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**EAR RECONSTRUCTION
CLINICAL AND PHYSIOLOGICAL EVALUATIONS**

Ear Reconstruction

Clinical and physiological evaluations

Martin Öberg

Academic thesis

With permission from the Medical Faculty at Lund University for presentation of this PhD thesis in a public forum in the Aula, Inga Marie Nilssons gata 46, Skåne University Hospital, Malmö, on Friday, November 30, 2012, at 09:00.

Fakulty opponent:

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HUS (Hospital district of Helsinki and Uusimaa), Finland



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Malmö 2012

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Abstract <p>Microtia is a congenital malformation where the auricle is not fully developed. In some cases the malformation is complete and the auricle is absent. In Sweden the incidence of microtia is about 2 per 10,000 births. Reconstruction of the external ear is possible by using autologous rib cartilage in three surgical steps: rib cartilage transplantation, ear elevation and final adjustments.</p> <p>Although the aesthetic result is most essential, there are also functional aspects of a reconstruction of the outer ear. To keep the ear free from injury, the skin depends on a functioning alert system: sensitivity to touch, heat and cold. However, the process of ear reconstruction necessarily includes surgical trauma that endangers these protective systems. The blood supply of the skin cover is also impaired during the different reconstructive stages. Little is known about the level and time scale of recovery of sensitivity and blood supply to the reconstructed ear after surgical bisection of nerves and vessels.</p> <p>Symmetry is important in ear reconstruction and the new ear should match the normal ear at the time of reconstruction as well as in the adult life. The potential growth of the ear is a subject of debate. We decided to investigate the precision of today's tools for size measurements. With this knowledge the issue of growth hopefully can be elucidated.</p> <p>A total of 54 patients with unilateral ear reconstruction, and 30 individuals with normal ears, were included in the studies. We evaluated sensitivity to heat, cold and touch in the reconstructed and normal ear. We also assessed blood flow before and after body heating to investigate the pathophysiological dynamics in the reconstructed ear.</p> <p>Digital morphometry for measuring ear size was compared to the manual methods: compass & ruler and callipers. Measurements were performed on individuals with normal ears. In digital morphometry we also measured reconstructed ears.</p> <p>Our findings show that there is a high degree of restoration of thermosensitivity in the reconstructed ear but the upper parts of the ear still show signs of reduced sensitivity to heat. Tactile sensitivity followed that of thermal sensitivity, with a high degree of restoration in combination with elevated thresholds in the upper parts. The basal blood flow in the reconstructed ear is compatible with that of the normal ear and its dynamic response to indirect heating is also similar. Digital morphometry shows a similar reproducibility as compass & ruler and callipers for measurement of normal ears. Digital morphometry can show great precision in measurements of reconstructed ears but there is high inter-individual variation between different assessors.</p>			
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Date November 30, 2012

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List of Papers

This thesis is based on the following papers, which will be referred to in the text by their Roman numerals.

- I Thermosensitivity in a reconstructed microtic ear Martin Öberg, Magnus Becker, Marthe Arktander, Maria Centerman, Henry Svensson & SO Wikström
Scand J Plast Reconstr Surg Hand Surg, 2008;42:190–193
- II Threshold of tactile perception in a reconstructed auricle Martin Öberg, Henry Svensson, Magnus Becker & SO Wikström
J Plast Surg Hand Surg, 2011;45:23–27
- III Blood flow dynamics in reconstructed auricles Samuel Grayson, Martin Öberg, Magnus Becker, Per Wollmer, Henry Svensson, SO Wikström
J Plast Surg Hand Surg, Accepted
- IV A comparison of digital morphometry and clinical measurements of ears Martin Öberg, Christoffer Björk, Johan Flodin, Magnus Becker, Henry Svensson, SO Wikström
J Plast Surg Hand Surg, Accepted with minor revisions

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Introduction

Microtia is a congenital malformation where the auricle is not fully developed. In some cases the malformation is complete and the auricle is absent, i.e., anotia. Associated malformations may occur and most common are facial clefts and cardiac defects. Conductive hearing impairment due to atresia of the auditory canal is seen in the majority of patients with microtia. The etiology is multifactorial; both genes and environmental factors are believed to play a role in cases of microtia (1). In Sweden the incidence of microtia or anotia is about 2 per 10,000 births (2).

Reconstruction of the external ear is possible by using autologous rib cartilage. Although the aesthetic result is most essential for the patient, there are also functional aspects of a reconstruction of the outer ear. The thin layer of skin is crucial for the survival of the cartilaginous framework of the reconstructed ear. To keep the site free from injury the skin is dependent on a functioning alert system: sensitivity to touch, heat and cold. However, the process of ear reconstruction necessarily includes surgical trauma that endangers these protective systems.

The blood supply of the skin cover is also affected during the different reconstructive stages. Little is known about the level of recovery of blood supply to the reconstructed ear after surgical bisection of arteries and veins to the recipient site. Investigating the recovery of blood supply can contribute to a safe and effective timing of the different stages of ear reconstruction.

Obtaining symmetry is a primary goal in ear reconstruction. The new ear is dimensioned to fit the normal contralateral ear of the child. The potential growth of the cartilage in the reconstructed ear is a subject under debate (3, 4). In order to assess any growth of the reconstructed ear, we decided to evaluate the precision of the methods used for measuring size.

The use of rib cartilage in ear reconstruction was described by Tanzer in the late 1950s

(5); however, the protocol for total ear reconstruction as we know it today was first developed by Brent in 1974 (6–9). In four stages, he performed a framework construction from rib cartilage, followed by a lobule transposition, elevation of the ear with skin graft and finally reconstruction of the tragus. In 1993, Nagata published a new technique, showing the possibility of reconstructing the auricle in only two surgical procedures (10–14). The Nagata technique is an excellent one in trained hands, but can otherwise be a serious challenge, as noted by Firmin based on her great experience with the two techniques (15). The development and refinement of their reconstructive techniques has made it possible to obtain three-dimensionally detailed ears, with an appearance similar to that of a healthy, normal ear. This development has led in our unit to a strategy based on three operative steps.

Embryology

The development of the outer ear starts from the first and second pharyngeal arch during the fifth week of pregnancy. Protuberances, also known as the hillocks of His, are formed around the first pharyngeal cleft and first detectable from the sixth week of pregnancy. These protuberances will form the specific anatomical landmarks of the external ear (Figure 1). The ossicles of the middle ear develop from the mesenchyme of the neural crest cells. The auditory canal derives from the cleft between the first and second pharyngeal arches (16). The auricles are initially formed at the base of the neck and will then migrate to reach their final location by gestational week 20 (1). In severe cases of microtia this migration is disturbed, resulting in a low position of the malformed ear (Figure 2). Sensorineural hearing is usually not impaired since the development of the inner ear is anatomically separate from the middle and outer ear during the initial embryological phase.

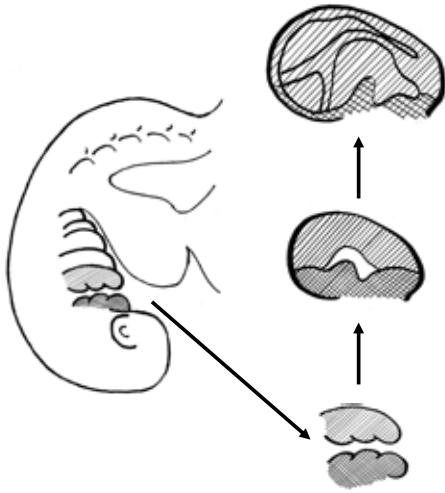


Figure 1. Schematic view over the development of the first (chequered) and second (lined) branchial arch to a mature ear (after Raymond W. Sze in *Hemifacial Microsomia in Pediatric Patients* (17))



Figure 2. Interrupted cranial migration of the ear. Associated malformations. [Printed with kind permission].

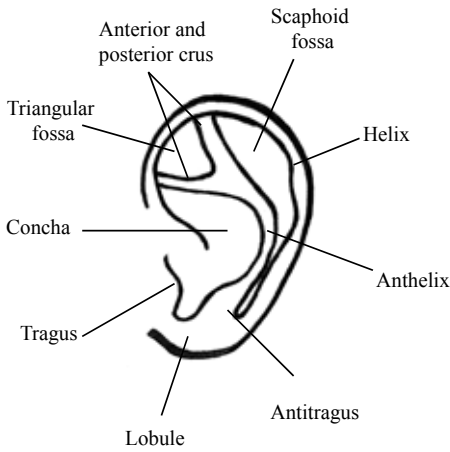


Figure 3. Anatomical landmarks of a normal ear

Anatomy of the normal auricle

The important anatomical landmarks of the ear are shown in Figure 3.

The blood for the auricle is provided by the posterior auricular artery, which is a branch from the external carotid artery. The anterior auricular artery derives from the temporal artery, which also contributes to the vascular supply.

The main sensory innervation of the normal auricle is provided by the posterior branch of the greater auricular nerve and the auriculotemporal nerve. A branch of the vagus nerve and the facial nerve also innervate the concha (18).

Types of microtia

Microtia includes a spectrum of deformities ranging from mild deformation of the auricle ranging from mild deformation of the auricle to anotia. There are different classifications based on the extent of malformation. When considering ear reconstructions, the most useful classification will emanate from the specific surgical conditions and limitations correlated with each type of microtia. Each type of microtia in such a classification will demand unique cartilage frameworks and/or incisions (Figure 4).

Microtia is often part of a spectrum of malformations named hemifacial microsomia



Concha type



Small concha type



Lobule type



Anotia



Figure 4. Classification of microtia shown as schematic drawings and photos of each type.

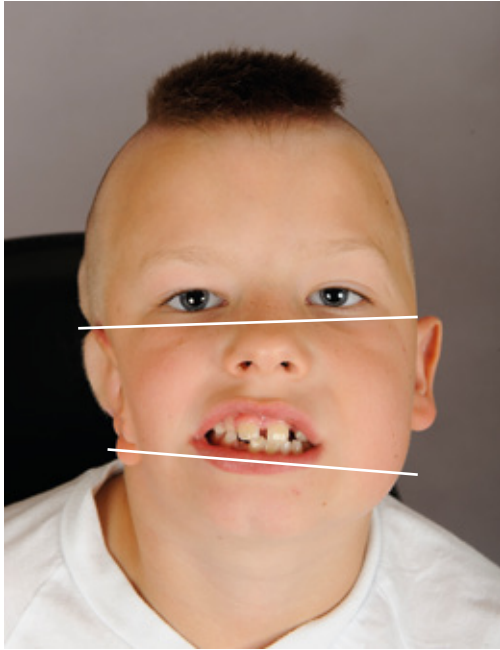


Figure 5. A boy with hemifacial microsomia and microtia under reconstruction. Note the scoliosis of the face. [Printed with kind permission].

(Figure 5)(19, 20). It ranges from slight scoliosis of the face to severe hypoplasia of several structures such as the mandible, maxilla, zygomatic temporal bone and muscles of mastication; structures that also emanate from the first and second branchial arch (17).

