

The Role of Laser Surface Imaging in the Evaluation of Craniomaxillofacial Disorders: The Singapore General Hospital Experience

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Abstract

The medical profession today, has the choice of many imaging techniques for documenting, investigating, assessing or planning treatment. Amongst them, the laser surface imaging system is emerging as a useful tool to capture and store digital data for reformatting into a three-dimensional computer model.

The laser scanning system captures only the surface morphology of a subject, and is highly appropriate for the evaluation of surface morphological changes of craniofacial disorders. Although originally acquired for the study of facial anthropometry, many other clinical uses have been found for the scanner and this paper describes our experience with the laser scanner in our department. These include archival, preoperative assessments, projective linear and surface measurements, area measurements, comparative analysis, planning and prediction of surgical outcomes, and in the fabrication of physical models and external prostheses.

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Introduction

The management of craniomaxillofacial disorders is not complete without the proper documentation of clinical information and the storage of images. It is usually long-term and has many follow-up sessions. Conventional photographic documentation still serves as the most convenient and quick method of documenting such cases. However, the ability to acquire three-dimensional images for archival, as well as for assessment and surgical planning, is advantageous because the surface morphology of craniomaxillofacial disorders can be captured using the Laser Surface Imaging system. Accuracy of data and good image resolution ensures that the surface images acquired are true replicas of the subject's surface morphology.¹ Each image requires only about 8 KB of computer disk space which can be stored and later retrieved for assessment. This includes both subjective assessments using multiple views and positions and quantitative assessments for linear and area measurements. The 3-D laser surface image may also be edited to predict surgical outcomes, and postoperative results can be followed up with serial scans and compared to preoperative records to assess the degree of improvement or relapse.

Although the laser scanner was initially acquired to document and assess normal subjects in the study of

facial anthropometry, our experience has shown it to be a useful tool for archiving the various cases seen in our department and for carrying out assessments. This paper looks into the other uses of the laser surface scanning system in support of total management of patients with craniomaxillofacial disorders. Bearing in mind that many imaging techniques are now available, the right choice of imaging methods to suit the patient's need must be made by the clinician.

Imaging Techniques

There are various types of imaging techniques used in diagnosis and treatment planning which can be broadly classified into methods involving radiation [X-rays and computerised tomography (CT)]; those using magnetic fields [magnetic resonance imaging (MRI)]; ultrasound techniques and methods relying on optical systems to capture surface data [photography and stereophotogrammetry].^{2,3} Studies have also been carried out using 3-directional photography to measure the three-dimensional coordinates on the human face.⁴ With advances in imaging technology, it is now possible to capture three-dimensional surface morphology using imaging systems which record the x, y and z coordinates of hundreds of thousands of digital data points on a selected surface.^{1,5} This usually requires a light source which is

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directed towards the desired surface and the reflected light is captured in the form of individual point location in Cartesian co-ordinates.

The multiple points or point cloud data from a scan are then computed to display a replica of the scanned model complete with a surfaced texture. Some systems may only provide the cloud data and would then require another Computer Aided Design (CAD) software programme to perform the surface-rendering feature. Commonly used light sources are a bright, white light shone through a grid pattern (the Moire fringe pattern) or a laser light beam in the form of a stripe which is passed over the desired surface (the Laser Scanner). Scanners are not only used for image capture but also for the purpose of carrying out anthropometric measurements based on repeatable landmarks,⁶ and in the assessment of three-dimensional changes in surface morphology.⁷

The Laser Surface Scanner

The laser surface scanner used in the Department of Plastic Surgery, Singapore General Hospital, was originally acquired from the Biomedical Department of the University College London (UCL) to scan normal cases and carry out facial anthropometric studies. Later, other cases with abnormal facial morphology were also documented and the system software tools were utilised to evaluate the extent of abnormalities and to carry out surgical planning.

As the description of the laser scan set-up and the principle and mechanics behind it have already been described in earlier papers,^{1,8} only a brief description of the system will be given here. This system employs a weak (1 mW) Class IIIA laser light source, which is fanned out into a stripe and directed at the object to be scanned. The vertical laser stripe would then describe the contours of the object for that particular cut and the reflected light is captured by sensors as digital information, through 2 sets of mirrors (Fig. 1). The data are then stored in the computer hard disk. Multiple cuts or stripes are taken in sequence by a controlled rotation of the subject in a motorised chair or pedestal in order to scan the entire selected region. The resolution of the image will depend on the space or distance between each adjacent point and the total number of points that are reflected towards the sensors will therefore be related to the number of cuts or slices taken for each scan. For clinical purposes, an error margin of 0.3 to 0.5 mm is considered adequate to give a good resolution. Industrial scanners would require accuracy in terms of microns. Other scanning systems may have a stationary subject with the scanning system revolving around them.

