ORIGINAL ARTICLE

A System for Three-Dimensional Shape Measurement and its Application in Microtia Ear Reconstruction

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Abstract. Microtia is one form of ear anomalies representing the defect of a partial or total loss of external ear. This paper describes new method of total auricular reconstruction which combines the use of tissue expander and the non-contact, 3-dimensional (3-D) shape measurement system. The anterolateral and posterior surface of the both sides of the ear of the patients were measured with the 3-D shape measurement system. The data from normal side was mirror-imaged electronically and transferred to the computer-controlled milling machine to create the life-sized, mirror-image wax model. These models were sterilized and used as a template or an aid during assembling procedure of the autologous cartilage framework in order to reproduce the 3-D configuration of the wax model. Seven cases were treated with this method and 5 cases (72%) were graded as excellent (superior to that result obtainable from conventional methodology), one each (14%) was good (better result) and fair (the same level). There are no poor evaluations. In two cases, the exposure of the expander, one of the major complications, developed. Although additional surgery was needed, excellent and fair result was obtained in these cases. It was concluded that the method presented here was evaluated as an overall good method and its application should be further extended. (Keio J Med 42 (1): 22-40, March 1993)

Key words: microtia, auricular reconstruction, three-dimensional shape measurement system, computer simulation surgery, tissue expansion

Introduction

Microtia is one form of the ear anomalies affecting the ear and represents the defect of a partial or total loss of external ear. The degree of the defect varies in individuals and some patients accompany auricular atresia and/or abnormality of the middle ear. About the half of the microtia patients have some characteristics of the first and second branchial syndrome such as macrostomia, facial nerve palsy and unilateral facial hypoplasia (mainly mandible).

Although this is a relatively rare anomaly with an incidence of one to 6,000¹ or 12,500², the reconstruction of the auricle of these patients has been a challenging problem for plastic surgeons because these patients not only suffer from the esthetic problem but also functional problems such as inability to wear eye-glasses, masks and hearing-aids. Auricular reconstruction for microtia patients still remains one of the most difficult surgeries in the field of plastic surgery. A lot of factors including

for example the size, shape, axis, texture, degree of undulation and shape of the posterior fold must be considered to achieve a natural looking auricle.

After Converse³ and Tanzer⁴ established the use of the autologous rib cartilage platform, numerous attempts and modifications have been added. One of the most important refinements is the use of the tissue expanders. Tanino^{5,6} and Hata⁷ have successfully introduced the tissue expanders, which have been well established in the other fields of plastic surgery, into the delicate surgery associated with auricular reconstruction. First the tissue expander is inserted under the temporal skin and inflated with saline to develop abundant skin. This enables the surgeon to insert more 3-D cartilage framework. However, the problem exists as to how we can manufacture "real" or realistic 3-D cartilage framework. If the contralateral external ear of the patient is nearly normal, the author proposes that the new ear should be reconstructed as much as possible the mirror-image of the contralateral auricle. This can be facilitated if a mirror image life-size

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model of the contralateral auricle is available at hand during surgery and can be used as an aid. However to date there has been no reliable method to make this kind of model.

A new non-contact 3-D shape measurement system using laser slit-lamp scanning⁸ has been originally developed in order to meet the growing demands for digital shape measurement in industrial design, fashion design and medical science. From basic experimental studies this system has proved to be especially useful for measurement of any part of human body. In this paper a new approach of the auricular reconstruction with the combined use of the non-contact 3-D shape measurement system and tissue expanders is described and evaluated and the possible utility of this system is discussed.

Patients

A total of 7 patients with congenital microtia (4 males and 3 females) underwent auricular reconstruction with this method between July 1991 and August 1992. Their age ranged from 7 years and 7 months old to 10 years and 2 months old. The mean was 9 years and 1 month.

The 5 male patients presented with microtia involving complete hypoplasia of the left side with atresia of external meatus although there were minimal variations. The other 2 female patients had microtia of the right side. One patient had complete hypoplasia type and another patient had conchal remnant type.

Method

3-D Shape Measurement System

The system used is the VOXELAN system which was developed, and is currently marketed by NKK

cooperation⁸. This system is composed of the optical head consisting of the laser beam generator, two rotating mirrors, charge-coupled device (CCD) camera and an image encoder, a personal computer and a video monitor (Fig. 1 and 2).

The principle of the system is shown in Fig. 3. Light from the laser slit lamp is scanned on the subject by two oscillating mirrors. The object and the light patterns on it are recorded by the CCD camera in front of the object and the field is divided into 256×240 pixels. The image encoder processes the image from the CCD camera in a real time manner to synthesize the encoded image of projection angle of the slit lamp when each pixel becomes brightest by the slit light. This image is then transformed to obtain the height image of the object by each pixel through the triangulation method. In order to prevent any "noise" from the background light or the coloration

Fig 2 Components of the 3-D shape measuring system (from the left, plotter, PC-9801RA with hard disc drive, video monitor, image encoder and laser controller and optical head).