Etiology – environment versus genes

An overview of the etiology of microtia was presented by Alasti and co-workers (1). The development of the middle ear and the auricle is complex and different tissue interactions take place during their embryogenesis. The etiology of microtia is likewise complex and multifactorial, in isolated cases as well as in syndromes including malformation of the auricle. Both genes and environmental factors may contribute. The Hox genes are one type of homeobox gene believed to be of importance for the development of the

second pharyngeal arch. The gene encoding the PACT protein is also important for the development of the outer ear. In Pact knockout mice there are reductions of the outer ear and the auditory canal. The ossicles are malformed and hearing is impaired. A mouse with a homozygous defect in the Tbx1 gene also has impaired development of the middle and outer ear. The human equivalent is seen in DiGeorges syndrome, where the TBX1 gene is deleted.

Environmental risk factors such as pre-eclampsia, acute maternal illness, anaemia, high maternal or paternal age and multiple births have been suggested as possible risk factors (2, 21). Some studies have indicated a higher risk of having a child with microtia if the mother suffers from diabetes type 1, but the number of cases in these studies is small and the finding must be interpreted with caution (22–25).

Pharmacological treatment during pregnancy can in some cases disturb the development of the ear and adjacent structures. For instance, the dermatological drug isotretinoin (Roaccutan®) and the immunosuppressive substance mycophenolate mofetil (Cellcept®) are both thought to be capable of inducing microtia. Excess vitamin A is known to be teratogenic in animal studies, resulting not only in microtia but also facial clefts and micrognathia.

Heredity

Most cases of microtia are sporadic. However, Mendelian inheritance has also been reported, illustrating the relevance of genetic factors. In Finland, for example, over 20 percent of the microtias were thought to be an inherited condition. Autosomal dominant inheritance with incomplete penetrance was seen in most cases but there was a possibility that several genes were involved. Autosomal recessive inheritance cannot be excluded in the remainder of the patients (26).

Syndromal microtia has also been described. Treacher-Collins syndrome, for example, includes hypoplastic facial bones, microtia, micrognathia and cleft palate (27).

Epidemiology

International studies on the prevalence of microtia or anotia show rates ranging from 0.83 to 3.45 per 10,000 births. The prevalence in Sweden is 2.35. There are clear racial variations, with high prevalence in Hispanics, for example.

The right side is affected in about 60% of the cases of unilateral microtia. Boys are affected more often than girls, with a ratio of 1.66. Bilaterality is seen in about 10% of the patients and is more often associated with other malformations, as is left-sided microtia to some extent (2). The reasons for these differences are unknown.

Ethics

All investigations of the patients participating in the studies were non-invasive and can be considered as a follow-up of the reconstructive result from a functional point of view. Permission to create a registry of the patients was obtained from the hospital authorities.

The contemporary treatment protocol at the Scandinavian Ear Reconstruction Centre

A patient with microtia can be a subject for ear reconstruction with autologous rib cartilage if he/she:

- is well-motivated
- is well informed about and able to grasp the main content of the surgical procedures as well as the expected result
- is informed about the pros and cons of ear reconstruction in relation to the alternatives (i.e. prostheses or doing nothing at all)
- has enough material to build a new ear (i.e. thorax circumference >60 cm)

Taking these requirements into account, a reconstruction is most often initiated at the age of seven years. Under these circumstances there

is a good chance that the patients will be happy with their reconstruction (28).

During the initial years of the program, the reconstructions were performed strictly according to the original Brent technique, but during the last decade we have used a three-stage procedure influenced by the techniques of both Brent and Nagata. Compared with the four-stage procedure, the lobule is not transposed as a separate stage and the framework is more detailed from the 3-dimensional point of view.

Stage I – construction of the cartilage framework

In the first stage of ear reconstruction, cartilage is harvested via a small 3–4 cm incision on the thorax. The area is widely undermined to gain access to the cartilage of the ribs. The cartilage is harvested, leaving the deep layer of perichondrium intact if possible (Figure 6). A standardised instrumental set-up is used for carving the framework (Figures 7 and 8). The different cartilage components and how they are assembled is shown in Figure 9.

In the recipient site, the lobule is transposed and the excess original cartilage removed. A subcutaneous pocket is created and the cartilage framework put in place. If possible, a subcutaneous pedicle is preserved in the concha area to ensure blood flow to the overlying skin. Excess costal cartilage is deposited subcutaneously near the ear to be used in the third stage. In order not to compromise blood supply, excess skin is left to be excised in the last stage (Figure 10).

Stage II – Elevation of the ear

The ear is elevated by separating the cartilage framework from the mastoid, preserving a thin layer of soft tissue on either surface. The ensuing defect, e.g., the posterior aspect of the ear and the mastoid area, is reconstructed with a full thickness skin graft from slightly above the inguinal fold (Figure 11).



Figure 6. Cartilage is harvested from the costal arch

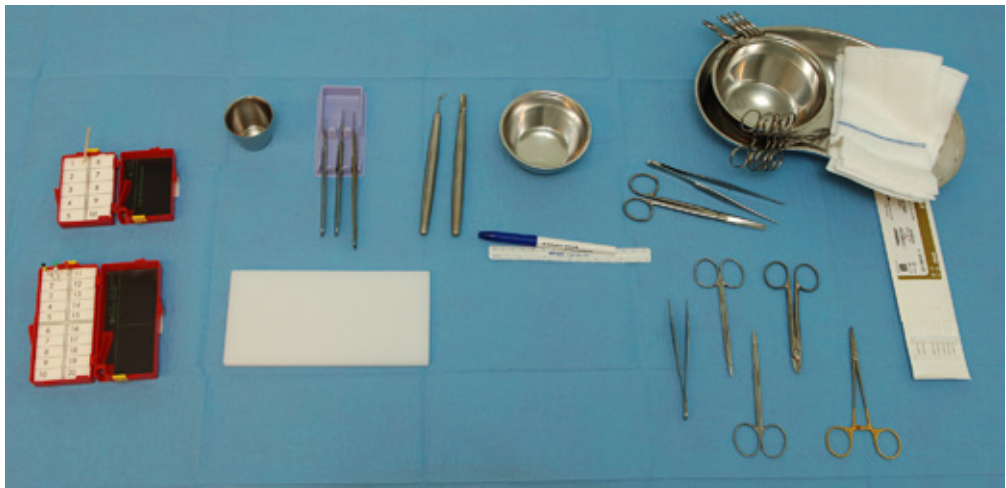


Figure 7. The standard setting of instruments including chisels for carving cartilage



Figure 8. Teamwork

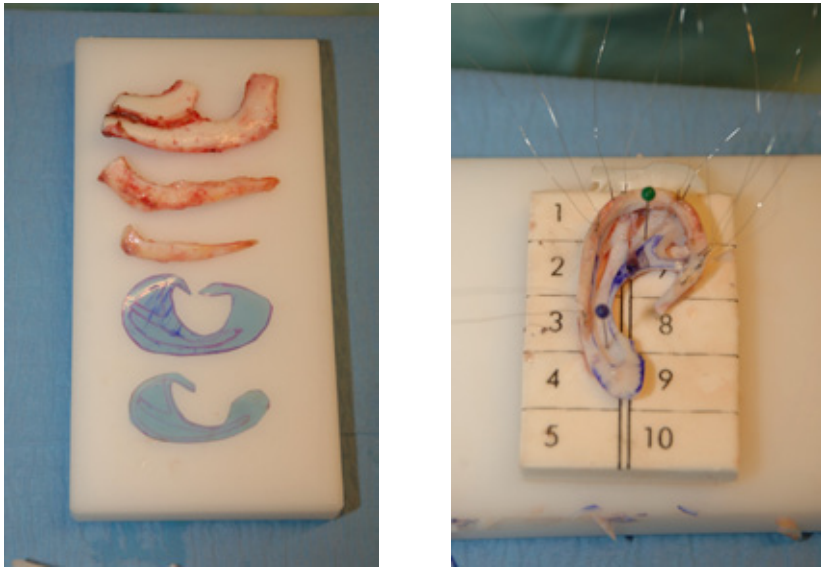


Figure 9. The pieces of cartilage are carved to shape the different components of the ear and then assembled with stainless steel wires.



Figure 10. Stage I. Transposition of the lobule. Cartilage framework set in place.

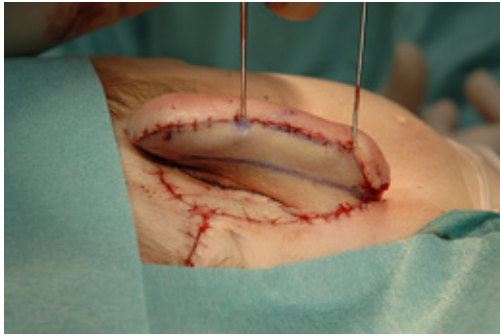


Figure 11. Stage II. Elevation and grafting.



Figure 12. Stage III. Cartilage wedge to enhance projection. Removal of excess skin.

Stage III – Projection and refinement

The cartilage that was deposited subcutaneously in the first stage is now used to form a wedge that is inserted behind the ear. The wedge enhances the projection of the ear. Surplus skin is finally excised (Figure 12).

The surgical trauma

Regardless of the technique used, the tissue of the recipient site is affected to some extent. Cutaneous nerves and vessels are necessarily bisected when incising and undermining the area. This creates a risk of compromising sensitivity and blood flow in the skin over the reconstructed auricle.

The protective sensitivity of the ear is essential to prevent damage to the reconstructed auricle. An ear insensitive to heat, cold or pressure could be more prone to developing ulcers. Such an ulcer in the skin can lead to infection of the cartilaginous framework, threatening the whole ear.

There is a necessary intermission between the different stages in the reconstructive process. The blood flow needs to be restored after the wide undermining in the first stage to allow an almost circumferential incision in the second stage. How fast this process occurs has not been studied previously. Consequently, the shortest intermission between the different stages of a safe reconstruction has not been defined.

Wound healing and angiogenesis

An overview of the wound-healing was presented by Martin and co-workers (29). The process of wound healing can be divided into four phases: hemostasis, inflammation, tissue proliferation and remodelling of the tissue. The phases overlap in time. When tissue is injured, blood leaks from vessels to produce a blood clot. The blood clot with its matrix of platelets and fibrin fibres serves as a temporary protection for the exposed tissue. As the platelets degrade, cytokines and growth factors seep out and start the healing process by attracting inflammatory cells. Monocytes and neutrophils are attracted to the wound-site, not only by the cytokines, but also by debris from bacteria. Apart from cleansing the wounded tissue, the neutrophils produce pro-inflammatory cytokines that can activate local fibroblasts and

keratinocytes. The process of reepithelialisation starts almost immediately after the injury by lateral migration of epidermal cells. The epidermal cells behind the row of migrating cells start to proliferate within a couple of days. New blood vessels grow into the wound site since the healing process requires energy and material for building tissue. This angiogenesis is mediated through an array of substances including fibroblast growth factors, vascular endothelial growth factor and angiotropin. Macrophages play an important role in angiogenesis and many angiogenic factors are produced by these cells. Low oxygen tension and high lactic acid concentration also promote angiogenesis.

In the second week after injury, the wound contracts and the tissue reorganizes. Fibroblasts develop capabilities of contraction by producing bundles of actin-containing microfilaments. By linking the cells to the extracellular matrix or to other cells, these myofibroblasts can cause wound contraction. Granulation tissue remodels to form a scar by continuous synthesis and degradation of collagen.