The whole scanning procedure, depending on the system used, may be as quick as 4.0 to 8.0 seconds for medical scanners and requires a special darkened room to prevent disruption of data capture by stray light.

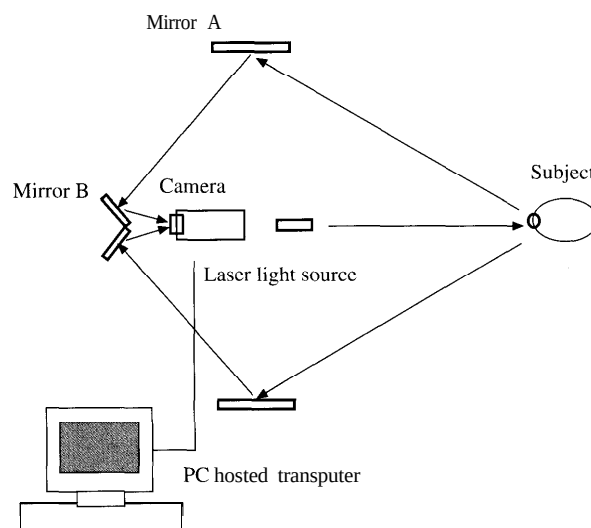


Fig. 1. Diagrammatic representation of the laser surface scanning system

The Laser Scan Image

The 20,000 or more digital data points are connected by a triangulation network, between every 3 adjacent points to form patches, which are then shaded to render a surface. This is referred to as the laser stripe triangulation method and various shading methods may be used to render the surface texture.

The final 3-D image viewed on the monitor is a good replica of the model or person who was scanned and measurements carried out have been shown to be reliable up to 0.5 mm.^{1,6,9} The 3-D computer model may be assessed for linear dimensions, proportions, deformities or irregularities of the surface morphology and measurements may also be carried out for recording or for assessments. Unlike 2-D images, the laser scan image may be assessed in any desired view and regions of interest can be highlighted by adjusting the "light source" to better define some features.

The Role of Laser Surface Imaging in Craniomaxillofacial Disorders

As in other medical disciplines, a preoperative and a postoperative photographic record is usually kept for most of the patients in the department. This provides a basic form of image record in 2-D form in the standard views and may be inadequate for assessing some of the craniomaxillofacial deformities and disorders. Two-dimensional images lack a perception of depth, the third dimension, and its interpretation is based on the view in which the image was captured and cannot provide accurate Quantitative values. With a three-dimensional image model, assessments may be carried out, in different viewing positions by rotating and tilting the image and many studies have shown the benefits of 3-D assessments.¹⁰⁻¹²

The time taken to capture the laser scan image is a

quick 8 seconds for a 180° scan and this relieves the patient from having to sit in the doctor's office for long periods, in order to be assessed and measured. The procedure is free of radiation and the 1mW laser beam is "eye safe". Repeated scans may be taken if necessary or follow-up scans may be taken for postoperative and longitudinal studies.

Since the inception of the use of the laser imaging system in our department in late 1993, we have carried out facial anthropometric studies on normal subjects and have also been scanning craniomaxillofacial cases routinely for archival and assessment.

Case Studies

Of more than 680 cases scanned to date, 37% (251 cases) were those with craniomaxillofacial disorders. A detailed breakdown of the variety of patients who were documented is shown in Table I. This lists the disorders with surface deformities in the craniofacial region as well as those with bony injuries and deformities. They also include maxillary hypoplasia following cleft lip repairs, facial defects following trauma, congenital defects and facial asymmetry and cleft lip nose deformities.

Assessments Tools

The system software can measure, both projective and surface measurements and the area and volume of a selected region. It can also mirror image and compare two image surfaces to detect changes or differences in surface morphology. This allows many objective assessments to be carried out apart from the subjective visual

assessment of the surface morphology from different views and positions.