Fig 1 Schematic diagram of 3-D shape measurement system (reprinted from Ucsugi and Inomata⁸).

Fig 3 Basic principles of 3-D shape measurement (reprinted from Uesugi and Inomata⁸).

of the object, the minimum intensity image is subtracted from the maximum intensity image, and effective area is defined as a *mask image*. Then image of the shape is generated only in the effective area by this masking procedure. A composite image of the bilaterally-generated shape image is generated (in order to eliminate blind spots) and then perspective distortion as a result of the optical lens system is finally corrected. The 3-D shape image is shown in grayscale or wire frame form. The block diagram of the system is shown in fig. 4.

The data can be stored in diskettes so that later manipulation such as calculation of surface area and volume can be performed.

The specifications of the system are shown in Table 1.

Measurement of the ear

The anterolateral and posterior surface of the both sides of the auricle were measured. The external ear is a very complicated object and meticulous positioning of the optical head and the patients' head was required to minimize the blind spots which were likely to exist conchal wall, just posterior to the tragus and the hooding of helix. Repositioning was aided by a video monitor which showed a live image of the ear, and the optical head was fixed so that the above mentioned area could be seen as much as possible. Although it took only 10 seconds (4 seconds for each scan and interscan interval

of 2 seconds⁹) to complete measurement, we found some difficulty in stabilizing the child's head during measurement and a chair with a head rest was used for later cases. However, even when there were motion artifacts the measurement could be easily repeated and reliable data could be obtained. It was more difficult to measure posterior surface of the ear because the narrow angle of the auricle and temporal skin did not permit the slit laser beam reach deep into the posterior sulcus. In this situation rotating the optical head upright and transforming the laser scanning to the vertical mode minimized the blind spots effectively (Fig. 5).

The mirror image, life-sized wax model

The contralateral external ear, as measured above, was then mirror-imaged electronically and transferred to a computer-controlled milling machine (CAMM-3 from Roland. Fig. 6). Mirror image, life-size wax models of the anterolateral surface and posterior surface of the auricle were made for each patient and prepared for reconstructive procedure. The wireframe and the solid wax ear models generated from the 3-D slit-lamp measurement data are shown in Fig. 7-9.

Operative procedure

Expanders

Fig 4 Blockdiagram of 3-D Shape measurement System (revised from Uesugi and Inomata⁸).

Four types of expanders were used in this study. KOKEN No. 1504 (fig. 10a) was used in case 1, 3 and 5. This is a rectangular based expander with a slightly curved shape, measuring 5.0cm (L) × 4.0cm (W) at the base, 4.0cm in height and with a volume of 55 ml. KOKEN No. 1483 (fig. 10b) was used in case 4. This is round in shape with the diameter and height of 5.0cm and a volume of 75 ml. PMT No. 3605–16 was used in case 2. This product is of the same shape and volume as the KOKEN 1483, but is made of soft expandable silicone eliminating wrinkle formation. PMT No. 3610–18

was used in case 6 and 7. This product is rectangular, 6cm in length, 5cm in width and 95 ml in volume, and is made of a softer elastic silicone material than No. 3605–16.

First stage (Fig. 11a–11d)

Under general anesthesia the temporal skin on the affected side was infiltrated with saline to which epinephrine had been added. The straight incision about 4–5cm long was placed in the temporoposterior hair bearing area. Sub-cutaneous dissection was performed

Table 1 Specification of the System

1) Three dimensional shape measurement system: VOXELAN system (NKK corporation)	
Size of measurement field:	130 mm × 122 mm
Working distance:	210 mm
Precision:	0.4% of the measurement field (0.5 mm)
Laser scanning time:	10 seconds
Shape reconstruction time:	30 seconds
Laser light source:	Diode laser 5 mW, 670 nm
Personal computer:	NEC PC9801DA or RA
2) Computer controlled milling machine: CAMM-3 (Roland)	
Working field:	180 mm × 150 mm × 150 mm
Resolution:	0.01 mm/step
Working speed:	1.2 m/min.

Fig 5 The optical head and a patient sitting on the dental chair. Note the optical head is rotated 90° in order to measure the retroauricular area.

anteriorly from this incision to temporal skin just under and across the remnant on the subfollicular plane. The tunnel from the incision and temporal area was made as narrow as possible so that the expander would not migrate into the hair-bearing area. The pocket was formed to just as the same size of the expander beneath the hairless skin in order to avoid expanding and recruiting the hairy scalp. Hemostasis was completed and a tissue expander was inserted. Normal saline to about 10–15% of maximum capacity of the expander was injected from the port. The port was buried in the subcutaneous pocket in the mastoid area from the same incision. A suction drain was left and the incision was closed in two layers. The

Fig 6 Computer-controlled milling machine (CAMM-3 from Roland).

color of the skin on top of the expander was observed carefully for a few days and the suction drain was removed, following which the patient was discharged.

After allowing about two weeks for firm healing, the first percutaneous injection of normal saline, usually 5–10% of the full expansion volume, began. Further injections were done once or twice a week and the volume each time was 6–7 ml depending on the pain, skin color and tension. For most of the patients it took 2 months to arrive at the full-or over-expansion to allow reconstruction.

