.

The color change ΔE was calculated according to the CIE L*a*b* system (Commission Internationale d´Éclairage 2004) using the equation:

$$\mathbf{\Delta E}=([\Delta L^*]^2 + [\Delta a^*]^2 + [\Delta b^*]^2)^{½}.$$

In this formula, L* describes the degree of lightness and darkness (the brightness) in a scale from 1 to 100, where 0 represents black and 100 represents white. The a* parameter describes red/green chroma: a high positive numerical value of a* means an intense red chroma and, respectively; a high negative value of a* means an intense green chroma. Correspondingly, the b* parameter stands for yellow/blue chroma: a high positive b* represents yellow chroma and a high negative numerical value represents blue chroma.

### 4.2.4 Measurement of blood flow (study V)

The mask was firmly attached to the subject´s head and the subject was acclimatized resting in a dental chair for 10 minutes, in a room temperature of

23°C. Both the reference-arm and the compression pad could be moved three dimensionally by the use of the metal wing nuts (Fig 10).

A laser Doppler perfusion Imager was used to measure the skin blood flow (Moor instruments; Wilmington, DE, USA). A low power (2mV) He-Ne laser beam was directed at the subject´s cheek through a computer-controlled optical scanner, which was placed approximately 30 cm above the subjects face. The laser beam scanned the skin at the subject´s cheek, over an area of 3.9 x 3.9 cm (100 x 100 pixels). The backscattered light, caused by the moving red blood cells, was detected by the photodetector of the LDI equipment and it was converted to an electrical output signal. The perfusion values (the flux) were then presented as color-coded images, where the blue color means a low perfusion, green to yellow indicates a mid-range perfusion and red indicates a high blood flow.

The blood flow measurements started with 6 baseline measurements before application of pressure from the compression pad of the face mask. The measurements were performed at four different sites: inside the ring, and at three sites outside the ring (Fig 13).

**Fig 13.** Scanning area of the skin with respect to the position of the pad (study V). The measurement sites are marked with blue. The position of the pad on the subject´s face is presented in Fig 10.

Then, the compression arm was positioned on the skin, and three more scans were performed: the first scan (A) as the pad only touched the skin, the second (B) with slight compression of the skin, and the third (C) as the pad was moderately compressing the skin, producing an induration of the skin of approximately 4-5 mm. Immediately after releasing the compression pad from the skin, another scan was performed, followed by three more scans. Each measurement lasted approximately 1 minute, with 2 minutes breaks in between them. One experimental session lasted 45 minutes for each subject.

### *4.2.5 Statistical methods*

The bond strength values in the tensile bond strength test were symmetrically distributed (study II) and, therefore, the test results were statistically analyzed with one-way analysis of variance (ANOVA) and Tukey´s post hoc test.

In studies concerning thermochromic pigment (studies III and IV) the changes in L*, a* and b* values were statistically analyzed. The color changes of the specimens within each group were separately analyzed by using paired samples t-tests. The differences between the groups were analyzed with repeated measures ANOVA. In study IV, the two half surfaces of each specimen were compared to each other by using paired samples t-test. Distributions of the changes in L*, a* and b* values were symmetrically distributed in each storage and concentration group during the artificial aging. In the repeated measures ANOVA the sphericity assumption was violated and $\varepsilon<0.75$, which means that the Greenhouse-Geisser correction was applied.

In study V, where the blood flow of facial skin was studied, the mean value, calculated from the six baseline measurements before the application of the face mask, was used as the baseline value. The differences between the separate baseline measurements were examined with the Friedman test for several related samples. As no statistical differences were found, the mean value of the baseline measurements, of each subject, could be used as a baseline value. The perfusion values of each of these sites during touch (A), light compression (B) and moderate compression (C) were compared to the perfusion values at baseline. After removal of the compression pad, the return of the perfusion was measured and compared to the baseline value. The statistical significances between the perfusion values measured before, during and after compression were calculated with paired samples t-tests.

All tests were two-sided, and *P*-values < 0.05 were considered statistically significant.

All statistical tests were performed with a statistical software (SPSS 19.0; SPSS Inc., Chicago, IL, USA).

# 5. RESULTS

## 5.1 Case report (study I)

The prosthesis was in use for 7 years, until the patient died, and there was neither clinical failure of the bonding between the FRC and the silicone, nor of the bonding between the magnets and the silicone. The prosthesis was professionally cleaned on a regular basis, and as the facial contour changed, the margins were corrected by altering the FRC framework. Some color corrections were also made by extrinsic coloration.

## 5.2 Tensile bond strength between FRC and maxillofacial silicone elastomer, comparison of three different primers (study II)

The tensile bond strengths between FRC and maxillofacial silicone elastomer are presented in Table 7.

**Table 7.** Tensile bond strength with different primers and surface structure

| Adhesive | Intact (not ground) (MPa/SD) | Ground (MPa/SD) |
|---|---|---|
| A-330-G | 0,76 (0.26) | 1.70 (0.70) |
| Sofreliner | 0.50 (0.11) | 1.16 (0.24) |
| VMS | 0.36 (0.16) | 0.47 (0.21) |

Comparing the bond strengths for intact FRC surface, A-330-G primer provided the highest mean bond strength (0.76 MPa), Sofreliner presented the second highest bond strength (0.50 MPa) and VMS primer the lowest bond strength (0.36 MPa). All primers presented significantly higher bond strength between the ground FRC surface and maxillofacial silicone: A-330-G gave the highest bond strength (1.7 MPa), followed by Sofreliner (1.16 MPa) and VMS primer (0.47 MPa). These results show that the grinding of the FRC surface resulted in more than double the tensile bond strength with both A-330-G and Sofreliner primer. The fracture type was classified as adhesive, cohesive or mixed. The results according to type of bonding failure are presented in Fig 14.