Linear projective measurements may be carried out between any two selected or marked points. Studies have shown these to be quite reliable^{6,9} and the surface measurements may also be determined from the same set of points. Shading a selected area on the scan image can provide the area measurement and volumetric assessment may be possible.

Editing the image or modifying patches of the surface allows one to either advance or push in selected regions and this tool, known as Surface Edit tool, has been used to predict surgical outcomes especially in orthognathic cases, for the benefit of both the surgeon and the patient (Fig. 2).

Mirror imaging allows flipping a "normal side" over, to be matched or "pasted" on to an "abnormal side" to present a possible surgical result. Better still, utilising an image super-imposing tool (Registration) to match an original image with that of a mirrored or postoperative image, will demonstrate discrepancies in surface heights. This provides the viewer with a contoured, colour coded map of the area studied, showing the shape and area of the defect as well as providing the difference in depth (surface height) between the affected and normal parts (Fig. 3).

Physical models of the image can be fabricated, making use of state of the art model making processes, known as rapid prototyping techniques. The laser scan data are first modified on a special CAD software, which then generate files that would instruct a rapid prototyping machine to make a physical model.

Current research is in progress to take this further and scan defect areas in the facial region to fabricate external facial prostheses. Test models have been successfully reported¹³ and ways to refine the final product are still being sought.

The above features of the Laser Imaging System can be used in preoperative or postoperative assessments of patients. The following work-up depicts some examples of the role of the laser surface imaging in various craniomaxillofacial disorders encountered in our department.

Preoperative Assessments

Archival: All cases undergoing surgical procedures in the facial region which would alter the surface morphology are scanned preoperatively to obtain a baseline image data which may be archived or retrieved for future reference. Archival of data is important as most of these cases, once operated upon, will have no means of referring to their original morphology and the data can be used to make physical models if the need should arise.

TABLE I: CRANIOMAXILLOFACIAL CASES DOCUMENTED WITH THE LASER SURFACE SCANNER (DEPARTMENT OF PLASTIC SURGERY, SINGAPORE GENERAL HOSPITAL)

Diagnosis	No. of cases
Apert's syndrome	1
Binder's syndrome	2
Cystic hygroma	1
Fibrous dysplasia	9
Facial asymmetry	19
Facial fractures	12
Facial defects (congenital and acquired)	15
Fronto-encephalocele	1
Haemangioma	2
Hemifacial microsomia	16
Mandibular deformities (prognathism, micrognathia, prominent angles)	15
Neurofibromatosis (plexiform)	10
Romberg's disease	3
Treacher Collins syndrome	2
Mid-face hypoplasia and facial disproportions related to post-cleft lip repairs (orthognathic surgery)	118
Cleft lip nose deformity	25
Total	251

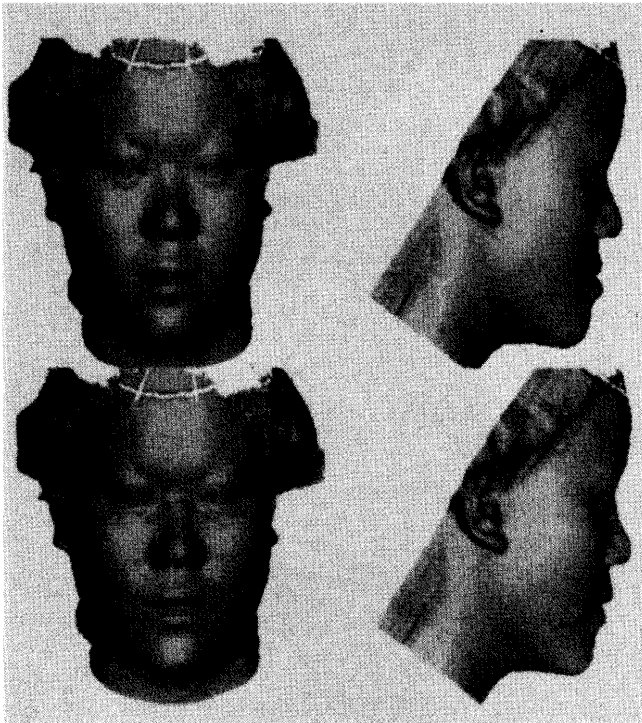


Fig. 2. *Surgical simulation.* Top: The two views of this subject shows mid-face hypoplasia for which a LeFort /maxillary advancement was planned. Bottom: An improved profile obtained by advancing the soft tissue surface in the maxillary area to simulate the surgical outcome.