Nerve regeneration

The basic principles of nerve regeneration have been outlined in several previous works. Bisecting an axon divides the nerve cell into a proximal and a distal part related to the cell body. Since the axonal transport of cell components is disrupted the ends of the bisected section will swell, in particular the proximal end, as the cell body will continue their production. The nerve terminal cannot synthesize these components and will degenerate as the axoplasmic flow stops. The distal axon segment will undergo a Wallerian degeneration over a couple of months. The myelin sheaths disappear, leaving clumps of debris. In the peripheral nervous system, macrophages will help to destroy this debris and also secrete factors that promote nerve regeneration by stimulating Schwann cell proliferation. Interleukin 1 is secreted by the macrophages and will stimulate the Schwann cells to produce nerve growth

factor (NGF). The clumps of debris will serve as a guide for the proliferating and migrating Schwann cells.

Configuration of the reconstructed ear

Achieving symmetry is a primary goal in ear reconstruction. The details of a normal ear should be represented in the reconstructed ear. The size of the ear is also of importance for a good end result. The amount of rib cartilage available depends on age and body constitution and may be a limiting factor. Figure 13 shows that the ear of a seven-year-old child will grow less than 7.5 mm until the age of eighteen (30, 31). Potential growth of the reconstructed ear in relation to growth of the normal ear is hard to predict and the subject is actually under debate. Clinical impressions regarding growth of the cartilage framework point both in the direction that growth does occur and that it does not. We even have examples of patients where the auricle has actually shrunk over a period of years. When determining growth, one problem is to distinguish between the size of the cartilage and size of the total ear, because the thickness of the skin is difficult to estimate (3, 4). Another problem is that all methods used for measuring size are encumbered with a certain random error. There are consequently different factors to relate to when deciding on the optimal moment for the first stage of the reconstruction, with the aim of obtaining symmetry in the long run, and obviously there are no clear answers. In searching for these answers, the first step is to evaluate the tools for measurements.

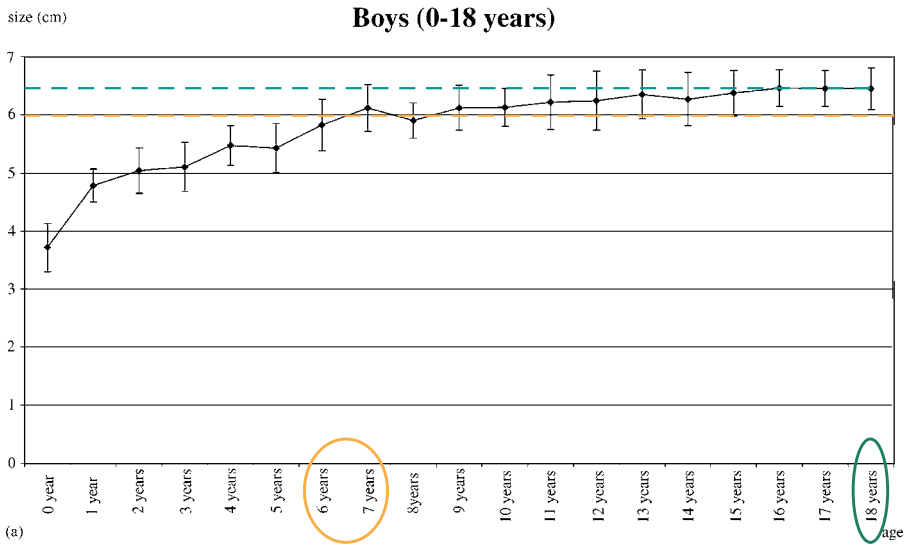


Figure 13. The growth of the normal ear according to Kalcioğlu *et al.*, (31). Reprinted with kind permission.

Aims of the study

- to quantify the degree of restoration of thermo-sensitivity in the reconstructed ear (I)
- to quantify the degree of restoration of tactile sensitivity in the reconstructed ear (II)
- to investigate the pathophysiology of skin blood flow in the reconstructed ear (III)
- to clarify the precision and reproducibility of digital morphometry, compass & ruler and calliper techniques for measurements on ears (IV)
- to evaluate the utility of digital morphometry for measurements in cases of microtia (IV)

Materials

Altogether 54 patients with unilateral microtia participated in the studies, of which 22 partici-

pated in more than one. They had all undergone ear reconstruction with autologous rib cartilage. How they participated in the various studies is shown in Table I. At least six months had passed since their last operation. Their ages ranged from 6–22 years at examination.

Eleven boys and eight girls were included in Study I. Their ages ranged from 10 to 20 years (14.6 ± 2.6 years). A mean time of four years (3.6 ± 1.7 years) had passed since their last operation. Additionally, eight healthy volunteers participated, aged from 8 to 19 years (12.9 ± 3.4 years) (6 girls and 2 boys).

Twenty-four boys and 15 girls were included in Study II. Their ages ranged from 8 to 21 years (median: 13 years). A median time of 20 months (6–60) had passed since their last operation.

Six boys and four girls were included in Study III. Their ages ranged from 9 to 22 years (median: 14 years). At minimum, 5 months days had elapsed since their final operation (range: 5 months–7 years).

Thirty students were included in the first se-

Table I. Participation in papers I–IV

Pat no	Article I Thermosensitivity	Article II Tactile sensitivity	Article III Blood flow	Article IV Digital morphometry (series II)
1		•		
2	•			
3	•	•		
4	•	•		
5		•		
6	•	•		
7	•	•		
8		•	•	
9	•	•		
10	•	•		
11	•	•		
12	•		•	
13		•	•	
14		•		
15	•	•		
16		•		
17	•	•		
18		•		
19		•		
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21		•		
22		•		
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29	•	•		
30	•	•		
31		•	•	
32		•		
33	•	•		
34			•	
35			•	
36		•		
37	•			
38	•			•
39	•	•		•
40	•	•		•
41				•
42				•
43				•
44				•
45		•		•
46			•	•
47				•
48			•	
49			•	
50			•	
51		•		
52		•		
53		•		
54		•		
Total	19	39	10	10

ries in Study IV. In the second series, photos of ten patients with unilateral microtia were analysed.

Methods

Sensory testing

In study I, a SenseLAB MSA thermo test with a 9 x 9 mm thermode was used for the Quantitative Sensory testing (QST).

In study II, the Semmes-Weinstein monofilament test (SWMT) was used to evaluate the protective sensitivity. A complete set of 20 monofilaments ranges from 1.65 to 6.65 (0.008–300 grams of target force). The most suitable for our purpose was the Touch-Test hand kit consisting of five different monofilaments, namely 2.83, 3.61, 4.31, 4.56, and 6.65 representing normal sensitivity, diminished light touch, diminished protective sensitivity, loss of protective sensitivity, and deep pressure sensation only, respectively.

Three areas were tested: the upper helix, the anthelix and the lobule.

Subjective evaluation of sensitivity

Using a simple chart, the patients in Study I were asked if the sensations of touch, heat and cold were more or less in the reconstructed ear or if the sensations were equal to the normal ear. They were also asked if they had ever noticed any difference in overall sensitivity.

Temperature

In study I, skin temperature was measured using a Tempett IR thermometer, SenseLAB. In study III, skin temperature was measured in °C using an electrical universal thermometer (Ellab, Type TE3; Electrolaboratoriet, Copenhagen, Denmark) while body temperature was measured in the auditory canal of the normal ear

(Thermoscan, Braun IRT4520, Braun GmbH, Kronberg, Germany).

Blood flow

In study III, Laser Doppler Perfusion Imaging (LDPI) (PIM II Laser Doppler Perfusion Imager, Lisca Development AB, Linköping, Sweden) was used to assess blood flow in the reconstructed ear and the normal ear. As Figure 14 shows, recordings were made from the helix/posterior crus, the concha and the lobule, representing three regions of interest (ROI).

Body heating

In study III, a tunnel shaped heating device (FAMA 1000 W, Burbach & Sohn, Vallendar am Rhein, Germany) was put over the torso in order to raise the body temperature. The heating device produced air at a temperature of 80°C, thereby exposing the torso to warmth.

Metric measurements

The ears were measured in study IV using compass & ruler (CR), calliper (CA), and digital morphometry (DM).

In CR, the tips of the compass were adjusted according to the height of the ear. The distance between the tips was measured with a ruler scaled in millimetres.

In CA, the tips of a calliper were adjusted according to the height of the ear without seeing the scale. Thereafter the distance was read from the calliper scaled in tenths of millimetres.

In DM, the photos were taken in profile with the ear and the camera levelled. A ruler was positioned adjacent to the ear. A digital image-processing program, Picsara 9.2 (Euromed Networks, Stockholm, Sweden) was used for the measurements after calibration against the ruler in each photo.

In the prospective part of study IV (series I) all ears were photographed using a NIKON D50 digital camera with a NIKON 18–55 mm lens

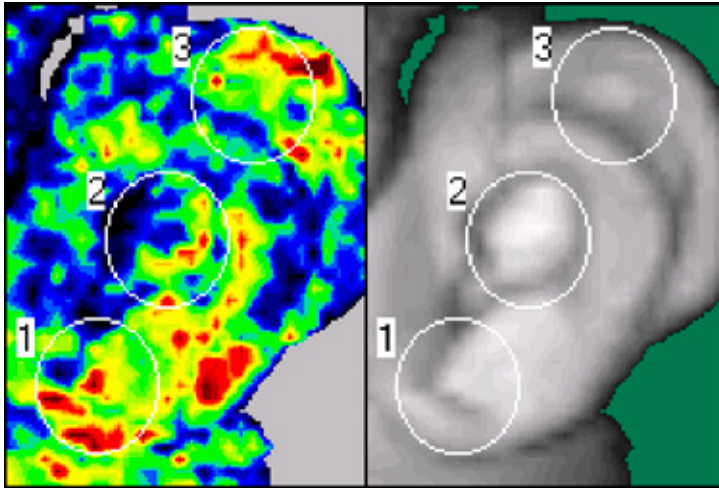


Figure 14: Representative image in LDPI showing the three ROIs and the blood flow distribution after indirect heating.

set to a focal length of 55 mm. All the photos in the retrospective part (series II) were part of our standardized routine follow-up and hence taken with different cameras.

Statistical analysis

The statistical tests in Studies I–III were performed using the Statistical Package for the Social Sciences (SPSS). Paired Student’s *t* test was used in study I where each value was compared to the control, i.e., the normal ear. In study II, Fisher’s exact test was used since the numbers in the different groups were small. Wilcoxon’s signed rank test was used in study III to analyse changes in blood flow and temperature.

Study IV, algorithms were created in Microsoft Excel for the calculation of random error and systematic error. Random error was calculated to reflect precision and expressed as a value \pm 2SD. Systematic error is the difference between means in two sets of readings. Intra-Class Correlation coefficient (ICC) is a general measure of agreement and is dependent on both random and systematic errors. ICC was

calculated in SPSS. Bland-Altman plots were drawn to detect any systematic variation over the range of readings (32).

Values are given as median and range or mean and standard deviation. A $p < 0.05$ is considered to indicate a significant difference.