Second stage (Fig. 11e–11i)

Under general anesthesia the expander was extracted through the same incision. The thick capsule of the fibrous tissue at peripheral edge of the expander was excised and/or incised. The capsule beneath the thin, expanded temporal skin was left untouched for fear that this might jeopardize the vascularity of the expanded flap. The cartilage of the remnant is extracted very carefully in order not to make holes and damage small vessels.

A skin incision about 7 cm long is placed on the anterior chest and 3 rib cartilages (usually 7th, 8th and 9th) were harvested, and the perichondrium, muscles and skin were closed in layers. Then the cartilage framework was assembled and sculpted using fine surgical stainless steel wires and nylon sutures. The mirror image, life-sized wax model was sterilized and the cartilage was

Fig 7 Appearance of the normal ear and wireframe expression of the 3-D data obtained from the Voxelan system.

Fig 8 Life-sized wax model from the same data as seen in Fig. 7. Note the characteristics of the auricle are clearly demonstrated.

Fig 9 a. Life-sized wax model and an enlarged (1.2) wax model b. Life-sized mirror image models.

Fig 10 Expanders used in this study. A total volume of from 55 ml to 95 ml was used. a. Koken #1504. b. Koken #1483. PMT #3605-06 (not shown) is the same size of Koken #1483.

assembled to reproduce the 3-D configuration of the wax model. In most of the cases the 9th cartilage was used as the helix, while the symphysis of 7th and 8th rib cartilage was used to make main frame of the platform and antihelix. Additional pieces from 7th and 8th cartilage were used to make the wall of concha. Accurate reproduction of concha and antihelix was stressed in this series. Any harsh or sharp edge were cut to make smooth surface to avoid showing through the very thin skin coverage.

The platform was then inserted under the temporal skin. The platform should be positioned symmetric with the facial axis. The positioning of the platform was very critical and was helped with then use of mirror-image film pattern on which the oral angle, nasal ala and lateral canthus were marked. After insertion of a suction drain, the incision was closed in two layers.

Bolster sutures were placed to eliminate the dead space between the temporal skin and the platform and to

define the contour of the skin on the platform. The skin color under the bolster suture was checked every day and the suction drain was kept in for one week. The bolster sutures were removed in 2 weeks.

Third stage and/or forth stage (Fig. 11j-l)

Transposition of the lobules of the remnant was done as the third stage. In 2 cases the imbedded platform was elevated from the temporal lesion, and full thickness skin grafting and small triangular flap transfer was performed to make retroauricular sulcus. Efforts to simulate tragus were carried out in some cases.

Results

The reconstructed auricle was evaluated under 4 categories (excellent, good, fair and poor) from both anatomical and aesthetic points. The location, the inclination of the axis, size, the degree of erection, the

Fig 11 Case 1. a. Close-up view of the ear on the normal side. b. Close-up view of the affected side. Microtia of complete hypoplasia type. c. Intraoperative view: Incision line in the scalp and the area of undermining for expander is shown. d. The expander used in this case is shown (KOKEN No. 1504, total capacity is 55 ml). e. Appearance just before the second stage. The expander is over expanded to 73.5 ml.

shape of the helix and antihelix and presense of high conchal wall and tragus were also included in the evaluation. From the aesthetic point, a natural-looking auricle was evaluated highly. 'Excellent' was graded superior to that result obtained from conventional method, 'good' for better result than conventional methodology, 'fair' for the same level and 'poor' means worse than the result obtainable by conventional methodology. In this series 5 cases (72%) are graded as excellent, one each (14%) was good and fair. There were no poor evaluations.

In 5 patients (Case 1, 2, 3, 6 and 7) in whom complication-free skin expansion was carried out, it was possible to reconstruct an erect, 3-D auricle. In 4 patients the skin was thin and pliable and its pinkish color resembled the contralateral natural auricle. These auricles were graded excellent. In one patient (Case 2) shrinkage of the expanded skin was severe compared to the rest of the cases, the retroauricular sulcus was lost and late elevation of the auricle with full thickness skin grafting was required. Although an erect, 3-D ear was obtained, some of the

Fig 11 Case 1. f. The life-sized wax model and the 7th and 8th rib cartilage (below the reverse film pattern). The 9th cartilage is not shown. g. The autologous cartilage framework is carved and assembled with the life-sized mirror-image model as an aid. h. Three dimensional cartilage framework and the wax model: anterior view. i. Same as above, posterior view. Note the reconstruction of the conchal wall to make a crested auricle. j.-l. 1-year postoperative appearance. Naturally erect auricle with deep convolution is shown.

Fig 12 Case 3 a. Preoperative view. Normal side. b. Affected side. Microtia of complete hypoplasia type. c.,d. Postoperative appearance of the reconstructed auricle. Well erect and natural looking auricle is seen.

original contour was lost and it was graded fair.