Implant or grafts, such as fat grafts or bone grafts may become unstable and could undergo resorption or shift. The surface changes could then be monitored by taking serial postoperative scans and carrying out comparative analysis with the archived image (Fig. 4).

Measurements: Cases with facial disproportion or asymmetry are scanned and anthropometric measurements are carried out to quantify the facial dimensions. This information can then be applied when planning the surgical correction. The ability to assess such deformities from various angles makes it superior to assessments using two-dimensional images

Changes in size and volume of abnormal facial growths, such as tumours or fibrous dysplasia are monitored by taking serial scans and comparing them to detect any change over a period of time (Fig. 5).

Jaw relationships, altered through surgery (e.g. orthognathic surgery), tend to relapse to their original positions over a period of time due to muscle pull and scarring. This reversal may be monitored with serial scans where visual assessments or measurements can be carried out.

Surgical Prediction and Planning: Patients requiring orthognathic surgery, be it for aesthetic purposes or to correct post-surgical cleft deformities require standard cephalometric prediction and model surgery using dental models. With a three-dimensional image of the pa-

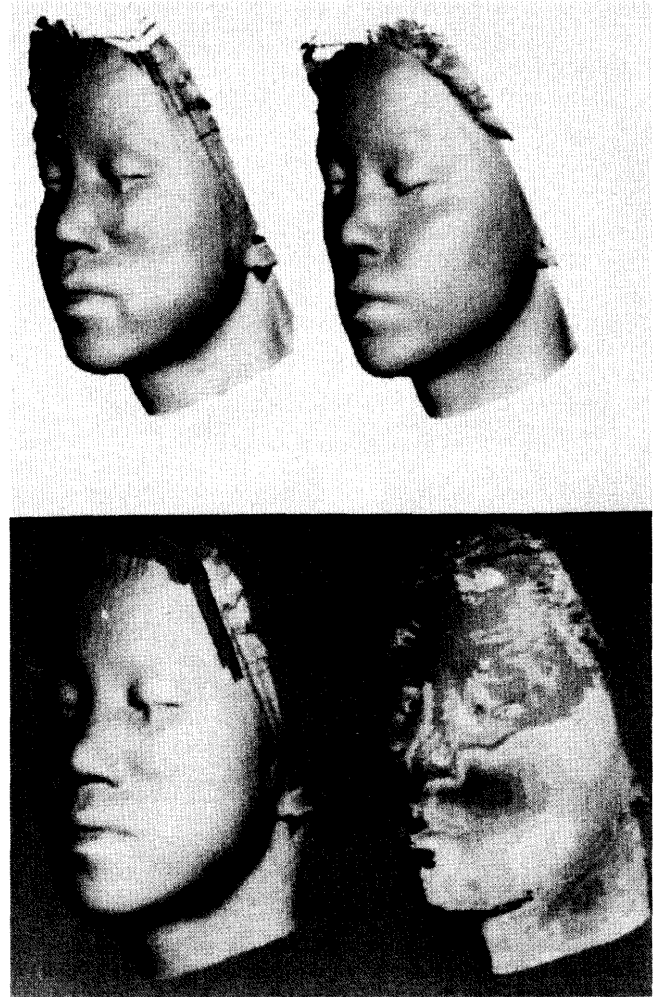


Fig. 3. *Assessment.* Top: The depression deformity in the left cheek is compared with the right cheek using a mirror image to visually assess the extent of the deformity. Bottom: By using Registration where the two images are superimposed, the areas of discrepancy are better highlighted and shown as colour coded contour bands which indicate the area and the gradual increase/decrease in the surface height.

tient the prediction of soft tissue changes that would follow surgery can be demonstrated using the Surface Edit tool.* A prerequisite to this exercise would be a knowledge of the proportion of soft tissue movement to the actual bony movement ascertained from earlier cephalometric studies.^{14,15} Each change in surface height is measured, therefore providing information on the extent of movements performed.

Changing the surface profile or morphology to achieve a desired result and then checking on the extent of movement is also possible. These predictions have been found to be very useful both for the patient as well as the surgeon, as the patient gets to see the likely three-dimensional outcome. Similarly, the surgeon will have a better idea whether the patient can accept the likely change and make alterations to his plans if necessary.

Patient Monitoring: Conditions where there is a definite or doubtful change in the surface height or mass, i.e.