Summary of the results

I. Thermosensitivity in a reconstructed microtic ear

Patients: Eight girls and 11 boys operated on for unilateral microtia took part. Their ages ranged from 10 to 20 years (14.6 ± 2.6 years). A mean time of four years (3.6 ± 1.7 years) had passed since their last operation.

Controls: Six girls and two boys were included to evaluate technical difficulties in measuring two ears, one after the other, and to evaluate differences between normal ears. Their ages ranged from eight to 19 years (12.9 ± 3.4 years).

Measurements: The lobe, the anthelix and the

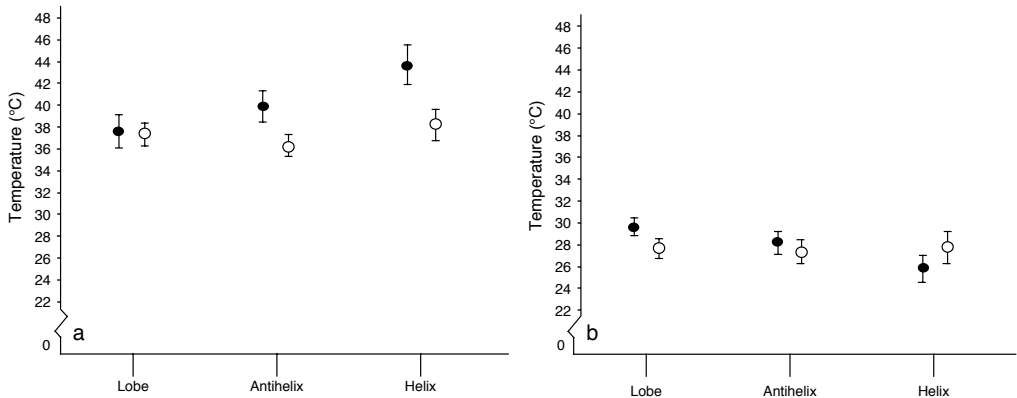


Figure 15. Perception thresholds for (a) heat and (b) cold assessed in the reconstructed and normal opposite ears of 19 patients (solid circles=reconstructed; open circles=normal)

upper helix were investigated on both sides regarding temperature and thresholds for heat and cold by using QST.

Results, patients:

Skin temperature

The reconstructed ear had a significantly higher skin temperature for all investigated areas (helix $30.6 \pm 1.2^\circ\text{C}$, antihelix $30.4 \pm 0.8^\circ\text{C}$ and lobe $30.2 \pm 1.2^\circ\text{C}$) compared with the normal ear (helix $29.3 \pm 1.5^\circ\text{C}$, antihelix $28.1 \pm 1.6^\circ\text{C}$ and lobe $28.6 \pm 0.9^\circ\text{C}$).

Heat

The upper two thirds of the reconstructed ear had higher heat detection thresholds than the normal ear (helix reconstructed ear $43.9 \pm 3.8^\circ\text{C}$, helix normal ear $38.3 \pm 3.0^\circ\text{C}$, antihelix reconstructed ear $39.9 \pm 3.0^\circ\text{C}$, antihelix normal ear $36.4 \pm 1.7^\circ\text{C}$) whereas no significant differences could be detected in the lobule (Figure 15).

Cold

In general, cold detection thresholds were normal in the reconstructed ear. In the lobule however, cold was detected at a higher temperature than in the lobule of the normal ear (Figure 15).

Results, controls:

There were no significant differences between the left and right ear for any of the investigated areas for skin temperature, heat, or cold.

Conclusion: The overall thermosensitivity was good in the reconstructed ear. However, higher detection thresholds for heat were found in the helix and antihelix regions, and in the lobule, cold was detected at a higher temperature than in corresponding areas of the normal ear.

II: Threshold of tactile perception in a reconstructed auricle.

Patients: Thirty-nine patients operated on for unilateral microtia. The median time after the reconstruction was 20 months (6–60).

Methods: The thresholds for protective tactile sensitivity were assessed using the Semmes-Weinstein Monofilament test.

Results:

The normal ear showed thresholds mainly of 2.83 but in some measures 3.61. In 11 of the

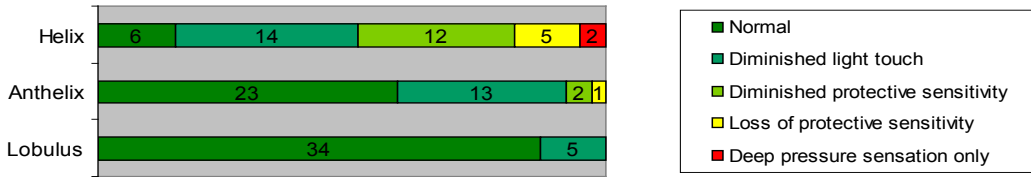


Figure 16. Sensitivity in the reconstructed ear.

patients there was a diminished perception to light touch, most commonly in the helical region. This is well within the range of acceptable sensitivity. The findings from the reconstructed ears are shown in Figure 16. The helix gave a poor result in seven patients and in one of them so did the anthelix. Acceptable levels of protective sensitivity were otherwise found in all measurements. The proportion of good results was 82% (95% CI 69 to 95) in the helix, and 97% (95% CI 92 to 103) in the anthelix. In the lobule there were no raised thresholds of protective sensitivity. Some of the patients had been reconstructed at an early age, and some at a later age. The interval between reconstruction and investigation also varied. However, we found no significant differences in sensitivity due to these factors.

Conclusion: Thirty-two patients had acceptable sensitivity in the whole ear, but the helix gave a poor result in seven patients and in one of them so did the anthelix.

III: Blood flow dynamics in reconstructed auricles

Patients: Ten patients who had undergone unilateral ear reconstruction. At minimum of five months had passed since the final operation.

Methods: Laser Doppler Perfusion Imaging was used to evaluate the blood flow in the reconstructed and the normal ear, before and after body heating.

Three regions of interest (ROI) were studied: the helix/posterior crus (ROI3), the concha

(ROI2) and the lobule (ROI1).

Skin temperature was measured in each ROI.

Results: Skin temperature in ROI3 was significantly higher in the reconstructed auricle than in the normal auricle. No differences were observed in the other regions. Indirect heating caused a significant rise of temperature in ROI3 only in the normal ear, whereas all ROIs in the reconstructed one showed significant temperature increases. The values for temperature are given in Table II.

Values for local blood flow are given in Figures 17 and 18. LDPI values were slightly higher in the normal ear compared with the reconstructed ear both before and after indirect heating, but the differences were not statistically significant. Indirect heating caused significantly increased LDPI values in all ROIs. Representative images are shown in Figure 14, page 23.

Conclusion: Skin blood flow recovers after 3-stage ear reconstruction and shows dynamic responses upon indirect heating that are compatible with those of the normal ear.

IV: A comparison of digital morphometry and clinical measurements of ears

Subjects: In a first series, the heights of both ears on 30 individuals were assessed by two people. In a second series, 15 people assessed the heights of the normal and reconstructed ears of 10 patients with unilateral microtia.

Table II: Findings in temperature (°C), medians and (ranges) in the normal and reconstructed ear before and after heating.

	ROI	Temperature before heating	Temperature after heating
Normal ear	3	31,2 (28,9–31,9)	32,3 (30,7–36,2)
	2	34,55 (31,2–36,1)	34,8 (33,4–35,9)
	1	31,3 (29,7–34,7)	32,45 (30,4–35,9)
Reconstructed ear	3	32,9 (31,55–34,15)	33,73 (32,7–34,55)
	2	34,55 (33,6–35,3)	35,05 (34,2–35,3)
	1	32,5 (29–34,3)	33,8 (32,8–35,2)

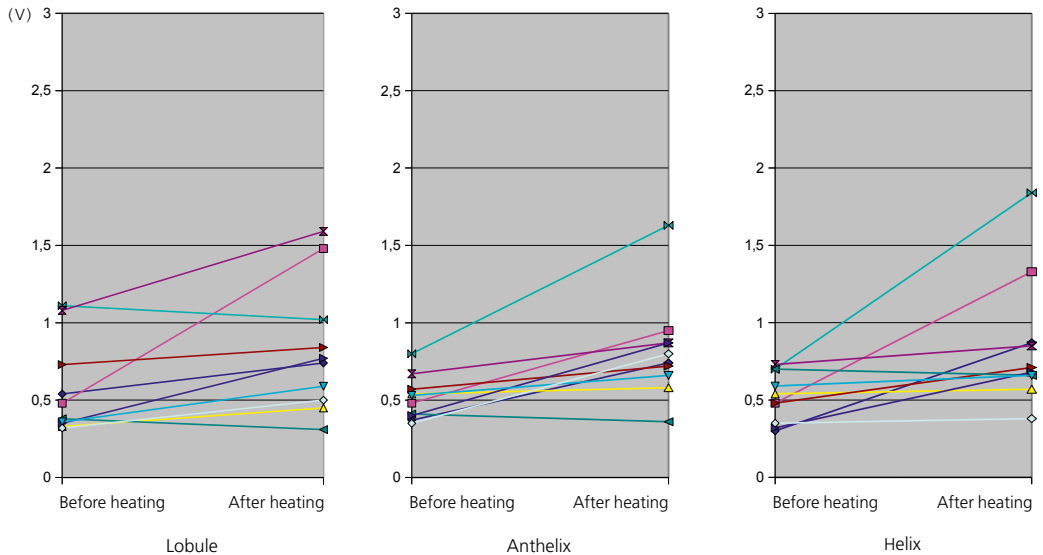


Figure 17: Findings in LDPI before and after heating in ROI 1–3 in the reconstructed ear

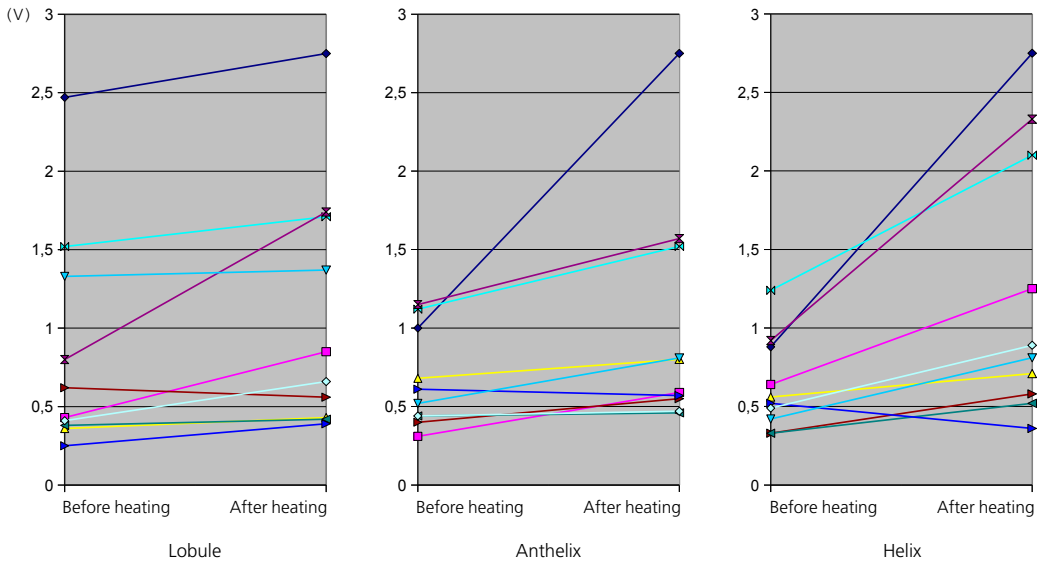


Figure 18: Findings in LDPI before and after heating in ROI 1-3 in the normal ear

Table III. Random error of the compass and ruler (C&R), calliper (CA) and digital morphometry (DM) expressed as random error (mm). Sixty ears of 30 persons were measured twice.