In 2 patients (Case 4 and 5) exposure of the expanders developed, but partial expansion was maintained and their auricles were reconstructed with a cartilage platform without a high conchal wall. In case 4 the auricle was rather flat, it has thin skin and contour was well-defined. It was evaluated as good. In case 5 the remaining cartilage was banked in the chest pocket and well-erected auricle was obtained with the elevation procedure with this banked cartilage and full thickness skin grafting. This auricle was evaluated as excellent. The patient data are summarized in Table 2.

From these observations the method presented here was evaluated as an overall good method and its application should be further extended.

Discussion

Conventional methodology and associated problems

Reconstruction of the auricle for microtia has been a challenging problem for plastic surgeons. Converse³ and Tanzer⁴ reported the use of autologous rib cartilage framework in 1958 and 1959. Since then their methods especially Tanzer's method has been widely used with numerous modifications. As far as the material for the framework is concerned, the autologous rib cartilage has been the choice for almost all surgeons. Some surgeons have advocated the use of other material such as a silicone platform⁹, but with the problems such as infection

Fig 13 Case 4. a. Preoperative view. Normal side. b. Affected side. Microtia of complete hypoplasia type. c. Exposed expander due to its wrinkle. Although not satisfactory, skin expansion is maintained to some extent. d. 4 month postoperative view after 4th stage operation. The retro-auricular area was reconstructed with 2 triangular flaps and full thickness skin grafting.

and lack of long-term reliability, this method has not been widely accepted. In the Department of Plastic Surgery at Keio University, Tanzer's original method and its further modification has been indicated and satisfactory results have been obtained. Figure (15) shows the above-average result from the conventional method. Her auricle is well reconstructed in its general shape. However a close-up view reveals some problems. This ear (Fig. 15d) looks flat and lacks vivid, 3-D configuration.

The causes of the problems of the conventional method can be summarized into 2 factors. One is the shortage of the skin which to drape the platform and the other is the lack of three-dimensional model to be used as a template or an aid.

The shortage of the skin alone or with low-set hair line can be the cause of many problems: the malpositioning

of the platform (low set ear, migration of the reconstructed ear into the face), hairy auricle (upper part) and loss of contour. In most of the microtia cases the temporal skin is not enough even for draping anterior surface of a modestly convoluted cartilage platform. The retroauricular side has to be skin grafted.

Hairy ear is also an annoying problem to both surgeons and patients. Because of the lack of the temporal skin, the upper part of the helix is likely to include hair-bearing skin. In some cases electrical or surgical depilation is indicated. In an attempt to avoid this problem the entire reconstructed ear are sometimes located too low and become more difficult problem to solve. Another problem is the need for elevating the auricle, which consists of separating the cartilage platform from temporal skin and full thickness skin grafting.

Fig 14 Case. 5. a. Preoperative view of the affected side. Microtia of complete hypoplasia type. b. Normal side. c. Exposed expander. This occurred during waiting period for the second stage after over expansion. The expander was maintained in place and skin expansion was kept continued although not satisfactory. d.,e. Final view. As the fourth stage ear elevation procedure with banked costal cartilage and full thickness skin grafting was performed. Note the well erect auricle with deep posterior sulcus.

The reverse film pattern has been widely used as a template or an aid. This can be taken from contralateral ear in unilateral microtia cases and the parents' ear in bilateral cases. Though this method is very simple and doesn't need any special instrumentation, it not only lacks 3-D information but also has inherent distortion resulted from copying the shape of the 3-D auricle into 2-dimensional film. A Polaroid picture of the normal side (in some cases parents' ear) or exposing the normal side in the operative field may help the surgeon to make

the platform more 3-D but still the surgeon himself has to make the 3-D mirror image in his mind. It has always been difficult to cover and reconstruct all the below-mentioned internal factors precisely.

Although the normal ear in young people has a thin and slightly pinkish skin, following conventional methods the reconstructed ear tends to have thick and rather yellowish skin. This can be improved by making the temporal skin flap very thin. However this increases the risk of skin slough and resulting infection and absorption

Table 2 Summary of Patients

Case	Name	Age	Sex	Side	Type	Expander	Total volume	Total no. of Operations	Result	Complications
1	■	9y2m	F	Lt	CH	Koken #1504 (55 ml)	73.5 ml	3	Excellent	None
2	■	7y7m	M	Lt	CH	PMT #3065-06 (75 ml)	61.5 ml	4	Good	Unsatisfactory expansion Ear elevation with FTSG
3	■	10y2m	M	Lt	CH	Koken #1504 (55 ml)	84 ml	3	Excellent	Partial skin necrosis healed by conservative therapy
4	■	9y11m	M	Lt	CH	Koken #1483 (75 ml)	58.5 ml	4	Fair	Flat platform due to the exposure of expander Ear elevation with FTSG
5	■	9y4m	F	Rt	CH	Koken #1504 (55 ml)	73 ml	4	Excellent	Exposure of expander Ear elevation with banked cartilage and FTSG
6	■	8y5m	F	Rt	CR	PMT #3610-18 (95 ml)	89 ml	2	Excellent	Reconstruction in progress
7	■	9y3m	M	Lt	CH	PMT #3610-18 (95 ml)	84 ml	2	Excellent	Reconstruction in progress

CH: Complete hypoplasia type

CR: Conchal remnant type

FTSG: Full thickness skin grafting

and deformity of cartilage platform.