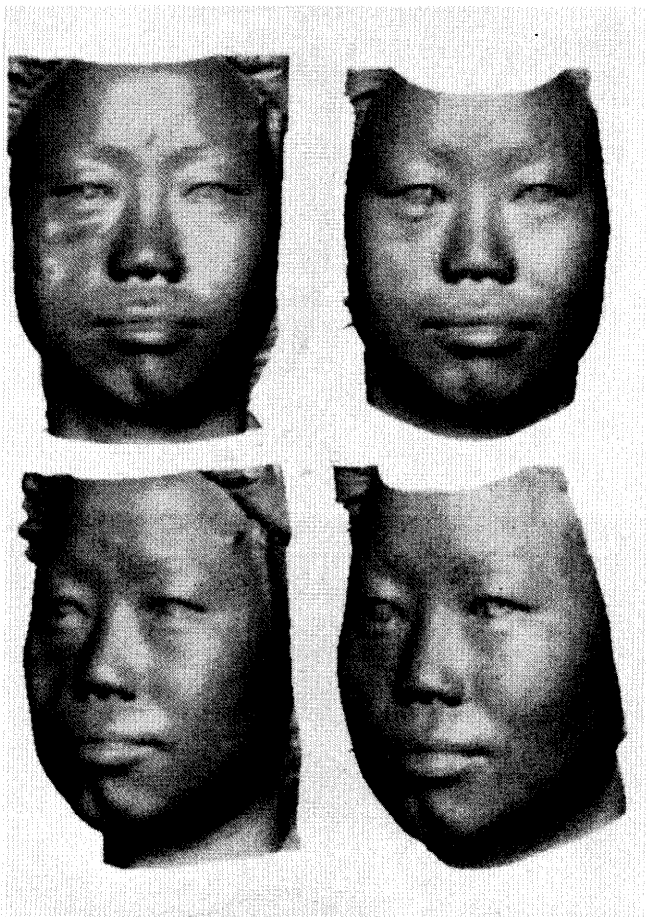


Fig. 4. Monitoring. A six-month follow-up scan of a patient, who had received treatment to correct her right cheek deformity (left), shows that the treatment had been effective and she had no relapse (right) except for her chin area.

swelling or tumour, can be monitored by taking serial scans at known intervals to determine the changes and to also quantify them. Monitoring of post-surgical results is also practised especially when relapse is anticipated.

Postoperative Assessments

Following surgical intervention, facial swelling and the rate at which it decreases and the time it takes for all the swelling to resolve can also be studied by taking serial postoperative scans. Comparative assessments of how a case is progressing at different stages of surgery provide data for longitudinal studies.

Relapse following craniofacial surgery where bony movements are involved is quite common and the surface scanner can provide essential information on the progress during the healing stages (Figs. 6 & 7).

It would be ideal for studying the development and progress of craniofacial deformities, such as craniosynostosis in young children, but the present scanning system cannot scan uncooperative young children. The arrival of an upgraded mobile scanning system will make that possible in the near future.