	Random error (mm)		
	C&R	CA	DM
A(1-2)	2.90	2.83	2.44
B(1-2)	3.10	2.24	2.69

Table IV. Systematic error.

	Systematic error (mm)		
	C&R	CA	DM
A(1-2)	-0.18	-0.23	-0.13
B(1-2)	-0.26	-0.16	-0.11

Table V. Random error, systematic error and Intra Class Correlation coefficient from first and second digital morphometric measurements by 15 assessors in 10 patients.

	Random error (mm) median (range)	Systematic error (mm) median (range)	Intra Class Correlation coefficient
Normal ear	0.47 (0.26-0.94)	-0.01 (-0.06-0.02)	1.00
Reconstructed ear	0.74 (0.32-2.97)	0,00 (-0.09-0.03)	1.00

Methods: The ears in the first series were measured using three methods: Compass & ruler, calliper and digital morphometry. In the second series only digital morphometry was used. All assessors were doctors or medical students at our institution.

Results: The most important results reflecting reproducibility in measurements of normal and reconstructed ears are shown in tables III–IV.

Conclusion: Digital morphometry has a high degree of reproducibility in a clinical setting but there is a definite inter-individual variation in performing the measurements. Validation of the assessor is necessary to estimate his/her random error in relation to the distances of interest in the particular study.

General Discussion

Considerations regarding the patients

Up to the present day, we have performed about 350 ear reconstructions. Fifty-four of these patients participated in the present studies. The samples in studies I–III were generated based primarily on when we had the opportunity to commence the different experiments and the coincidence of the patients' routine clinical follow-ups. Only a few patients were investigated beyond the follow-up protocol. In study IV, however, the experimental photos were chosen based on a consecutive series of patients operated on in 2001–03. The indication for reconstruction was unilateral microtia with one exception of traumatic amputation in Study III.

Because the patients were recruited from the perspective of clinical follow-up, both patients from the previous four-stage era and the contemporary three-stage era were included. In fact, about half of the patients were reconstructed in four stages. However, the sample should still be representative of the contemporary treatment protocol as the key procedures, undermining and

elevation, are basically the same. Our findings are in line with this assumption and any differences in results should be in favour of the three-stage protocol due to its lesser surgical trauma.

The sample consisted of patients who were reconstructed from 6 to 22 years of age. This reflects that we were faced with a number of individuals with microtia in whom reconstruction had been postponed when we started our structured care of this group of patients. Currently treatment is instituted at the age of 6–7 years as a rule. Children's improved capacity for tissue repair is in favour for an early reconstruction, but the results regarding tactile sensitivity were equally as good in the older patients. One advantage with an early reconstruction could be a shorter period with the deviant ear, reducing the risk of psychosocial discomfort. This association is difficult to prove but our contemporary research on patient's satisfaction focuses on these matters (28).

Considerations regarding the methods

Techniques for measuring sensitivity

Sensitivity can be evaluated in various ways, for instance in terms of two-point discrimination (18, 33, 34) and vibration perception (35, 36). We chose to evaluate perceptions of heat, cold and pressure because these modalities are most relevant for the reconstructed ear. The Semmes Weinstein Monofilament test is an established method for measuring tactile sensitivity. It is easy to use, has an acceptable reliability (18, 34, 37, 38) and has been used before to evaluate protective sensitivity in the head and neck region (39).

Quantitative Sensory Testing (QST) can be used to assess a variety of perception modalities including thermal perception. Laser heat stimulation is an alternative method to assess thermal perception thresholds. It has been suggested as a more sensitive and specific method to detect thermal sensory abnormalities (40). Both methods provide a quantitative measure of thermal

perception in terms of thresholds. We used QST as it is easy to handle and has been proven reliable in previous studies (36, 41–43).

Techniques for assessing skin blood flow

Some methods for measuring blood flow relate to flow in larger arteries or veins whereas other better reflect the microcirculatory blood flow. The microcirculatory blood flow of the skin can be studied with various techniques, for instance temperature, xenon clearance, fluorescein flowmetry, indocyanine green fluorescence angiography (44, 45), capillaroscopy (46–48) and laser Doppler perfusion monitoring and imaging (49–52).

Surface temperature is easy to measure using conventional thermometer probes. However, skin temperature is just an indirect measure of skin blood flow and the interrelation between skin blood flow and temperature is mostly ambiguous (52). For the monitoring of finger skin blood flow after replantation, however, the method has been shown to be suitable (53).

In Xenon clearance the isotope ^{133}Xe is injected or is allowed to diffuse into the skin and its clearance rate is then monitored. The main drawback with this method is that it is rather cumbersome and requires handling of a radioactive agent.

Fluorescein flowmetry is based on the intravenous injection of the molecule fluorescein, which is distributed throughout the body including the skin area under study. Fluorescein emits light when exposed to ultraviolet radiation. The topographic distribution of light can be calculated and displayed over time in a video recording. Indocyanine green (ICG) is an alternative fluorescent that binds more strongly to plasma proteins and fluoresces in the near infrared spectrum (44). Fluorescein or ICG angiography is almost exclusively used in the field of ophthalmology where, for instance, retinopathy can be diagnosed (54). By a curious coincidence, laser fluorescence angiography with

ICG has actually been used in connection with ear reconstruction, namely, to show the effect of preserving a subcutaneous pedicle in the concha area and to chart the vascular anatomy of the dysplastic auricle (55). A disadvantage with the method is that it requires an intravenous injection and there is a risk of hypersensitivity with adverse reactions (56).

Capillaroscopy is based on direct inspection via a microscope. Furthermore, for quantitative analyses the most common application is to the nail bed. The method requires a substantial instrumental set-up and was not considered suitable for our clinical measurements.

The laser Doppler method had already been introduced in the 1970s and gained acceptance over the years as an important method of studying blood flow both in experimental and clinical settings (57). In clinical settings, the fact that it is completely non-invasive is a distinct advantage. An important improvement in the technique was the introduction of the imaging principle whereby not only a small spot of the skin could be studied but also a larger area. The influence of spatial variations was consequently reduced. The Laser Doppler Imaging-technique (LDPI) does not deliver blood flow values in quantitative terms, but rather baseline values from which changes can be monitored (49, 50). This makes the method particularly suitable for investigating a response to a stimulus, such as presumed blood flow increase due to vasodilatation following indirect heating.

Restoration of sensitivity and skin circulation after ear reconstruction

Numbness, or even loss of sensitivity, is a regular finding after surgical interventions. These disturbances may be temporary or permanent, at least to some degree. The findings in the present studies indicate an over all successful functional restitution after ear reconstruction regarding both sensitivity and blood flow. However, we noted regional differences in the ear.

Sensitivities to both thermal and tactile stimuli were normal in the lobule. The helix, however, showed reduced restitution to some degree. In seven patients a monofilament of 4.56 or higher had to be used to evoke a sensation of pressure. This pattern of impaired tactile perception could also be seen when investigating perception of heat. The temperature had to be increased to 43.9°C whereas the normal ear already responded at 38.3°C. Differences in perception of cold were, on the other hand, tiny and mostly confined to the lobule. Findings in the anthelix can be considered to be somewhat in between those of the helix and lobule. Presumably this hierarchy reflects the consequences of the surgical trauma, where the helix is subjected to an extensive intervention whereas the lobule is almost untouched surgically. The capacity for nerve restitution in the distant helix obviously has its limitations, whereas the nerve supply to the lobule may be essentially maintained during the reconstructive procedures.

Whereas some presumably permanent deficits were noted regarding the sensitivity of the upper ear, no significant difference in basal skin blood flow was noted. Body heating is supposed to release vasoconstrictor tone with an ensuing vasodilatation. This vasodilatation was actually monitored in the auricle, where LDPI values increased significantly in all ROIs. However, body heating using a device over the torso may have additional effects on both the peripheral and central circulation and this may explain why the individual response to heat varied to some extent.

Thoughts on metric measurement in ear reconstruction

Metric measurement is an important tool in reconstructive surgery, even so regarding ear reconstruction. The normal ear grows 5–7.5 mm from the age of seven to eighteen. In the best case scenario the microtic ear, reconstructed at the age of seven using the normal ear as a template, maintains symmetry through adolescence.

This requires a capacity for growth in the cartilaginous framework. Two previous studies have addressed this issue but further investigations are necessary for a definitive conclusion. Consequently, the development of methods allowing metric measurements are important and of particular interest in the field of ear reconstruction.

Regarding metric measurements, digital morphometry (DM) is an interesting alternative to previous manual methods. Measurements with compass & ruler and calliper are best suited with the patient present, whereas the patient does not have to be present at the time of measuring with DM. As long as the photographic setting is standardized, the photo can even be taken at a remote studio and then transferred to the specialised centre for analysis. Furthermore, the material can be re-evaluated if necessary at any time. Analogue photographs also allow these opportunities but are far less easy to handle.

In this study we have shown that DM has a random error, which is the most important indicator of reproducibility, of the same magnitude as the manual methods. However, there is a strong inter-individual variation in reproducibility, with a random error that can vary from tenths of millimetres to almost 3 mm. Three mm is rather close to 5–7.5 mm, which is the magnitude of change that would be interesting to observe in ear reconstruction. Although we noted random errors of 2–3 mm in magnitude, most of our assessors managed to produce random errors smaller than one mm when measuring reconstructed ears. This precision is sufficient to detect any clinically relevant growth of the cartilage framework. Nevertheless, any long-term evaluation of growth using DM must be preceded by an evaluation of the actual assessor's unique performance.