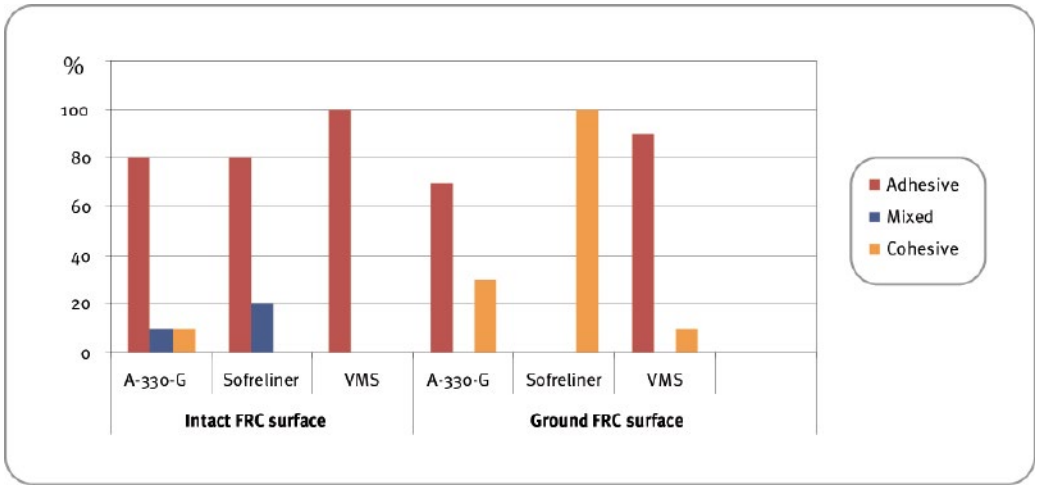


**Fig 14.** Fracture type according to primer and surface structure (study II).

With an intact FRC surface, all the VMS primer test specimens (100%) showed adhesive bonding failures. For the Sofreliner primer, adhesive bonding failures occurred in 80%, while the remaining 20% bonding failures were cohesive in nature. The A-330-G primer showed 80% adhesive bonding failures, 10% mixed failures (both adhesive and cohesive bonding failure on the same substrate) and 10% cohesive failures. Grinding the FRC surface resulted in more cohesive bonding failures: Sofreliner presented 100% cohesive failures, A-330-G showed 30% cohesive failures, the rest being 70% adhesive failures, and VMS primer showed 10% cohesive failures. All specimens remained intact at the PMMA-FRC interface.

According to ANOVA, both the surface treatment of the FRC and the used primer had a significant ($P<0.05$) effect on the tensile bond strength between the FRC surface and silicone elastomer.

## 5.3 Use of thermochromic pigment in maxillofacial silicone (study III)

All of the silicone elastomer specimens containing thermochromic pigment showed visually detectable color changes after they were stored in a cold environment. According to the spectrophotometer, color changes were detected in all color values L*, a* and b* as the temperature decreased from room temperature to -19°C.

The color changes, presented as the change in the L*, a* and b* color values, are presented in Fig 15.

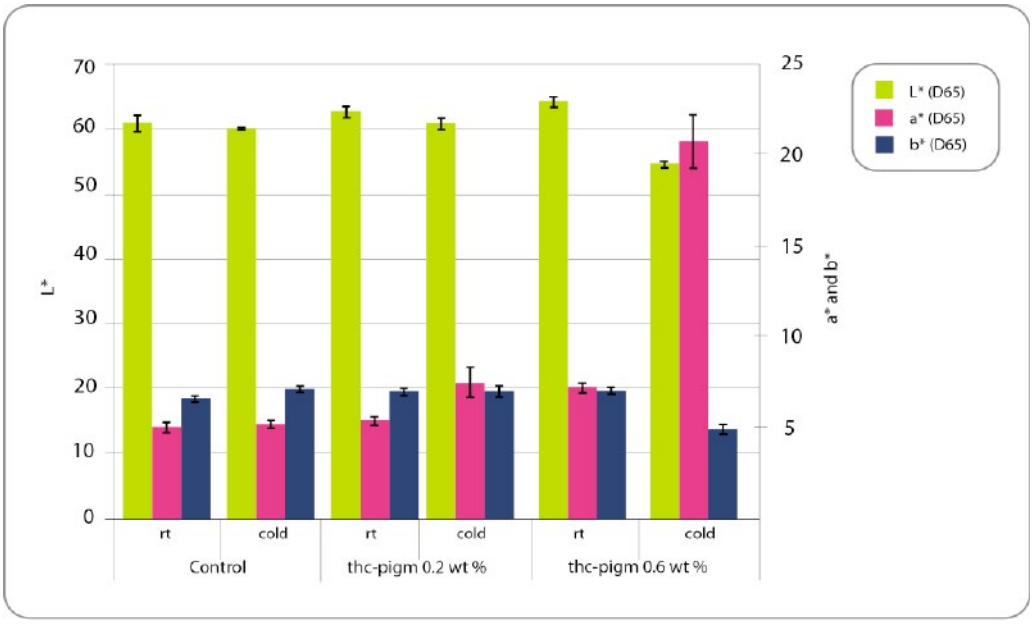


**Fig 15.** Changes in color values L*, a* and b* of the silicone elastomer discs. rt = room temperature; cold = specimens stored for 50 min at - 19°C; thc-pigm = thermochromic pigment.

The control group specimens containing no thermochromic pigment presented a mean a* value of 5.00 in room temperature and 5.13 at decreased temperature. The corresponding a* values of the 0.2 wt% thermochromic pigment group were 5.31 and 7.39 while the a* values of the 0.6 wt% group changed from 7.15 at room temperature, to as high as 20.74 at -19°C.

Wilcoxon signed rank test showed that the color differences between the a* and L* values at room temperature and decreased temperature were statistically significant in both 0.2 wt% and 0.6 wt% groups ($P$=0.002). According to repeated measures ANOVA, a statistically significant difference ($P$<0.001) for all L*a*b* coordinates was detected among the groups. The post hoc test indicated that for a* and L* values all the groups differed from each other ($P$<0.001). For the b* values, differences were detected between the control and 0.6 wt% groups and between the 0.2 wt% and 0.6 wt% groups ($P$< 0.001), but not between the control and 0.2 wt% groups ($P$=0.304).

Visually, the color change towards increased redness was clearly noticeable in the 0.2 wt% and 0.6 wt% thermochromic pigment specimen groups.

The overall color change of the specimens, described as ΔE from room temperature from cold, were 0.95 for the control group, 2.66 for the 0.2 wt% thermochromic

pigment group and as high as 16.81 for the 0.6 wt% thermochromic pigment group. This overall color change was visually detectable in both 0.2 wt% and 0.6 wt% group.