Reconstruction of the 3-D external ear

There are a lot of points requiring attention when reconstruction of a natural and real 3-D external ear is planned. They can be divided into external and internal factors. The external factors are the position, size and inclination of the axis of the auricle. The internal factors are the shape of the individual auricle. A smooth helix and high conchal wall are very important because they are easily seen aspects of the ear. The antihelix is also important because it lies on top of the conchal wall. The tragus should be reconstructed because it casts shadow on the anterior edge of the conchal cup resembling the external meatus. In order to improve above mentioned problems, it is clear that the surgeon requires both the 3-D cartilage framework and a plentiful supply of a thin and pliable temporal skin through which every detail of the framework can be shown.

The life-sized mirror image model was useful in constructing the 3-D cartilage framework by giving precise details of the auricle and by relieving the surgeon from having to construct the 3-D mirror image from the Poraloid print in his mind. The model was enabled with the use of 3-D shape measurement system and this is the first published clinical application.

The expander was able to provide satisfactory amount

of temporal skin although still not enough. The most important point in the author's opinion is that the anterior surface and the mid portion of the ear (i.e. the tragus, retrotragal pit, concha, high conchal wall and helix, antihelix and retroauricular sulcus if possible) should be reconstructed at the time of the platform insertion with the expanded skin. The retroauricular area of the upper part should only be covered if there is abundant skin because this area is easily reconstructed by full thickness skin grafting.

Use of tissue expanders in ear reconstruction

The first published report of the use of tissue expanders for ear reconstruction goes back to Neumann¹⁰ in 1957. And then Oneal *et al*¹¹ in 1984 and Quaba¹² in 1988 reported a case report. They all were indicated for the reconstruction of posttraumatic partial auricular defect.

Mutimer and Mulliken¹³ reported a case report of the correction of cryptotia using tissue expander.

Tanino *et al.*⁵ began to use tissue expanders for microtia ear reconstruction from 1983 and their results were published in 1988. Their operative procedure consists of at least 4 stages. In the first stage the Radovan type expander is inserted into the temporal subcutaneous pocket. The autologous cartilage framework is usually made of the 6th, 7th and 8th costal cartilage and is roughly assembled at this time and buried in a sub-

Fig 15 Auricular reconstruction with conventional methodology. a. Preoperative view. Microtia of complete hypoplasia type. b. Autologous cartilage platform and the reverse film pattern used as an aid. c. 2-year postoperative view after elevation and reconstruction of conchal cup with full thickness skin grafting. Natural looking auricle is obtained. d. Close-up view shows flat auricle lacking clear convolution.

cutaneous pocket adjacent to the donor incision in the chest. Inflation of the expander is begun 2 to 3 weeks after its placement and is carried out once a week with increments of 5-10 ml normal saline to the maximal expansion in 2 months. At the second stage (3 months after placement of the expander) the expander is removed and the capsule around it is excised. The prefabricated framework is retrieved from the chest pocket and final detailed carving is carried out and then embedded in the temporal pocket. At the third stage the auricle is detached from the temporal skin utilizing a full-thickness skin grafting from the inguinal lesion. Then the rotation of the lobulus is done at the fourth stage. If the depilation is needed it is done at the fifth stage. He evaluated that in his 35 cases 26 cases (74%) exhibited excellent to good

result, and 8 patients (23%) had only a fair result (loss of contour) and one patient (3%) had lost his expander owing to skin necrosis followed by infection. Complications are: exposure of expander in five patients (14%), exposure of cartilage framework in four patients (11%) and loss of contour in eight cases (23%).

Tanino's problems are believed to lie not only in high complication rate but also in the inadequate use of expanded skin. The author agrees with Tanino that his main purpose of utilizing an expander for auricular reconstruction is bringing out contour details. However recruiting hairly skin into the helical rim and scapha and the elevation of the reconstructed auricle with full thickness skin grafting should be avoided as far as possible. The author believes this could be fascilliated

with the use of a more 3-D framework which has distinctive, high conchal wall and economical use of the expanded skin.

Hata *et al.*⁷ in 1988 reported their efforts to reconstruct an erect auricle without skin grafting using skin expanders. Their operation was performed in 3 main stages. At the first stage the lobule is switched back and the remnant cartilage is removed. At the second stage a rotated semielipsoid tissue expander (70 ml) is inserted and then inflated to full expansion. At the third stage the ear framework is made from 6th, 7th, and 8th rib cartilage as needed in their original fashion and inserted into the temporal subcutaneous pocket. Although the advantages of expansion such as minor donor site morbidity (no need for skin grafting), good color and texture match and near normal sensation are well recognized, insufficient erection of the Hata group's reconstructed auricle seems to be a problem. The complication rate is rather high and 3 patients (43%) out of a total of 7 had complications resulting from skin expansion, and 4 cases (57%) in whom protruded auricle was reconstructed were conchal remnant type or constricted type. Only in one patient with complete hypoplasia could an erect auricle be obtained. This may be partly due to the particular design of cartilage platform in that study. A more anatomically-shaped 3-D framework with conchal support could contribute better to a naturally-protruding ear.