Autologous reconstruction – alternatives and future prospects

Before commencing the procedure of ear reconstruction, the patient has to be informed about

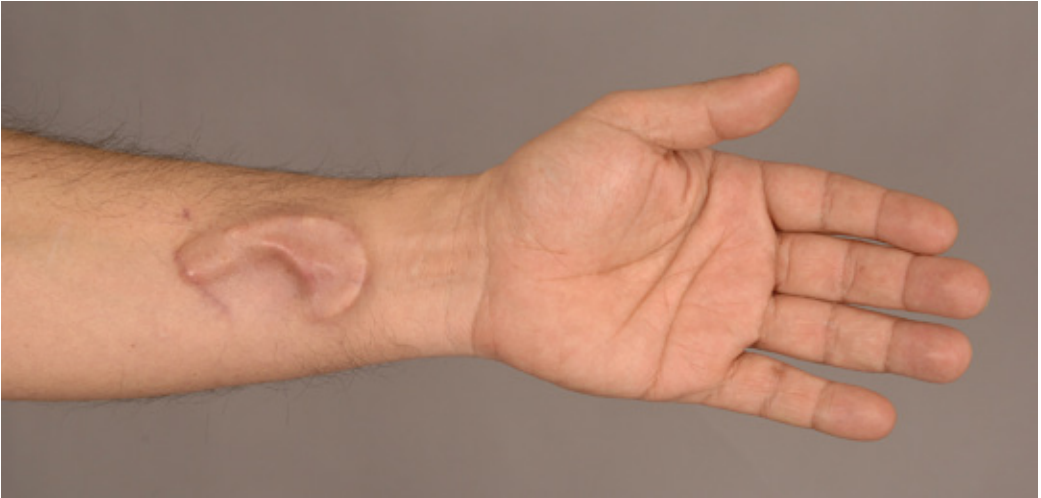


Figure 19. Stage 1 in the free pre-laminated forearm flap for total ear reconstruction

the alternatives and their pros and cons. To refrain from surgery should always be considered an alternative, especially if the patient is not fully motivated or has expectations that are not realistic. An ear-prosthesis can provide a cosmetic result that is better than what is usually possible when using human tissue in reconstructive procedures. It requires little or no surgery. An ear-prosthesis has other limitations though. It is removed and cleaned every evening and has to be applied again in the morning. This procedure can remind the patient that the prosthesis is not an integrated part of the body. It also needs replacement regularly due to wear and tear. For obvious reasons it lacks any sensitivity to touch, heat, cold etc. The ear-prosthesis does not follow the normal changes of skin colour due to seasonal pigmentation or blushing, for instance, which make the prosthesis look unnatural.

The use of porous polyethylene for ear reconstruction is a method that has been developed during the last decades. The preformed polyethylene framework is covered by a temporoparietal fascia to enable transplantation of a covering split thickness skin graft. In trained hands the results are good and the risk of exposure of the framework is low (58). There are no reports on tactile or thermal perception in these ears how-

ever, and an ear without protective sensitivity could be more prone to injury and exposure of the underlying framework. Compared with an autologous framework, the effects of exposure of an exogenous framework are probably worse.

The local conditions in patients who are subject to ear reconstruction can vary considerably. Scarring due to previous surgery or trauma can impair or even preclude a nice draping of the skin over the cartilage framework. An ear-prosthesis can be a reasonable alternative in these patients. If a reconstruction with autologous tissue is still desirable it can sometimes be performed by use of tissue expansion. By using a “balloon” with a port for saline injections, adjacent normal skin can be expanded step by step to such a degree that it can subsequently cover the cartilaginous framework. In severe cases, where the amount of uninjured tissue is very limited, a pre-laminated free flap might be the only possible autologous reconstruction. In a first stage, the cartilaginous framework is placed in a skin pocket on the volar aspect of the forearm (Figure 19), or alternatively on the anterior aspect of the thigh. After a few months, the construct can be raised as a free radial forearm flap, or alternatively as an anterolateral thigh flap. In this microsurgical procedure, the vessels of the pedicle of the flap are connected

to the facial or temporal artery and vein (59).

Another type of autologous tissue engineering is based on the possibility of culturing cells. An overview of this topic is presented by Sterodimas and co-workers (60). Briefly, three components are necessary: cells, soluble factors and biomaterials. In this context, embryonic stem cells or adult stem cells are most often the origin. However, even dermal fibroblasts can be manipulated to develop stem cell properties. By using different soluble factors, cells can be driven in various directions, for instance, into chondrogenic differentiation (61). Even differentiation into an endothelial cell-like cell type has been found (62). Together with the third factor, a suitable scaffold, it should thus be theoretically possible to create an ear in the laboratory for further implantation *in vivo*, and there are reports indicating that this will be possible in the future (63). Although attractive in concept, much remains to be further developed and improved in terms of biotechnology and surgical techniques before the bioengineered ear is in daily clinical practice.

Conclusions

- There is a high degree of restoration of thermosensitivity in the reconstructed ear but the upper parts of the ear still show signs of reduced sensitivity to heat (I)
- Tactile sensitivity followed that of thermal sensitivity, with a high degree of restoration in combination with elevated thresholds in the upper parts (II)
- The basal blood flow in the reconstructed ear is compatible with that of the normal ear and its dynamic response to indirect heating is also similar (III)
- Digital morphometry shows a similar reproducibility as compass & ruler and callipers for measurement of normal ears (IV)

- Digital morphometry can show great precision in measurements of reconstructed ears but there is high inter-individual variation between different assessors (IV)

Summary

Microtia is a congenital malformation where the auricle is not fully developed. In some cases the malformation is complete and the auricle is absent. In Sweden the incidence of microtia is about 2 per 10,000 births (2). Reconstruction of the external ear is possible by using autologous rib cartilage in three surgical steps: rib cartilage transplantation, ear elevation and final adjustments.

Although the aesthetic result is most essential, there are also functional aspects of a reconstruction of the outer ear. To keep the ear free from injury, the skin depends on a functioning alert system: sensitivity to touch, heat and cold. However, the process of ear reconstruction necessarily includes surgical trauma that endangers these protective systems. The blood supply of the skin cover is also impaired during the different reconstructive stages. Little is known about the level and time scale of recovery of sensitivity and blood supply to the reconstructed ear after surgical bisection of nerves and vessels.

Symmetry is important in ear reconstruction and the new ear should match the normal ear at the time of reconstruction as well as in the adult life. The potential growth of the ear is a subject of debate. We decided to investigate the precision of today's tools for size measurements. With this knowledge the issue of growth hopefully can be elucidated.

A total of 54 patients with unilateral ear reconstruction, and 30 individuals with normal ears, were included in the studies. We evaluated sensitivity to heat, cold and touch in the reconstructed and normal ear. We also assessed blood flow before and after body heating to investigate the pathophysiological dynamics in the reconstructed ear.

Digital morphometry for measuring ear size was compared to the manual methods: compass & ruler and callipers. Measurements were performed on individuals with normal ears. In digital morphometry we also measured reconstructed ears.

Our findings show that there is a high degree of restoration of thermosensitivity in the reconstructed ear but the upper parts of the ear still show signs of reduced sensitivity to heat. Tactile sensitivity followed that of thermal sensitivity,

with a high degree of restoration in combination with elevated thresholds in the upper parts. The basal blood flow in the reconstructed ear is compatible with that of the normal ear and its dynamic response to indirect heating is also similar. Digital morphometry shows a similar reproducibility as compass & ruler and callipers for measurement of normal ears. Digital morphometry can show great precision in measurements of reconstructed ears but there is high inter-individual variation between different assessors.

Populärvetenskaplig sammanfattning på svenska – Summary in Swedish

Mikroti är en medfödd avvikelse där ytterörat inte utvecklats normalt. Defekten kan variera från att örat nästan är normalt till att det saknas helt och hållet, s.k. anoti. I Sverige inträffar detta i c:a 2 fall per 100 000 nyfödda. Pojkar drabbas i större utsträckning och höger sida är den vanligaste. Båda sidor drabbas i c:a en tiondel av fallen. Förträngning av yttre hörselgången ses hos en majoritet av patienterna med mikroti och det föreligger i dessa fall en hörselnedsättning eftersom ljudet inte når innerörat.

En ensidig mikroti kan rekonstrueras i tre seanser genom att använda det egna revbensbrosket. Brosket formas till ett öra och placeras i en ficka under huden på örats plats för att i ett senare skede resas och slutligen finjusteras. Rekonstruktionen kan påbörjas när bröstkorgsfånget är tillräckligt. Patienten skall också vara välmotiverad och så långt möjligt är förstå vad operationerna kommer att innebära i form av tid på sjukhus, smärta, konvalescens etc. I praktiken kan rekonstruktionsförandet därmed oftast påbörjas vid 6–7 års ålder.

Under de tre kirurgiska stegen kommer mottagarområdet att utsättas för ett flertal snitt där såväl nerver som blodkärl måste delas. Vidare görs en friläggning under huden så att brosket kan få plats. Huden som täcker örat riskerar därmed att mista viktiga skyddsfunktioner såsom känsel för värme, kyla och tryck. Ett rekonstruerat öra utan dessa skyddsfunktioner i huden skulle mycket väl kunna löpa större risk för sårbildning till följd av skador av olika slag. Ett sår i huden skulle i sig kunna äventyra det underliggande broskskelett och därmed hela rekonstruktionen.

Att utvärdera känsel för värme, kyla och tryck i det rekonstruerade örat är således angeläget och inom ramen för våra studier har detta skett. Vi

har också undersökt blodflödets återhämtning och reglering.

Det rekonstruerade örat dimensioneras för att matcha det normala örat. En sjuåringens öra växer mindre än 7,5 mm fram till 18 års ålder. Huruvida det rekonstruerade örats brosk växer är omdebatterat men klinisk erfarenhet samt vissa vetenskapliga rön talar för att det finns en tillväxtpotential hos det transplanterade brosket. I ett led att på sikt kunna utvärdera brosktillväxten i anslutning till öronrekonstruktion har vi i första hand utvärderat mätmetoden digital morfometri, dvs. storleksmätning på digitala foton med därtill avsedd mjukvara. Metoden jämfördes med de två manuella metoderna passare & linjal samt skjutmått.

Våra fynd visar att det finns en hög grad av återhämtning av känseln för värme och kyla i det rekonstruerade örat även om något nedsatt känsel för värme noterades i örats övre del. Känsel för tryck visade samma mönster med en hög återhämtning i kombination med något höjda tröskelvärden i den övre delen. Blodflödet i det rekonstruerade örat var väsentligen lika med det normala örat och vid kroppsuppvärmning ökade blodflödet på likartat sätt. Digital morfometri visade samma grad av slumpfel som passare & linjal samt skjutmått när normala öron mättes. Digital morfometri kan visa hög precision även vid mätningar på rekonstruerade öron, men det finns en individuell variation från bedömare till bedömare.

Sammanfattningsvis återhämtar sig det rekonstruerade örats känsel och cirkulation på ett tillfredställande sätt. Digital morfometri förefaller vara en lämplig metod för att mäta örats dimension och tillväxt, förutsatt att man bestämmer den enskilde användarens precision och förmåga att reproducera sina resultat vid upprepade mätningar.

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Paper I

ORIGINAL ARTICLE

Thermosensitivity in a reconstructed microtic ear

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Abstract

The aim of this study was to evaluate thermo-thresholds in autologous reconstructed microtic ears. Nineteen patients with unilateral microtia were investigated no less than two years after the last operation (3.6 ± 1.7 years). Their normal corresponding ear acted as controls. Eight healthy children were also investigated to illustrate technical differences between measuring the two sides. Thermal sensitivity was tested quantitatively using a SENSELab MSA Thermotest. The skin temperature was also tested. Three different areas of the ear were examined: the lobe, the antihelix, and the helix. The reconstructed ear had a significantly higher skin temperature for all investigated areas compared with the normal ear (reconstructed ear $30.2 \pm 1.2^\circ\text{C}$, normal ear $28.6 \pm 0.9^\circ\text{C}$). For the controls there were no significant differences in any area. For the patients there were small differences in perception of cold between the reconstructed and the normal ear. There were significant differences in the antihelix region and the helix in heat perception in the reconstructed ear compared with the normal one (helix reconstructed ear $43.9 \pm 3.8^\circ\text{C}$, helix normal ear $38.3 \pm 3.0^\circ\text{C}$, antihelix reconstructed ear $39.9 \pm 3.0^\circ\text{C}$, antihelix normal ear $36.4 \pm 1.7^\circ\text{C}$). The reconstructed ear had a changed thermosensitivity, but there did not seem to be any clinical disadvantages.