## 5.4 Artificial aging of maxillofacial silicone elastomer specimens colored with thermochromic pigment (study IV)

The color difference, ΔE, between the non-irradiated half of each silicone specimen, as compared to the UV-irradiated half, and the change of the separate color values L*, a* and b* during the process of artificial aging, are presented in Fig 16 and 17.

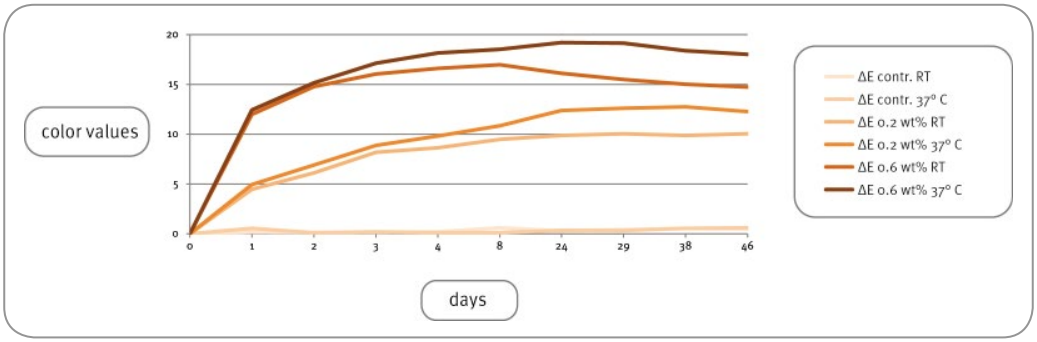


**Fig 16.** The overall color-change, **Δ**E, throughout the aging process of the silicone specimens.

As early as after just one cycle of UV irradiation high ΔE values were detected in the specimens in groups 2 and 3 containing thermochromic pigment. High ΔE values were demonstrated both in those silicone specimens that had been stored in an incubator, at 37°C, and in those stored at room temperature. After one cycle of UV irradiation, the mean ΔE value of the specimens in group 2 was 4.47 (RT) and 4.94 (incubator), respectively. In group 3, the color change ΔE was 11.98 (RT) and 12.44 (incubator). Looking at the separate color coordinates L*, a* and b*, the greatest changes were detected in the a* value, which describes the redness. During the 37 days the mean a* value of the UV exposed surfaces of the test group 2/RT changed from 7.23 to 11.63 and in group 2/37°C from 7.24 to 13.88. In group 3 /RT and 3/37°C, the corresponding a* values changed from 14.30 to 14.46, and from 14.39 to 17.25, respectively.

As it is shown in Fig 17, both the change in a* value and the ΔE of the specimens of group 2 seemed to cease rising after 24 days of artificial aging (11 x 6h of UV irradiation). In group 3, the specimens of which contained a higher concentration

of thermochromic pigment, the same trend was seen already after 8 days, when the maximum redness was noticed. The changes in a* value in studies III and IV are presented in Fig 18.