Bauer¹⁴ reviewed reported experience of ear reconstruction using tissue expander, including the data of Hata *et al.*⁷ and concluded that skin expansion is best indicated for conchal type microtia and cases grade 2 and grade 3 constricted ear, but that classic microtia (complete atresia) is not indicated because those cases can be reconstructed better without tissue expansion than with it. He also noted that the use of tissue expansion only to avoid skin grafting to the retroauricular sulcus alone is not sufficient reason for its indication. This indication of tissue expansion is perhaps contradictory, in that mild cases need skin expansion and severe cases do not need it. However it is accepted that avoidance of a skin graft to the retroauricular sulcus alone is not sufficient explanation to use skin expansion. It is clear that in classic microtia the temporal skin area is so small and the well-vascularized pliable skin is needed to reconstruct the complicated convolutions of the anterior surface of the auricle especially from the tragus to the deep portion of the concha and the high and distinctive conchal wall. So expanded skin should be used mainly for anterior surface of the auricle not for the reconstruction of the retroauricular sulcus.

Skin expansion and its advantages

Skin expansion is a relatively new technique of pro-

viding donor tissue, resulting an increase in the surface area of the expanded skin. Although soft-tissue expansion such as the expansion of the skin over the slow-growing tumor or the abdomen of the pregnant women is a natural process, its introduction into plastic and reconstructive procedures is relatively new. Neumann's 1957 report¹⁰ for the reconstruction of post-traumatic partial amputated ear was the first trial. The modern era was opened by Radovan's implantable, inflatable device with a semirigid backplate and a self-sealing remote injection port. From 1976 he began to present his work with this appliance for various kinds of problems¹⁵.

In 1980's the advantage of skin expansion was demonstrated both experimentally and clinically. Cherry *et al.*¹⁶ showed in a porcine model experiment that expanded skin has a significantly augmented survival length (117% compared with controlled flaps). Austad *et al.*¹⁷ showed in the guinea pig model, that the expanded skin epidermis is not thinned but the dermis and panniculus carnosus become significantly thinner. Pasyk *et al.*¹⁸ in 1988 showed that the thickest capsule was observed between 2 and 2.5 months of expansion and at 2 years after completion of expansion the expanded skin underwent normalization, with the dermis and subcutaneous tissue demonstrating a thickness similar to that before expansion. The capsule was completely absorbed in 2 years. It was demonstrated by Thompson¹⁹ that the fibrous sheath disappears within 2 weeks after removal of the silicone implant.

Moreover Ito's recent experimental work in rabbits²⁰ shows that pressure has a negative effect on cartilage acceptance and that skin expansion utilizing an expander is advantageous not only from the appearance but also from the point of the cartilage.

Problems in the use of tissue expanders in microtia total ear reconstruction

The selection of the expander and extent of expansion

The size of the expander was determined from the data of the previous reports of Tanino^{5,6} *et al.* and Hata⁷ *et al.* and by direct measurement of the patients' ear and remnant. Adhesive tape was applied and surface distance from posterior edge of the beard to temporal hairline was measured in all the seven patients. The average surface distance was 64.1 mm on the affected side and 113.3 mm on the healthy side. A distance of 49.2 mm were supposed to be obtained with the over-expansion of the 55 ml expander or full expansion of 95 ml expander. However because of the degree of the shrinkage of the expanded skin, this seemed insufficient for total ear reconstruction of a fully erect ear. It was thus determined to use the expanded skin primarily for the reconstruction of the anterior surface and mid-portion of the auricle and not for retroauricular area of upper part. In 5 patients

on whom the skin expansion was done without any complications it was possible to reconstruct erect, 3-D auricle. These patients had 61.5 ml–84 ml saline in their expanders. One patient who had a limited saline injection of 61.5 ml needed full thickness skin grafting to the retroauricular area but 3-D ear was successfully obtained. Judging from the above data the tissue expander should be inflated to at least 75 ml to cover a well-erect, 3-D ear. This figure does not differ a lot from the optimal volume recommended by Hata *et al*⁷. However in order to reconstruct the total undulation including concavity just posterior to the tragus and conchal wall and helix, a larger capacity expander should be used to provide abundant skin. Although the shape of the expander seems nothing to do with the final result, the soft, non-wrinkle and seamless type of expander is desirable.

PMT No. 3610–18 (6 cm in length × 5 cm in width) just fits nicely in the temporal non hair-bearing area and meets the above-mentioned requirements at this time.

Whether the expansion should be left in place for a while in order to prevent shrinkage is another unsolved problem. It is known that the expanded skin shrinks less when the expander is kept in place for a few months. However, this principle should perhaps not be applied in this region, because the skin is too thin to withstand every day minor trauma. In this series, Case 5. developed exposure in this waiting period so at this time the second stage is scheduled immediately when a satisfactory skin surface area is obtained.