Key Words: *Microtia, reconstruction, thermo, sensitivity, surgery*

Introduction

Total reconstruction of the external ear with an autologous costal cartilage graft was described by Tanzer in 1959 [1] and since 1974 Brent has published important articles [2,3] in which he described his four-stage approach for ear reconstruction with transplantation of an autologous cartilaginous framework. In 1993 Nagata [4] introduced his two-stage technique. These two surgeons have both made important improvements in the aesthetic results of correction of microtic ears. The development and refinement of their reconstructive techniques has given us the possibility of obtaining three-dimensionally detailed ears, with an appearance similar to that of a healthy, normal ear [3,5–7].

At the Scandinavian Ear Reconstruction Centre in Malmö, we have corrected more than 250 ears using our three-stage procedure, which is based on

the techniques of Brent and Nagata [2,6]. Most of our patients are otherwise healthy children under the age of 10.

Although the aesthetic result is essential for the child, the functional aspect of the auricle is also important. To prevent damage to the reconstructed auricle the patient must be able to feel pain, heat, and cold.

The aim of this study was to find out whether or not the reconstructed ear was sensitive to cold and heat.

Patients and methods

Patients

Nineteen patients operated on for unilateral microtia underwent quantitative sensory testing (QST) for thermal sensitivity [8,9]. Their ages ranged from 10 to 20 years (14.6 ± 2.6 years) (8 girls and 11 boys).

A mean four years (3.6 ± 1.7 years) had passed since their last operation. The normal opposite ear served as a control.

Controls

QST was also done on a group of eight healthy controls, aged from 8 to 19 years (12.9 ± 3.4 years) (6 girls and 2 boys). This group was used to evaluate technical difficulties in measuring the two ears one after another, and to evaluate differences between normal ears.

Skin temperature

The skin temperature was assessed for three predetermined areas (the lobe, the antihelix, and the upper helix); the same sites on the normal ear were used as control. A Tempett IR thermometer, SENSELab was used.

Quantitative sensory testing for thermal sensitivity

Thermal sensitivity was tested quantitatively using a SENSELab MSA Thermodest with a thermode of 9×9 mm based on the Peltier principle (in which the intensity and direction of the current controls the surface temperature of a test electrode = thermode) [10]. All measurements started from skin temperature. The test was done in a closed and quiet room. To obtain the threshold of perception of non-painful cold and warmth, five cold stimuli followed by five warm stimuli were given at a rate of $1^\circ\text{C}/\text{second}$, with a random interval between stimuli of 4 to 6 seconds [11]. The subject was instructed to press the button of a handheld switch to terminate the stimulus at the first sensation of cold or warmth. The means of these perception thresholds were calculated as the cold or heat perception threshold. Three predetermined areas (the lobe, the antihelix, and the upper helix) were tested, and the same sites on the normal ear were used as control.

The thermode had an initial temperature of 32°C , which is the accepted temperature at which the skin does not react to a sensation of heat or cold. The thermode gave five cold stimuli during which the temperature dropped to 10°C , before returning to its start temperature of 32°C . During the five following warm stimuli the temperature of the thermode rose to a maximum of 50°C , before returning to 32°C . These temperatures are proved not to induce skin injuries when exposed to the skin for the short period of time that the testing lasted.

The patients had a break of about five minutes, which gave them an opportunity to allow the

reconstructed ear to "rest" as they had been lying on the reconstructed ear while the non-reconstructed side was being tested.

Questionnaire

The questionnaire consisted of four questions, the first that allowed for a spontaneous answer about whether or not the patients had ever noticed any difference in sensitivity between the two ears, and the remaining three being more specific, dealing with differences in touch, heat, and cold. This was done between testing the normal ear and the reconstructed ear.

Statistical analysis

We used the Statistical Package for the Social Sciences (SPSS 11.0 for Windows). We used the paired Student's *t* test to compare the reconstructed ear with the normal ear for heat and cold perception on each of the three sites. For each group we looked at the significance using a 95% confidence interval, the standard deviation, and the mean. Values were expressed as mean \pm standard deviation.

Results

Patients

Skin temperature. The reconstructed ear had a significantly higher skin temperature for all investigated areas (lobe $30.2 \pm 1.2^\circ\text{C}$, antihelix $30.4 \pm 0.8^\circ\text{C}$, and helix $30.6 \pm 1.2^\circ\text{C}$) compared with the normal ear (lobe $28.6 \pm 0.9^\circ\text{C}$, antihelix $28.1 \pm 1.6^\circ\text{C}$, and helix $29.3 \pm 1.5^\circ\text{C}$).

Heat. The reconstructed ear had higher heat detection thresholds than the normal ear. In the lobe there was no significant difference. There were significant differences in the antihelix region and the helix in heat perception in the reconstructed ear compared with the normal one (helix reconstructed ear $43.9 \pm 3.8^\circ\text{C}$, helix normal ear $38.3 \pm 3.0^\circ\text{C}$, antihelix reconstructed ear $39.9 \pm 3.0^\circ\text{C}$, antihelix normal ear $36.4 \pm 1.7^\circ\text{C}$) (Figure 1a).

Cold. The reconstructed ear showed lower cold detection thresholds than the normal ear. In the lobe we found a significant difference (reconstructed ear $28.9 \pm 1.6^\circ\text{C}$, normal ear $26.9 \pm 1.8^\circ\text{C}$), but in the antihelix and helix there were no significant differences (Figure 1b).

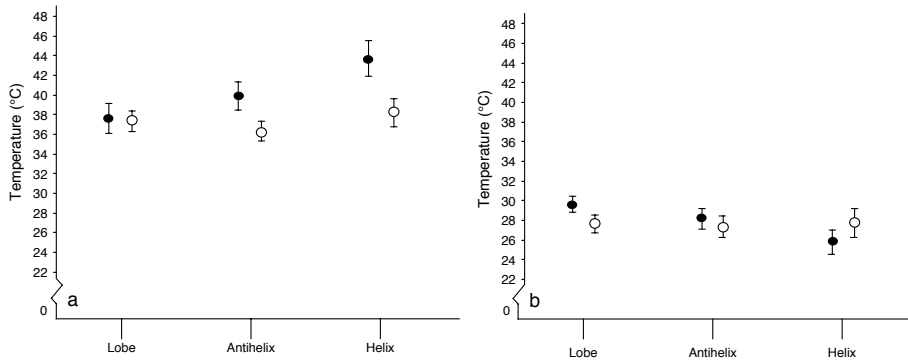


Figure 1. Perception thresholds for (a) heat and (b) cold assessed in the reconstructed and normal opposite ears of 19 patients (solid circles =reconstructed; open circles =normal).

Questionnaire. To the first question: if the patient had ever noticed any difference in sensitivity between the two ears, 8 patients said yes and 11 said no (Table I). For touch and cold there were no differences between the outcomes “less” or “equal”. For “heat” 16/19 tell a difference between the reconstructed and the normal ear. It was uncommon for them to be more sensitive in the reconstructed ear (2/19).

Controls

There were no significant differences between the left and right ear for any of the investigated areas for skin temperature, heat, or cold.

Discussion

Quantitative sensory testing (QST) has been developed to help mainly in the diagnosis of different neuropathies [12]. It is a well-documented method.

The peripheral nerve fibres that transmit the thermal stimuli are well-known. C-fibres are thin, non-myelinated fibres that transmit heat at a rate of approximately 0.5 m/s. A-delta-fibres, on the other hand, are thin, myelinated fibres that transmit cold at a rate of about 25 m/s, so cold stimuli are transmitted much faster than warm. The transmitting speed is of greater importance the farther away

from the central nervous system the stimuli are applied to the receptors. Considering that the ear is so close to the central nervous system, the differences in velocities for cold and warm stimuli may be excluded as possible factors that affect the outcomes of the perception threshold measurements in our study.

Of great importance when evaluating our results are both room and skin temperature. If the surrounding room temperature is low it would result in vasoconstriction of the peripheral vessels and a change in the perception threshold of cold stimuli. In turn a warm surrounding room temperature would result in vasodilatation, and this would affect the cold perception threshold. Somedic (the manufacturer of the thermode) has recommended that the surrounding room temperature is optimal when at about 22°–23°C. We found during the tests that the room temperature fluctuated from 22° to 24°C, so we do not think that any of our results can be explained by the room temperature.

A last neurophysiological factor worth addressing is spatial or temporal summation. There are many different sizes of thermode. We chose to use the 9 × 9 mm thermode, as the testing sites on the ear required a small area of application. Decreasing the stimulator area, though, increases the threshold, as fewer receptors are activated. Stretching the skin is the same as using a small thermode or probe; it results in fewer receptors being available for stimulation [13]. One can safely conclude that the smaller the thermode, the larger the variability in perception thresholds. However, children below the age of 16 are still growing and have a higher receptor concentration than do adults [9]. This is because the skin has not yet been stretched out to its maximum. The thresholds, measured correctly, are therefore lower in children than in adults.

Table I. Number of patients (total 19) denoting differences between the reconstructed and the normal ear for touch, heat, and cold.

Sensation	More in the reconstructed ear	Less in the reconstructed ear	Equal
Touch	2	9	8
Heat	1	2	16
Cold	2	7	10

The temperature was significantly higher in the reconstructed ear, which was an unexpected finding. This could also contribute to a higher heat threshold for the reconstructed ear than the normal one.

Finally, as expected, we found no differences in thermo-thresholds in the controls between the left and right ear.

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Paper II

ORIGINAL ARTICLE

Threshold of tactile perception in a reconstructed auricle

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Abstract

There are more important outcome variables than the aesthetic when it comes to a successful result in reconstruction of the ear for microtia. The protective sensitivity, for example, is important to avoid damage to the skin covering the cartilaginous framework. We studied 39 patients with unilateral microtia and recorded their skin sensitivity more than six months after the last operation. The Semmes-Weinstein Monofilament Test (SWMT) was used to assess the threshold of protective sensitivity in three particular areas: the helix, the anthelix, and the lobule. The opposite ear served as control. A monofilament of 4.31 or less was regarded as acceptable protective sensitivity. Thirty-two patients had acceptable sensitivity in the whole ear, but the helix gave a poor result in seven patients and in one of them so did the anthelix.

Key Words: *Microtia, reconstruction, threshold, tactile, sensitivity, surgery*

Introduction

When Brent first published his four-stage technique in 1980, and later in 1992 reported his experience after two decades with 600 cases, he set a new standard in the art of reconstruction of the ear [1–3]. He constructed a framework from rib cartilage in the first stage, followed by a lobule transposition, raising of the ear with a skin graft, and finally reconstruction of the tragus and improvement of projection. In 1994, Nagata published a new technique that showed the possibility of reconstructing the auricle in only two surgical procedures. The first stage included transposition of the lobule and construction of the cartilaginous framework, while in the second stage the framework was raised and supported by a stent, following which coverage was achieved by temporalis fascia before the skin graft was applied [4–7]. This framework was more sophisticated in its three-dimensional appearance than previous techniques. The Nagata technique is an excellent one in trained hands, but can otherwise be a serious challenge, as

noted by Firmin based in her great experience with the two techniques [8].