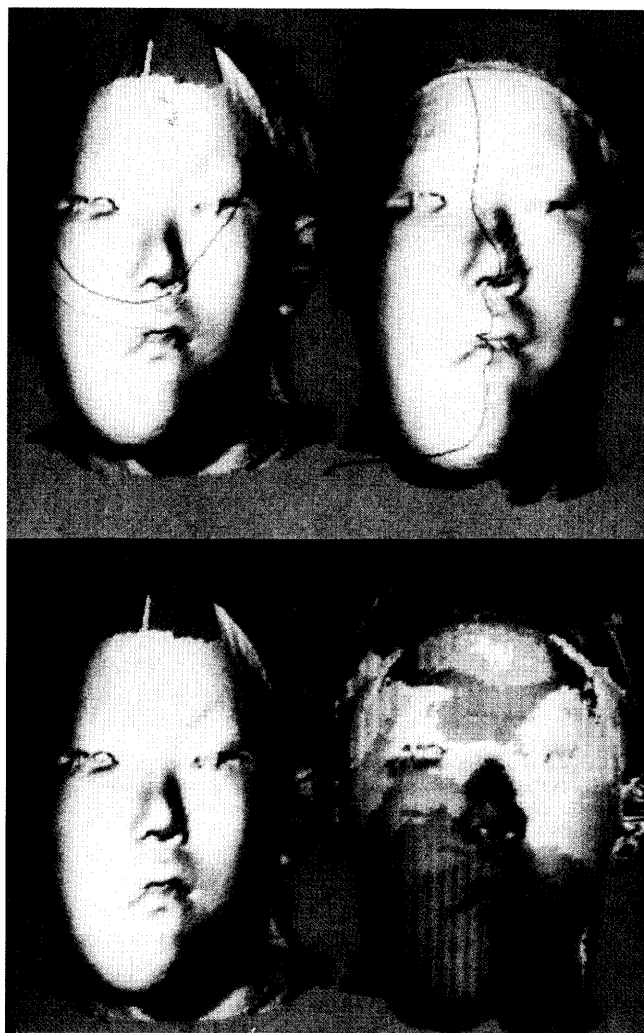


Fig. 5. Monitoring. A one-year follow-up of a child with plexiform neurofibromatosis. Monitoring has shown a significant increase in the size of the growth as indicated by profile lines (top), and better seen in the superimposed comparison where growth in the mandibular region is more noticeable (bottom). The child had also grown considerably within the one-year period.

Physical Models

The laser surface scanner was recently employed to explore the feasibility of fabricating 3-D models from the laser scan data. Although it is commonly known that 3-D CT scans can be converted directly to instruct modelling machines to fabricate physical models,¹⁶ a few extra steps had to be taken to first convert the laser surface data for use in a CAD (Computer Aided Design) software where the computer modelling is completed. The programme can then generate special files which would instruct the Rapid Prototype Machines (RPM) to fabricate the 3-D physical models.

These models may be used, either as reference and study models of rare and interesting cases, for planning purposes, for teaching or simply for archival.

Further research is being carried out in this line to focus on defective areas of the face which can be camou-

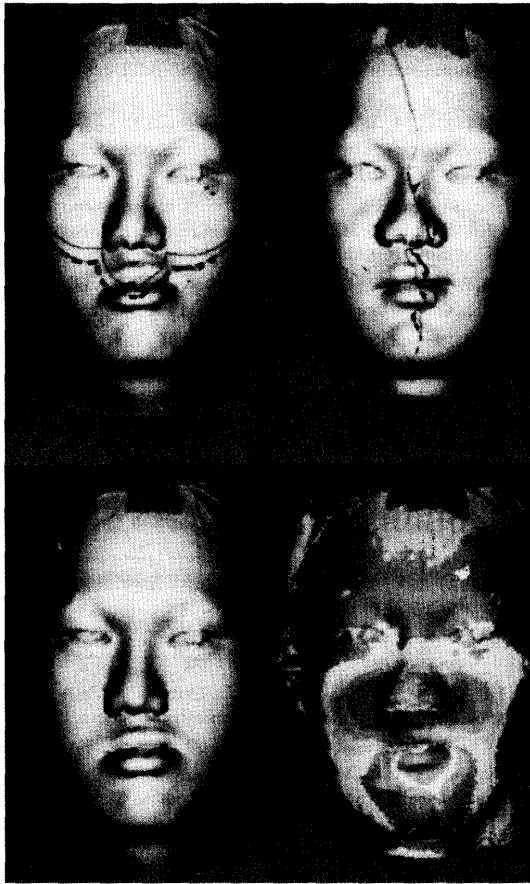


Fig. 6. Top: Follow-up scan on a patient who had a maxillary advancement together with a mandibular setback operation showing the postoperative changes in the vertical profile as well as changes over the cheek in the horizontal profile. The cursor (on the tip of nose) may be moved to any location on the face to determine the changes in three-dimensions. Bottom: The colour coded contour bands indicate maximum advancement in the paranasal region gradually sloping away to the original surface level at the malar areas following the advancement. The chin region shows negative colour changes, indicating the surface there had receded when compared to the original image on the left.

flaged by an external facial prosthesis. A project report was recently completed on the process of making the mould of a nose into which silicon would be injected to make an external prosthesis. This involved state-of-the-art rapid prototyping systems and vacuum casting methods in making the mould.