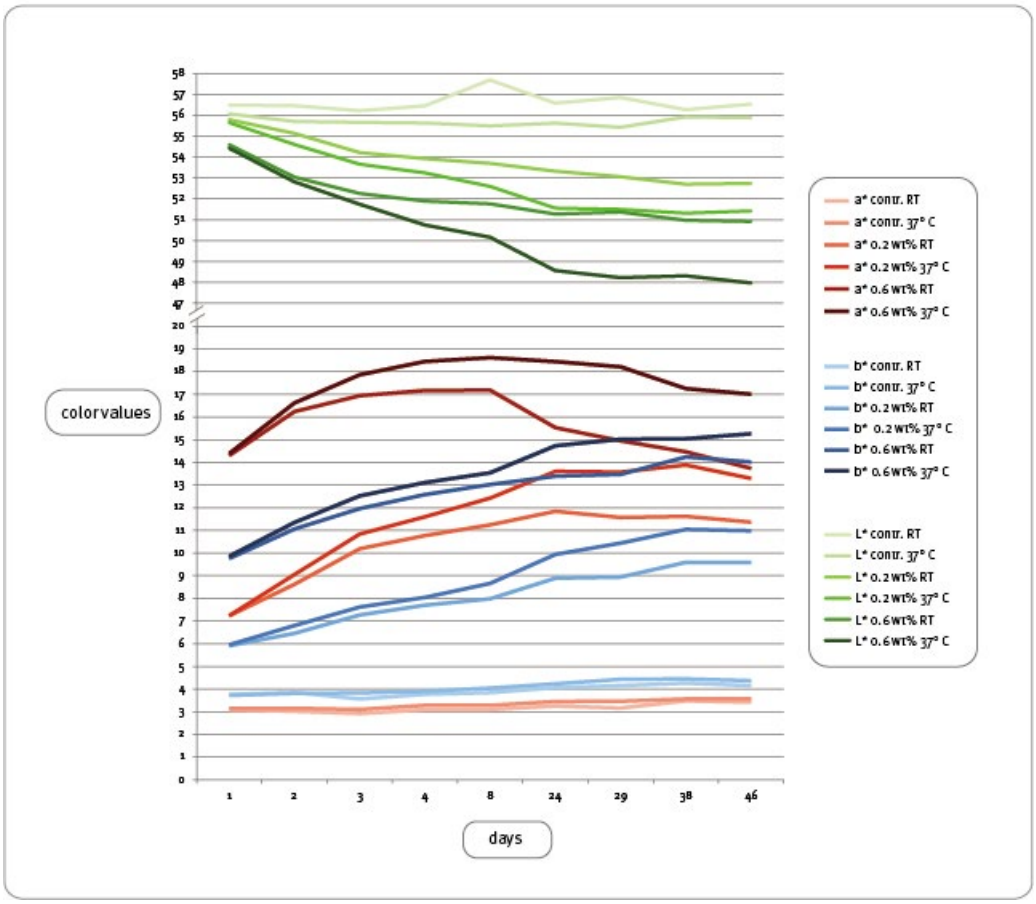


**Fig 17.** The change in color values L*, a* and b* during the artificial aging process of the silicone specimens.

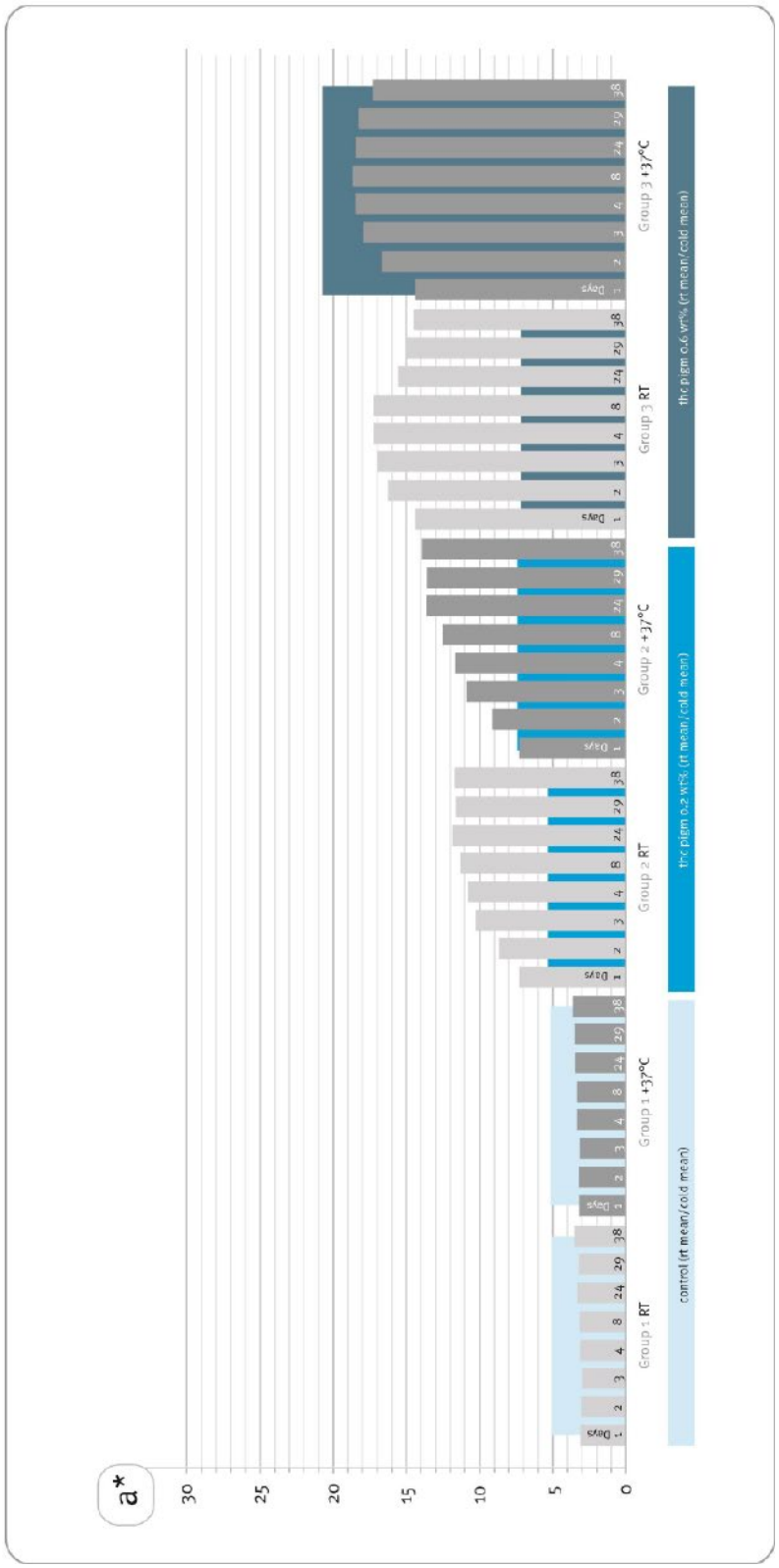


**Fig 18.** Comparing the changes in a* values, it can be seen that the color change against red, due to artificial aging, of group 2 (0.2 wt% thermochromic pigment) is even more remarkable than after storage in cold (studies III and IV).

Throughout the aging process, the specimens containing thermochromic pigment, stored in an incubator, showed a higher ΔE value than those stored at room temperature. When the specimens stored at room temperature are compared to those stored in an incubator, at 37°C and in 97% humidity, the higher a* and b* values of the specimens stored in the incubator were statistically significant ($P<0.001$) among the specimens containing thermochromic pigment. The visible color changes of the silicone elastomer specimens are shown in Fig 19.

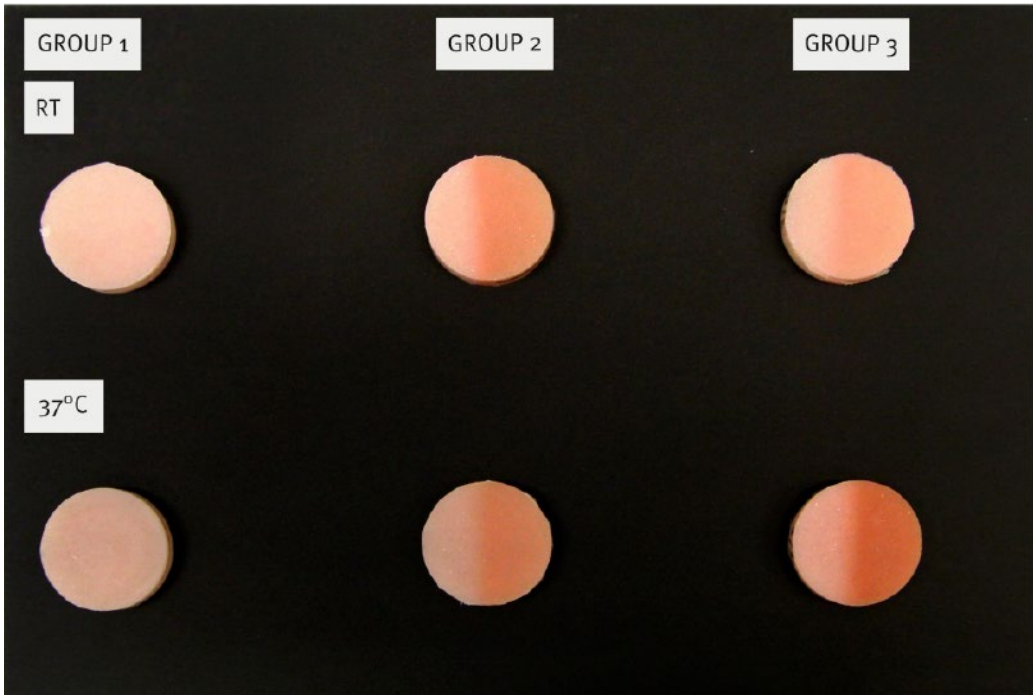


**Fig 19.** The color change of the UV exposed silicone specimens after 46 days. Group 1= control group, group 2 contained 0.2 wt% thermochromic pigment and group 3 contained 0.6 wt% thermochromic pigment (study IV).