At the Scandinavian Ear Reconstruction Centre of the Department of Plastic and Reconstructive Surgery at Skåne University Hospital we now have 14 years' experience with more than 300 reconstructed ears. Initially we adhered strictly to the Brent technique, but during the last nine years we have used a three-stage technique influenced by both the Brent and Nagata techniques. Compared with the four-stage procedure, the lobule is nowadays not transposed as a separate stage, and the framework is more detailed from the three-dimensional point of view.

When we reconstruct the auricle with autologous cartilage, multiple skin incisions are necessary during the different stages. Obviously, this renders it at risk of compromising the sensitivity of the skin over the reconstructed auricle. Most patients treated for ear deformities are children, and although the aesthetic result is essential for the child, the functional aspect of the auricle is also important. The protective sensitivity of the ear is essential to prevent damage to the

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reconstructed auricle, particularly during childhood and adolescence as unintended physical trauma is common during this period of life. A small unnoticed ulcer in the skin covering the cartilaginous framework can lead to infection, that may threaten the whole ear. Consequently, further evaluation of protective sensitivity after reconstruction was deemed important. In this study we used the Semmes-Weinstein Monofilament Test (SWMT) to test touch in three areas of the reconstructed ear and compared the findings with the non-operated ear in patients operated on for unilateral microtia. The study started in 2002 with consecutive measurements in 32 patients who had had the four-stage reconstruction. In 2008 we supplemented the series with another seven measurements in consecutive patients who had had the three-stage reconstruction.

Patients and methods

Surgical procedure

In the first stage a cartilaginous framework is placed in a widely-undermined subcutaneous skin pocket. The bottom plate of the framework is built of the two lowest confluent rib cartilages. The first free-floating rib cartilage serves as the helical rim. When the framework is completed, excessive pieces are deposited in a pocket cranial to the ear, to be used as spacers in the final stage. In the second stage, the lobule is transposed to its anatomical position. The retroauricular sulcus is created in the third stage. An incision is then done around two-thirds of the circumference and the ear is extensively raised as an anteriorly-based flap. Finally the tragus is reconstructed and its projection improved.

In our contemporary surgical protocol the lobulus is transposed in connection with the cartilage implantation to reduce the number of stages from three to four.

The patients are followed up in the outpatient unit at regular intervals and in some instances minor complementary operations are necessary in the later teens, when a stable reconstruction is normally achieved and no further growth or adjustments are expected.

Patients

As a part of this routine clinical follow-up we included an evaluation not only of the aesthetic result, but also a test of the functional recovery of the sensitivity. In this way we managed to investigate 39 patients in the outpatient unit. The ears had been reconstructed from 1995–2008. The median age of the patients at

the time of reconstruction was 10.5 years (range 6–19); median age 13 years (8–21) at the time of follow-up, and median time after the reconstruction 20 months (6–60).

Twenty-four patients had the right ear operated on, and 15 the left. Twenty-four were boys and 15 girls. Thirty-two patients were operated on by the original four-stage Brent technique, and seven patients by our contemporary three-stage technique.

Semmes-Weinstein Monofilament Test - SWMT

Patients were tested in a closed and quiet room with a thermostatically-regulated room temperature of 20°C (minimum).

The tactile perception thresholds of both the reconstructed and the normal auricle were assessed with SWMT. The complete set of 20 monofilaments ranges from 1.65 to 6.65 (0.008–300 g target force). The most suitable for our purpose was the Touch-Test hand kit consisting of five different monofilaments, namely 2.83, 3.61, 4.31, 4.56, and 6.65 indicating normal sensitivity, diminished light touch, diminished protective sensitivity, loss of protective sensitivity, and deep pressure sensation only, respectively.

Three areas were examined: the apical part of the helix, the anthelix, and the lobule. The plastic filaments were applied to the skin in an ascending order and prodded until a positive response was achieved. The same procedure was applied to the other ear, which served as control.

The filaments were tested from a methodological point of view (Table I). The clinical test was simulated by prodding the filament to a scale until it bent. This procedure was repeated three times for every filament to evaluate the true target force.

Calculations and statistics

The threshold of sensitivity of 4.31 has been used to describe morbidity of the great auricular nerve after parotidectomy, and was defined as a sufficient functional level of protective sensitivity [9]. We

Table I. Expected compared with measured target forces of the monofilaments when prodded against a scale.

Filament	Target force (g)			
	Expected	Measured		
2.83	0.07	0.06	0.06	0.06
3.61	0.4	0.42	0.4	0.41
4.31	2	1.99	2.05	2.01
4.56	4	4.2	4.2	4.2
6.65	300	180	180	190

therefore considered a sensitivity corresponding to 2.83, 3.61, and 4.31 as acceptable outcomes. Sensitivity levels of 4.56 and 6.65 were regarded as insufficient functional levels of protective sensitivity, and thought to indicate a poor result.

The proportion of good results was calculated with a 95% confidence interval (CI) for the helix and the anthelix.

The median age at operation was 10.5 years and the median time after reconstruction was 20 months. The patients were accordingly divided into groups related to early (6–10.5 years) and late (10.5–19) reconstructions, and short (6–20 months) and long (20–60) follow-up.

Fisher's exact test was used to assess the influence of age and time after the final operation on whether the result turned out acceptable or poor.

Results

The opposite ear showed thresholds mainly of 2.83 but in some measures 3.61. In 11 of the patients there was a diminished perception to light touch, most commonly in the helical region. This is well within the range of acceptable sensitivity.

The findings from the reconstructed ear are shown in Figure 1. The helix gave a poor result in seven patients and in one of them so did the anthelix. Acceptable levels of protective sensitivity were otherwise found in all measurements.

The proportion of good results was 82% (95% CI 69 to 95) in the helix, and 97% (95% CI 92 to 103) in the anthelix. In the lobule there were no raised thresholds of protective sensitivity.

There was no significant difference in sensitivity between the groups with early and late reconstruction, nor was there a difference between the groups with short and long follow-up.

Discussion

Many reports have been published about the different surgical techniques for reconstruction of the ears

and their cosmetic results [3,8,10,11], but little about the functional results, such as sensitivity.

There are only a few reports about the skin sensitivity of a normal ear [12,13], and a MEDLINE search (key words: skin sensitivity, reconstructed auricle) gave no results about the reconstructed auricle, except for our own previous report on its thermo-sensitivity [14].

The main sensory innervation of the normal auricle is provided by the posterior branch of the greater auricular nerve and the auriculotemporal nerve. A branch of the vagal nerve and the facial nerve also innervate the choncha [13]. One could presume that the same nerves are involved in a microtic ear regarding the sensitivity of the area of the plain skin.

Tactile perception can be measured with SWMT with acceptable reproducibility. It has been widely used in studies of the sensitivity of the skin, particularly in monitoring recovery after hand injuries [15]. It has also been used to describe the cutaneous sensitivity in other domains including normal ears [16]. The thresholds of sensitivity in the face and neck are generally low and, for the purpose of minute differences, SWMT has its limitations even when used with the finest filaments [13]. In this study we focused on measurements around the level of protective sensitivity, and used filaments suitable for the purpose.

Another issue is calibration of the filaments [17]. Our control of the filaments showed concordant values for 2.83, 3.61, 4.31, and 4.56, corresponding to expected target forces of 0.07, 0.4, 2, and 4 g (Table I). Filament 6.65, however, had a force considerably below the expected one, so the two measurements on this level may indicate loss of protective sensitivity rather than only deep pressure sensation.

SWMT and its outcomes are dependent of these factors, and other factors may exert their influences as well. The handling of the device itself may play a part as well as differences in perception and concentration between adults and children. Costas et al. [13], for instance, used 13 measuring points in the face of adults and found mainly thresholds of 1.65, and there were no thresholds over 2.83. Posnick et al. [16] also

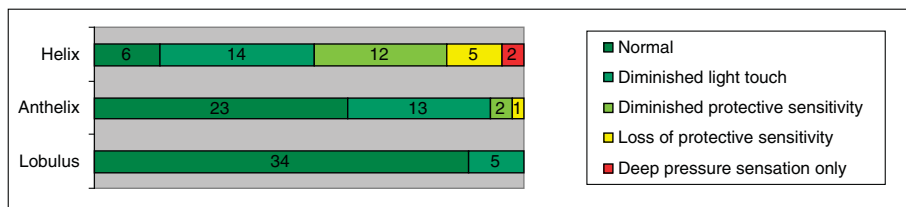


Figure 1. Sensitivity in the reconstructed ear.

measured the face including the lower helix and lobule, and found a mean threshold of 1.99. The findings of thresholds of 3.61 in a few instances in a normal ear may indicate that SWMT in our setting gave slightly increased thresholds. However, the opposite ear was used as control for the measurements of the reconstructed ear, which eliminated this possible systematic inaccuracy. If any, the consequence of these slightly raised thresholds would give an even better outcome.

Despite these limitations of SWMT, we considered that the method was the most suitable for detecting the threshold of protective sensitivity in a reconstructed ear. The additional advantage with SWMT is that it is simple to use and we found it to be easily understood and accepted, also by the younger children in our series.

No studies exist to our knowledge within the field of ear reconstruction about pathophysiological states after operation. The most comparative application related to our aim was the study of morbidity after sacrifice of the great auricular nerve during parotidectomy by Ryan and Fee [9]. Their definition of sufficient protective sensitivity was adopted for interpretation of our findings.

In the separate surgical stages various incisions are made on and around the ear under reconstruction, which bisect small branches of the sensory nerves in the area. The minimum follow-up time of six months was considered more than enough for restitution of sensitivity. Nerve regeneration is normally about 1 mm/day [18], and the distances to be bridged are only a few cm. There was obviously an initial rapid recovery as we noted no differences between measurements before and after 20 months. Nerves may regenerate better and faster in young people, but there were no differences between early and late reconstruction.

We decided to do this study within the time schedule of our normal follow-up. A prospective study was not considered necessary to elucidate the relevant variables. Our sample actually gave us a representative series and there were no complications, infections, or other adverse events compared with the total series of patients that we have operated on.

The mean age at the time of reconstruction was 11 years, which reflects the series as a whole from that time. However, the tendency is that ears should be reconstructed before the age of 10. In our experience they can actually be done from the age of 6 years if the thorax is large enough, and the patient is well-motivated. The possible advantage of early operation should be less psychological stigmatisation from the malformation during childhood.

With the development of the Brent and Nagata techniques, great achievements were made in the

possibilities of reconstructing the auricle with good or even excellent aesthetic results both as far as framework and skin colour match are concerned. With these techniques as a baseline, our follow-up results, 6–60 months after the operation, additionally showed that the reconstructed ear had good functional sensitivity. In just a few cases we found diminished protective sensitivity in the helical region. In our previous study we found good functional sensitivity to both heat and cold, which is important for preoperative information and in the decision-making before reconstructing an ear.

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Paper III

Paper IV