The handling of the capsule

The handling of the capsule around the expander is still controversial. Tanino *et al.*^{5,6} remove all of the capsule except where the skin is too thin. Hata *et al.*⁷ generally did not remove the capsule and incised only one third of the circumference. In this series the author's team did not take the capsule out except for the anterior and upper portions because the skin is too thin and the small axial vessels run just above the capsule, so that removing the capsule may negatively affect the vascularity of the expanded skin. The anterior part of the capsule near the remnant and upper portion were removed because the capsule tissue might have obscured the contour of the anterior crus of the helix and tragus. Although other portions of the capsule were in general not removed, in most of the patients the base of the hard triangular capsule at the edge (peripheral margin) was incised in deep layer with meticulous care not to damage the fine vessels on the capsule in order to obtain advancement of the skin in a central direction. Capsules are expected spontaneously to resolve rapidly from Thompson's observation¹⁹ and the author feels that they need not be removed, especially with the risk of skin necrosis.

Retraction or shrinkage of the expanded skin

It is known that the expanded skin retracts to some extent although the mechanism is not fully explained, and that the expanded skin tends to contract less on a rigid framework.

The extent of shrinkage seems to differ by location. Scalp skin is likely to retract more than the non hair-bearing temporal skin so in this series the scalp was not expanded and not recruited for helix. The cases with the greater total expansion volume tended to have thinner, more pliable skin and obtained better anterior draping and posterior sulcus.

Exposure of the expander

Exposure of the expander is one of the worst complications of the tissue expander. Although case 4 and 5 developed this problem, excellent and fair result could be obtained. From the author's experience this complication can be well handled with meticulous care and does not affect a lot to the final result. In such a case avoidance of infection and banking of rib cartilage for later auricular elevation should be considered.

Utility of the 3-D shape measurement system for human figure measurement

Advantage of noncontact 3-D measurement system

The advantage of free surface (non-contact) measurement is that it doesn't create any distortion caused by pressure during measurement and it is safe, clean and easily repeated.

In order to obtain 3-D measurement, 3-D digitizer has been often used. In the medical field, some of these examples are the anthropometrical measurement of the human skull and documentation of the occlusion cast model of patients with the cleft palate²¹. However 3-D digitizer is not appropriate for large areas of in-vitro measurement in humans because the object must be on the digitizing table and the human body is made up of multiple smooth and complicated surfaces. In such a case, the measurement points tend to be too many, and the object need to be absolutely still for a long period of time.

On the other hand, despite the fact that it is inferior in accuracy to the digitizer, the free surface 3-D measurement system based on a laser slit-lamp scanner is very suitable for human measurement because it enables quick pattern measurement.

Introduction of free-surface measurement technology to the medical field

Moss and his group^{22–24} developed a specially-designed no-contact laser scanning system for studying changes in the facial form. Their system consisted of scanning head with two laser beams, rotating mirrors

and a video camera employing DMA (Direct Memory Access) interface and Norsk computer. The patient is seated on a chair which is rotated by a stepper motor under computer control. The data for each profile is obtained in one twenty-fifth of a second. Geometrical transformations are then applied to convert the raw data into a set of approximately 300 spatial coordinates. The precision of this system is 0.5 mm. The data of the entire face consisting of 24,000 measurements is recorded in approximately 30 seconds. Data is sampled at intervals of 1 degree over the nose and intervals of 3 degree over the rest of the face. The facial coordinates are stored in the computer disc and floppy discs. Moss and his colleagues also developed a three-dimensional visualization technique for skull and facial skeleton from CT scans and proposed the possibility of surgical simulation.

Cutting *et al.*²⁵ in 1988 introduced the Echo Scanner manufactured by Cyberware Laboratories. The principle of this system is somewhat more simple compared to Moss's system. The scanning head has only one laser beam and the patient is seated on the computer-controlled rotating chair but has a higher resolution of 500 scan lines in each video frame.

The data are transferred to a Silicone Graphics Iris 2400 graphics workstation and processed to produce three-dimensional images using the group's original software. A point-to-point three-dimensional measurement capability is provided.

Although at the time their paper was written there was no practical utilization in the literature, the authors proposed the possible usage of the system in maxillofacial surgery, breast surgery, rhinoplasty and body contouring surgery such as liposuction.

The Voxelan system

As the principle and hardware construction of the Voxelan system have been discussed and shown before, only the difference between the Voxelan system and the above-mentioned systems are discussed here.

The principle and hardware construction is similar to Moss's system in that both system have adopted the triangulation method with one VTR camera and 2 rotating mirrors. Although both Moss and Cutting use a compute-controlled rotating chair for full-face measurement, this tends to create many blind spots. From the experience of the author of the present study and his group, the optical head should be rotated freely to measure complicated human parts. In order to make full face measurement, compilation of the data from various angles is more appropriate, and the mobile arm and software are now being developed to accomplish this.