## 5.5 Facial skin microcirculation under FRC framework (study V)

The six baseline measurements performed prior to positioning of the compression pad of face mask showed no statistical differences at any of the measurement sites. The mean values (n=10) of skin blood flow at baseline are presented in Table 8.

**Table 8.** Mean values (SD) of the baseline perfusion values inside the ring (R) and at areas 1, 2 and 3. (n=10). *P*-values are based on Friedman´s test for several related samples.

| Area | meas. 1 | meas. 2 | meas. 3 | meas. 4 | meas. 5 | meas. 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 |

The compression of the skin resulted in a brief tendency for blood flow to increase inside the ring, and a slight tendency for blood flow to decrease outside the ring. When the compression ceased, no reperfusion reactions, such as post-vasodilatation or post-vasoconstriction were detected, and the blood flow returned to baseline values very quickly. An example of the blood flow response to the applied pressure is presented in Fig 20.

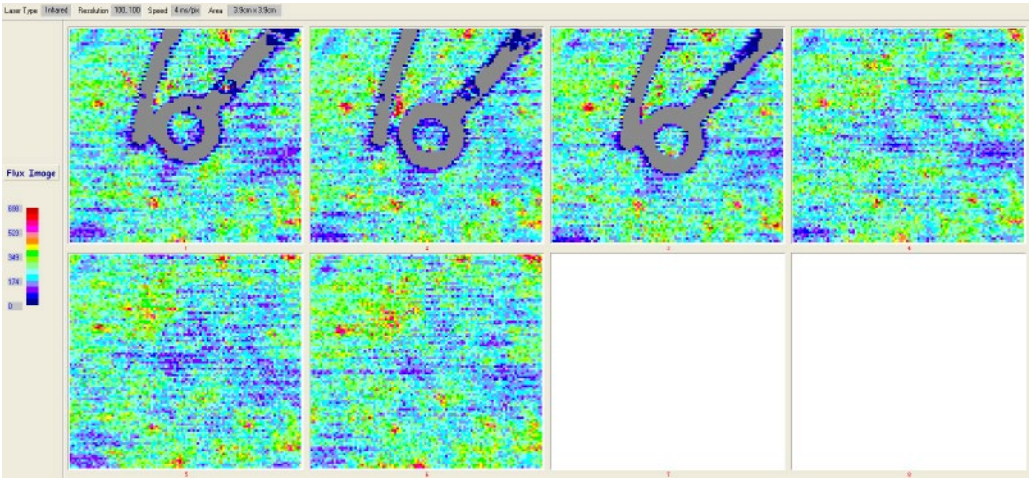


**Fig 20.** LDI scans of one subject. Skin blood flow is presented as color coded images. Blue color means a low perfusion, green to yellow indicates a mid-range perfusion and red indicates a high perfusion (study V).

None of the compressions (touch, light compression, moderate compression) led to any marked effects on the local skin blood flow at any of the measurement sites. No differences were found between the blood flow of the compressed skin and the baseline values measured before compression. However, inside the ring of the compression pad, a tendency to increased blood flow was detected during compression while the blood flow outside the ring tended to decrease (Table 9).

**Table 9.** Mean perfusion values at baseline, during compression and after compression of the skin (n=10).

| Area | Baseline perfusion | Touch (A) | Light compr. (B) | Compr. (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) |

# 6. DISCUSSION

## 6.1 General discussion

The general aim of this series of studies was to study the possibility of enhancing the quality of maxillofacial prostheses. The aim was to investigate the suitability of using a framework, constructed of fiber-reinforced composite, in maxillofacial silicone elastomer prostheses. There was some clinical experience of using FRC frameworks in maxillofacial prostheses, using the technique which is described in the case report (study I). The purpose was to find a suitable bonding agent for bonding the FRC to the maxillofacial silicone (study II) and to investigate the possible harmful effects the compression, applied to the facial tissues by the prostheses margin, especially by the ends of the fiber beams of the FRC framework and with a prostheses which is been retained by implants, could have on the blood flow (microcirculation) of the underlying skin (study V).

Further, to make a maxillofacial prosthesis, such as a nose or an ear, look more natural, a thermochromic pigment which is colorless in room temperature and changes to red in a cold environment, was studied. At first, it was evaluated if the thermochromic qualities of the pigment would function in a maxillofacial silicone elastomer (study III). Two different pigment concentrations were tested: 0.2 wt% and 0.6 wt%. The ability of the thermochromic pigment to withstand UV radiation was studied by using artificial aging (study IV). The artificial aging process was performed by irradiating the maxillofacial silicone elastomer specimens, which were divided into two groups regarding storage of the specimens in between the cycles of UV irradiation: half of the samples were stored in darkness, at room temperature, and the other half was stored in an incubator, at 37°C and a humidity level of 97%.

## 6.2 Case report (study I)

The silicone elastomer used to fabricate the facial prosthesis in the case report is the medical grade silicone MDX4-4210 (Dow Corning Corp., Midland, MI). This silicone has, due to many good qualities, been a popular material for facial prostheses. Both the mechanical and physical properties of this material have been thoroughly studied (Lewis and Castleberry 1980, Abdelnnabi et al. 1984, Bell et al. 1985, Yu et al. 1980, Wolfaardt et al. 1985, Sanchez et al. 1992, Haug et al. 1992 and 1999).

The prosthesis was retained by osseointegrated implants, by using magnets as retentive elements. The magnets were attached to the FRC framework, which functioned as a rigid housing for the attachments. During repetitive removal of the prosthesis, both the surfaces between magnets and FRC, and between the FRC framework and the silicone elastomer have to withstand adhesive failure. The tensile bond strength between the FRC and silicone elastomer of the bonding agent used in the case report, was examined further in study II.