Discussion

The commonly used means of investigative imaging in the medical field are X-rays and CT scans,¹⁷⁻¹⁹ MRI and ultrasonography. For capturing surface details and morphology, the laser surface scanning system is the method of choice. Characteristics of 3-D laser scan images are often compared to 3-D CT scan models. While both image types are visualised on the computer monitor, it must be noted that the amount of data generated from a computerised tomogram is different in nature and size and permits visualisation of the underlying structures, which the laser scan images cannot. Computerised imaging systems are being used quite frequently now,

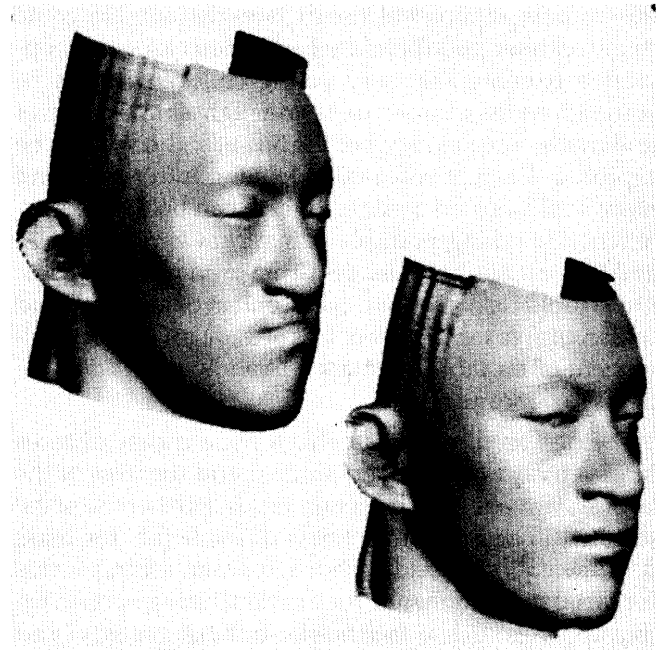


Fig. 7. A long-term follow up of a case of post-cleft lip deformity over a period of 22 months. The patient had undergone various stages of surgical correction for the maxillary hypoplasia, protuberant mandible, upper lip deformity and nasal tip deformity. The baseline archival image is seen on the left while the right image shows the final result.

and computer assisted surgical simulation has been practised by many institutes and centres.²⁰ Some units make use of both the 3-D CT images and the surface scan images to create composite images which provide a more realistic result when carrying out surgical assessments.* For reasons of safety, speed and economy, a surface scan image is advisable, if only surface features need to be analysed.

Advantages: The low 1 mW power, Class IIIA laser beam is considered eye-safe, and each scan requires less than 10 KB of disk space. Each image may be stored, copied or transferred with speed and ease, using a personal computer. As the time taken for a 180° scan is less than 8 seconds, a repeat scan, if necessary, should not be unduly time-consuming for both the subject and the doctor. The patient does not have to sit for long periods in the doctor's office to be assessed, as the doctor can retrieve the scanned image and carry out his assessments in the patient's absence. Both qualitative and quantitative assessments of surface morphological defects or changes can be carried out and surgical planning and prediction of outcome is also possible. Patients' progress can be monitored and studied longitudinally. The ability to fabricate physical models, using the laser scan data, has taken us to newer heights in making use of the laser scan imaging system.

Disadvantages: At present, some disadvantages exist, which limits the scope of the laser imaging tool. The requirement of a darkened environment during the scan means that a special room is required. The structure of

the scanning equipment also dictates that subjects come to the scanner and therefore bedridden cases, uncooperative patients and very young children cannot be scanned. As the scanner uses a laser light source, areas of undercuts, which are out of the line of sight, will not be captured. Current research is looking into newer and more sophisticated scanners which can take in the undercuts by taking multiple scans from various angles and then merging the images to make one whole image. This would do away with the problem of shadows and undercut areas and prevent loss of details. Future development of portable scanners will allow bedridden patients to be scanned.

The case studies indicate that a wide variety of cases has been documented and studied and the uses of the laser scan image have been numerous. Further use of the scanned images in other fields of medicine, for mass documentation of study cohorts, for establishing norms for facial measurements, for manufacturing surface fitting apparels such as face masks for burn patients²² and customised oxygen masks for pilots, headgear for soldiers and pilots alike²³ or for building a data base of three-dimensional images of known criminals for future identification and reference are being explored and used in other countries.

Conclusion

The laser scanner has been in clinical use for nearly a decade and we are finding more ways to make use of its features. Collaboration with Nanyang Technological University has also given us insight into other uses of this digital imaging system and we need to explore its usefulness further in the area of craniomaxillofacial surgery and other medical fields.

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