The principle of Cutting's system is different from the Voxelan system. As Cutting's system uses only one laser beam the resolution tends to become low when the object being measured is at an angle because the slit

lamp projected laser beam diverges, or becomes wider, on the object.

The use of both systems in a dark room is recommended in order to reduce interference from extraneous light sources because they do not have any light-masking process.

The accuracy depends on the degree of the projected angle of the laser beam, the width of the beam, the speed of the beam and system resolution. If the object is 10–30 cm and the angle of the laser beam is 45°, accuracy is determined by the system resolution. In other words, accuracy is determined by the number of pixels: when the pixel resolution is 256×240 and the measurement field $130 \text{ mm} \times 122 \text{ mm}$, the accuracy range is to within 0.4%, (0.5 mm) and is thus almost negligible for auricular reconstruction. Although the accuracy goes up to 0.2% with the high resolution model of 512×480 pixels, this system is not recommended for human measurement because of long measurement time required, which is double the standard system. The accuracy and resolution of the milling machine is also very high (0.01 mm/step), and is thus also negligible.

For measurement of human subjects the speed of measurement is a very important factor. The laser scanning time is 4 seconds for one beam and is carried out on both sides, so the measurement can be completed in just 10 seconds. From the author's experience this is short enough for measurement of the ear, face, hand and chest of the adult patient. However a chair with a headrest is needed to immobilize the head of the microtia patients.

The shape reconstruction time is about 30 seconds: the result can be checked on the TV monitor immediately and the measurement can be repeated. The measurement of the both the anterior and posterior surfaces of the both sides of ears took about 10 minutes. As this system employs a high resolution scanning system and real-time encoding of projection angle of slit lamp, it gives a high rate of reliability and repeatability.

In the measurement system based on the triangulation method, as the angle between the scanned (laser) light and the axis of the lens system of the TV camera determines the accuracy, the shadow area i.e. blind spots increases as the object gains in surface complexity. This system can minimize blind spots by collecting data from 2 directions creating different shadows, and then extracting effective area by a process of image subtraction. However it was impossible to eliminate the blind spots just under the hooding of the helix and posterior surface of the tragus because it has the only one TV camera and therefore inevitably result in some blind spots. Fortunately these area are situated out of normal view, and are not expected to be reconstructed. Blind spots can be effectively eliminated by adjusting the optical head so that the axis of the lens system of the TV camera cuts the object at the same angle as through the TV

monitor. For the anterior surface measurement of the ear with the hooded helix, a slight elevation of the angle was appropriate. In most of the measurement of the posterior surface, the head was rotated through 90.

Although at this time the measurement and creation of the ear model are done for both anterior view and posterior view separately, i.e. 2 models for one ear, the creation of composite data from multiple angles will become possible in the near future by the development of special software.

Comparizon of the methods for making ear model

In this paper the usefulness of the mirror image life-size wax model taken from the normal side is clealy demonstrated as an aid to reconstruction. Although the reverse film pattern is still useful in precise positioning of the cartilage framework, the framework itself should be assembled three-dimensionally with the aid of the mirror image model.

It is however not easy to make a simple cast model of the external ear as is expected, other than using this method. The ear is too soft to take an impression with the usual dental materials and there will always be some degree of distortion. Because of the extremely complicated auricular configuration, it is easy to break or damage the dental molding material when the cast model is being detached from the mold.

Making mirror-image model can only become possible with the help of either artristic work or computer technology. The former is time consuming and expensive. It may be possible to make mirror-image ear model based on the data from computed tomography (CT) and

magnetic resonance imaging (MRI). However CT has a problem of the resolution (0.5 mm in axial plane and at the most 2 mm in vertical plane) coupled with the radiation exposure, and is not practically indicated for the deformities of body surface soft tissue only. MRI for this purpose, while more accurate and better than CT for soft tissue work, is not cost-effective.

Further applications for auricular reconstruction

Determination of the size of the tissue expander

Hata *et al.*⁷ reported the mean surface area of ten normal adult Japanese ear as 52 cm². However as each ear differs a lot in size and shape so does the surface area. Recently a new software (3-D Sphinx from Kashimura Co. Ltd.) has been developed to calculate distance, surface area and volume from the data obtained with the three-dimensional surface measurement system (Fig. 16). Although this software need more refinement and calibration, it is expected to provide practical and useful data in determing the size of expanders.

Application in reconstruction of bilateral microtia

In bilateral microtia patients, it would be wise to measure the parents' ear and make the life-sized model from this data and reproduce the cartilage framework to simulate that ear model. Characteristics of the parents' ear can be combined, such as the size from the father, and the shape from the mother. This concept of customized ear designed should be welcomed as most families have few children.

Fig 16 Screen display of 3-D Sphinx (from Kashimura Co. Ltd.) measuring surface area of the auricle.

Postoperative evaluation and documentation

Although the documentation of the postoperative result can be achieved by anthropometrical measurement and photography, 3-D digital data and life-sized model have a distinct value for evaluation and documentation.

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