## 6.3 Adhesion of FRC framework to maxillofacial silicone (study II)

Because there is a discrepancy between the elastic properties of the FRC and the maxillofacial silicone elastomer, it is important that there is a strong bond between these materials. Various types of stresses, in various directions, are affecting facial prostheses. The highest stress is formed when the prosthesis is repetitively removed from the retentive suprastructure, to which the prosthesis is retained by clips or magnets. The aim of this study was to investigate the bonding properties of glass FRC to maxillofacial silicone. Several studies have been conducted concerning the bond strength between dental soft silicone liners and acrylic resin. However, there is a wide variety of testing methods used in these studies, which makes it difficult to directly compare the results.

The test set-up for this study was chosen to test tensile bond strength by using the set-up according to ISO 22401, which ensures an even stress distribution at the adhesive interface. The bond strength between the substrates was studied with respect to the used primer and comparing intact and roughened (ground) FRC surface.

Comparing the primers, the A-330-G primer provided the highest bond strength. This is one of the primers recommended by the manufacturer (Dow Corning Corp., Midland, MI) of the maxillofacial silicone MDX4-4210 used in the study. This primer contains methyl ethyl ketone and dichloromethane as solvents. The polymer matrix of FRC contains a linear PMMA-polymer network and a cross-linked diacrylate polymer network (Lastumäki et al. 2003). The solvents of A-330-G primer are known to be good solvents for polymethyl methacrylate, and it is likely that the high tensile bond strength is due to dissolution of the polymer matrix of the FRC. Hatamleh and Watts studied the bond strength of the maxillofacial silicones TechSil S25, Cosmesil M511, and Cosmesil Z004 to acrylic resin, using different primers. Maxillofacial silicone Cosmesil Z004 showed the highest bond strength to acrylic resin used with A-330-G primer (Hatamleh and Watts 2010a). In a study performed at Mahidol University, maxillofacial silicone

MDX4-4210 showed high bond strength to acrylic resin. The highest bond strength was reached by using Epicon primer (manufacturer Dreve Denfamid, solvent not known), followed by A-330-G (Tri, 2006). A recent study by Haddad et al. presented the highest peel bond strength between acrylic resin and MDX4-4210 silicone by using Sofreliner primer (99.5 % methylenechloride, 0.5 % PMMA organosiloxane; Tokuyama Dental), compared to the bond strength presented by mechanical retention (scratches to the acrylic resin surface) and Dow Corning 1205 Primer (Haddad et al. 2012).

The tensile bond strengths were significantly higher, with all primers, at the ground FRC surfaces. This is understandable because the microstructure of the interface is very important. Surface roughness enhances adhesion because it provides micromechanical retention and also a better wettability of the surface. The wetting of the interfacial surfaces is required for adhesion to occur (Marshall et al. 2010). In the current study, the ground FRC surfaces tended to show more frequent cohesive bonding failures, which means that the tensile bond strength between the silicone and FRC was higher than the tear resistance of the silicone itself.

Grinding also exposed the glass fibers of the FRC. Therefore, it was unexpected that the VMS primer presented the lowest tensile bond strength of the tested primers. The VMS primer (2% vinyltrimethoxysilane, ethylacetate-based) contains a silane-coupling agent, which should react with the hydroxyl groups on the surface of the glass fibers, forming a siloxane network to which the silicone could adhere. The silane should also enhance the surface wettability, which would make the silicone adhere maximally to the irregularities of the rough surface. According to McCabe (McCabe et al. 2002), a primer containing ethylacetate provides a stronger bond between a soft silicone liner and acrylic resin, compared to a toluene-based primer.

The bonding failures in the present study were only visually inspected and analyzed. It seemed accurate enough, as the surface of the substrate was either smooth, in adhesive bonding failure, or had remnants or larger pieces of silicone still sticking to the surface in cohesive or mixed failure. Of course, a SEM analysis of the surfaces would have been more exact, and, evaluating the results, the division of specimens into groups according to the surface area of the bonding failure was rather rough, but done due to the size of the groups of specimens. However, the statistical analysis showed a distinct statistically significant difference between the groups and it can be concluded that a glass FRC substructure can be successfully bonded to maxillofacial silicone MDX4-4210 using a primer containing methyl ethyl ketone and dichloromethane solvent.

Roughening the FRC surface by grinding is recommended, as it improves the bond strength even further.

## 6.4 Use of thermochromic pigment in maxillofacial silicone (studies III and IV)

The first pigment study (study III) showed that the thermochromic pigment used in the study, ChromaZone Free Flowing Powder pigment red 15 C (Thermographic Measurements Co.Ltd, Honiton, UK) was suitable for use in silicone elastomer MDX4-4210 (Dow Corning Corp., Midland, Michigan), used for fabrication of maxillofacial prostheses. According to Seeboth and Lötsch, a concentration of 0.1 – 1.0 wt% thermochromic pigment is needed in polymers such as paints, plastics, and rubber to produce a thermochromic effect (Seeboth and Lötsch 2003). Of the two concentrations used in our studies, the 0.2 wt% concentration made the silicone specimens look naturally reddish in a cold environment while the 0.6 wt% concentration caused a color change that was too remarkable to be natural.

A significant temperature decrease (-19°C) was chosen to investigate the ability of the thermochromic pigment to change color in a cold environment. However, the AVAs (arterovenous anastomoses) present in the skin of the nose and the earlobes begin to function as soon as the skin temperature drops below +10°C (Midttun and Sejrsen 1996, Braverman 2000), which means that the color of the skin may, in some individuals, change at temperatures above zero degrees. Each leuco dye has a specific color temperature and thermochromic colorants can be tailored to have a well-defined transition temperature. The response to the temperature change is usually rapid and is limited only by the thermal conductivity of the colored polymer (Christensen 2003). However, in our study we did not investigate the temperature at which the color change of the thermochromic pigment started. In clinical use, this quality should be considered and, if possible, the pigment should be designed according to individual needs to suit the patient in question.

The used thermochromic pigment is a leuco dye incorporated in microcapsules, but the exact chemical composition of the pigment used is not known. Leuco dye-developer-solvent systems consist of three main elements: an electron-donating chromogenic compound (the leuco dye), an electron acceptor (developer) and a matrix component (solvent) (Muthyala 1997). The exact molecular mechanism of the color-forming reaction of thermochromic LDs is still unknown. Several different reversible thermochromic leuco dye-developer-solvent systems are

known. The electron-donating chromogenic compound can be represented by a phenylmethane or fluoran derivate. When the lactone ring is closed, the leuco dye (color former) is colorless or weakly yellow. As a reaction with an electron-accepting developer occurs, the lactone ring opens and a zwitterionic structure is formed. As a result of a change in the electron system the dye becomes colored. When the solvent is in a molten state, it functions as an inhibitor of the color-forming reaction, which keeps the leuco dye colorless. During the cooling process, a crystallisation takes place, and a color is developed as the dye interacts with the developer. The reversible thermochromic effect is explained by a competition between interactions of dye-developer and solvent-developer. Polymers can be doped with thermochromic additives in many ways: leuco dye-developer-solvent systems, inorganic pigments and conjugated polymers. Of these, the leuco dye-developer complexes are the most important (Seeboth and Lötzsch, 2008). Microencapsulated, thermochromic pigments have been studied by Lakio and coworkers (2010) as heat indicators during a fluid bed drying process used in the pharmaceutical industry. The purpose of the thermochromic pigment was to detect heat during a pharmaceutical drying process, where heat sensitive materials where involved. Studies concerning the use of thermochromic pigments in silicone elastomers were not found.

It is known that the leuco dyes are sensitive to both UV light and visible light. The photostability is particularly dependent on environmental factors, such as the substrate itself, the presence of water and oxygen (Caine et al. 2002). Successful studies concerning the photo-fading process have been performed. It is possible to use leuco dye-matrix-stabilizer systems, where the photo-fading process of the leuco dye is almost completely inhibited. However, these stabilizer systems do not possess reversible thermochromic qualities (Oda 2008). During the interfacial polymerizing process, called microencapsulation, where the color changing pigment and its solvent is covered with a shell to serve as a protective membrane against the environment, UV inhibitors can be added. There is ongoing research to improve the resistance of LDs to UV radiation (Ogrodnik 2008).

In study IV, artificial aging by UV exposure and storage in a warm and humid (moist) environment clearly affected the color of the specimens containing thermochromic pigment. The temperature of 37°C and the humidity was chosen to mimic the contact with the skin. As early as after one 6 hour exposure to UV radiation, the color change, $\Delta E$ value, was over 4. As a $\Delta E$ value of $> 1$ is considered to be detectable by a trained human eye, a value over 4 after just one cycle of UV irradiation is very remarkable and it shows that the thermochromic

pigment used in the study is extremely sensitive to UV radiation. Since the face is one of the body parts which is exposed to the most sunlight, it means that the pigment is not suitable for use in maxillofacial silicone elastomer, as such.

Thermochromism also exists among inorganic materials, such as metal salts and metal oxides. These possess both thermostability and light stability, but they have fixed switching temperatures, which are not suited for the temperatures used in this study. They are not transparent and they usually are toxic. The microencapsulated leuco dye-developer-solvent systems show good switching qualities and are commercially available for temperatures between -25 and +65°C (Seeboth and Lötzsch 2008).

Conventional color pigments used in maxillofacial silicones are also known to be susceptible to UV radiation and other environmental factors. Different color pigments are susceptible to the environmental factors to a different extent. Theoretically, it would be possible to incorporate UV stabilizers in the shell of the microcapsule. Different kinds of UV blockers have already been used as separate pigments in the maxillofacial silicone elastomers and might also be possible to be used in combination with thermochromic pigments. Titania and zinc oxide are used as sunscreens in cosmetics. UV-shielding nano-oxides, $TiO_2$, ZnO and $CeO_2$, have been successfully tested as opacifiers in A-2186 silicone maxillofacial prostheses (Han et al. 2010). Kiat-amnuay et al. studied the dry earth opacifier pigments artskin white and titanium white, and concluded that they did protect the maxillofacial silicone A-2000 from color degradation (Kiat-amnuay et al. 2009). However, these oxides are relatively non-transparent and have a high photocatalytic activity which can affect the other substrates. They also affect the appearance of the maxillofacial silicone, which should have a slight "translucent" appearance to resemble natural skin. Li and coworkers studied nanoparticles (3-5 nm in diameter) of zinc oxide-doped ceria, which possess both transparency and UV absorption qualities. The zinc oxide also tended to diminish the catalytic activity (Li et al. 2002). In a recent study by Han et al. (2013), a mineral-based UV light protecting agent, titanium white dry pigment and silicone intrinsic white pigment were studied as opacifiers in maxillofacial silicone MDX4-4210/Type A. They concluded that all these three opacifiers protected the pigmented silicone from color degradation due to artificial aging.

Artificial aging, as used in the current study (study IV) by using humidity, raised temperature and exposure to UV light is, of course, not comparable to natural aging in a natural environment. Similarly, the acquired time needed to make physical changes in the physical properties of a facial prosthesis in clinical use is not comparable to the time used in the artificial aging process.

It is also known that outdoor weathering exposes facial prostheses to different constituents of the atmosphere, such as sulphur dioxide, ozone, nitrogen oxide, and weather phenomenons such as rain, wind, cold and snow. According to Sampers, artificial aging might lead to more rapid changes in the material than natural use and natural weathering would do (Sampers 2002). However, it is very unlikely that the thermochromic pigment should be stable enough for clinical use in natural conditions.

The sample size of the thermochromic pigment studies (n=12 per group) was not very large. However, the data analysis showed statistically significant differences between the groups, which means that the selected sample size was large enough. The follow up of the color change ended after 46 days, when the color ceased to change.

## 6.5 Skin microcirculation under FRC framework (V)

According to the results of the study, the face mask did not give rise to any marked changes in the blood flow of the facial skin. The mask was constructed with a compression pad to correspond to one of the extensions of the FRC framework of a maxillofacial silicone prosthesis compressing the facial skin in order to keep the margin tightly in place against the skin during facial expressions and jaw movements. The compression pad was designed in the shape of a ring to enable facial skin blood flow measurement by laser Doppler technique. The laser Doppler imaging technique is considered to be a reliable technique for measuring skin blood flow, and it has also been used to measure blood flow changes in the orofacial area (Kemppainen et al. 2001a,b, and 2003).

In the present study, the compression of the skin was seen to cause only a short lasting reduction in blood flow in the area close to the compression pad. The spatial differences between the measurement sites were small, and even the strongest compression force did not induce marked skin blood flow changes or signs of reperfusion under the compression pad or at any of the other measurement sites close to the compression pad.

It is not known what the critical amount of pressure is to create tissue damage. In long-term care, pressure-evoked harmful effects and pressure ulcers are a frequent problem. There are both extrinsic and intrinsic risk factors for developing pressure ulcers. Poor nutrition has also been associated with pressure ulcers, but there is not enough evidence of a causal relationship (Bluestein and Javaheri 2008). The pathogenesis of pressure ulcers is multifactorial, including local

ischemia and pressure- evoked tissue rupture and damage (Gawlitta et al. 2007, Bluestein and Javaheri 2008, van Gilder et al. 2008). The highest compression force used in this study was designed to be higher than that of the pressure of a beam of a FRC framework in a clinical situation, and it was calculated to be 5.5 kPa. The compression force of the applied "light" pressure in this study resembles a peripheral end of a fiber extension of a tightly fitting prosthesis´ margin. This is the site where the compression on the facial skin is the highest, and it could be estimated to be ~ 2-3 kPa. The soft, resilient silicone margins of a facial prosthesis, which usually is retained by implants, will apply an even smaller pressure on the skin. The amount of pressure needed to develop tissue change is not exactly known. Landis proposed the "critical pressure" to develop tissue damage to be 4.27 kPa (32 mmHg) (Landis 1930) while later studies found significant blood flow decrease under experimentally applied pressure of 5.3 kPa (Colin and Saumet 1996) and 6.47 kPa (Fromy et al. 2002) which may lead to a significant decrease in the skin blood flow of the sacral area and on top of the ankle bone, respectively.

The test subjects of the present study were young and healthy individuals with a, presumably, ideal skin blood flow. However, diabetic patients are more susceptible to blood flow decrease as a result of applied pressure to the skin and may, therefore, have a higher risk of developing pressure ulcers than healthy subjects (Fromy et al. 2002).

The present study, performed with 10 healthy, young adults showed rather high individual differences in skin blood flow. By using the results of this study, which had a rather small test group, power calculations can be performed to estimate the size of suitable test groups in further studies concerning facial skin blood flow. Studies with test subjects of older age, who possibly also have compromised blood flow, should be performed to confirm the safety of using a facial prosthesis with a slightly skin compressing FRC framework and prosthesis margin.

## 6.6 Clinical considerations

Debonding of the silicone from the acrylic resin base or clip carrier is a frequent problem in clinical use of facial prostheses (Visser et al. 2008). Adhesion of the FRC framework to maxillofacial silicone shows bond strength high enough to offer a solution to this problem. This is shown in study II, and clinically in the case report (study I), where the fabricated prosthesis was in use for 7 years. Since the average life span of a facial prosthesis is as short as 1.5 - 2 years, this is

a very promising result. The FRC framework does also have many other clinical advantages compared to acrylic resin in smaller facial prostheses, such as ear-prostheses.

For clinical use, there are several requirements for the thermochromic pigment to fulfil. Thermochromic colorants are generally expensive as they require a highly specialized fabrication process. On the other hand, the amount of thermochromic pigment powder needed for coloration of a maxillofacial prosthesis should probably not raise the costs of a facial prosthesis too much.

There are also health issues, as the prosthesis has to be in close contact with the facial tissues. According to the manufacturer, the studied thermochromic pigment is non-toxic, however, the exact chemical composition of the pigment is not known. Reversely, the possible effect of body fluids, like sweat, and of the skin microflora on the prosthesis material has to be considered.

Further, the handling properties of this pigment should be enhanced. It was difficult to get the pigment evenly mixed in the maxillofacial silicone, even though the viscosity of the silicone felt low enough. The pigment possessed a lot of static electricity, which caused the powder to cluster. This is seen as small, red spots in the silicone of the ear prosthesis in study III. Though, it is the high sensitivity of the pigment to the UV light which still limits the clinical use of it. If the resistance to UV light is enhanced, the pigment might have clinical implications, especially in countries with distinct seasonal variations in weather.

## 6.7 Suggestions for further research

Regarding the use of glass FRC framework in facial prostheses, further studies are needed to evaluate the proper design of the FRC framework in different kinds of facial prostheses. Especially in ear prostheses, a small framework fabricated of FRC could be even more clinically suitable than a clip carrier base made of PMMA. Studies concerning the bonding of magnets or metal clips directly to the FRC framework could be performed to find the most suitable bonding agent for this purpose.

Larger studies concerning facial skin microcirculation should be performed on different age groups and, if possible, also on subjects who have undergone radiation therapy. These patients are likely to be rehabilitated with facial prostheses due to cancer surgery. The laser Doppler imaging technique also seems to be a suitable technique for studying facial blood flow in larger study

groups. However, the facial mask used in study V could be redesigned to fit more comfortably for the study subjects.

Further studies concerning the use of UV absorbers in polymers, such as maxillofacial silicone elastomers, colored with thermochromic pigments could be performed. However, these kinds of studies have to be done in cooperation with specialists in the field of polymer chemistry.

# 7. CONCLUSIONS

Based on the case report and the four studies, it can be concluded that:

1. A framework of pre-impregnated, unidirectional fiber-reinforced composite (FRC) can successfully be clinically used in a facial prosthesis fabricated of maxillofacial silicone elastomer.

2. The tensile bond strength between pre-impregnated, unidirectional FRC and maxillofacial silicone elastomer can be improved by roughening the FRC surface. Comparing three different primers (Gold Platinum primer A-330-G, VMS primer and Sofreliner primer), the highest tensile bond strength is achieved with Gold Platinum Primer, which contains methyl ethyl ketone and a dichloromethane solvent. By roughening the surface and using a primer, the FRC framework of a maxillofacial prosthesis can be successfully bonded to the maxillofacial silicone.

3. A thermochromic pigment has reversible color changing capacities when used in maxillofacial silicone. Concentrations of 0.2 wt% and 0.6 wt% thermochromic pigment in maxillofacial silicone show instrumentally measurable and visually detectable color changes after stored in a freezer, as compared with color stored at room temperature.

4. A warm and moist environment and especially exposure to UV radiation, leads to early and remarkable color changes of maxillofacial silicone containing thermochromic pigment. The pigment is not suited, as such, for clinical use in maxillofacial prostheses.

5. A FRC framework of a facial prosthesis, which compresses the facial skin at the margins of the prosthesis, does not affect the microcirculation of the facial skin in young and healthy individuals.

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Rosita Kantola

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