SKELETAL CHANGES AND STABILITY FOLLOWING VARIOUS ORTHOGNATHIC SURGICAL PROCEDURES FOR CORRECTION OF MANDIBULAR RETROGNATHIA

By

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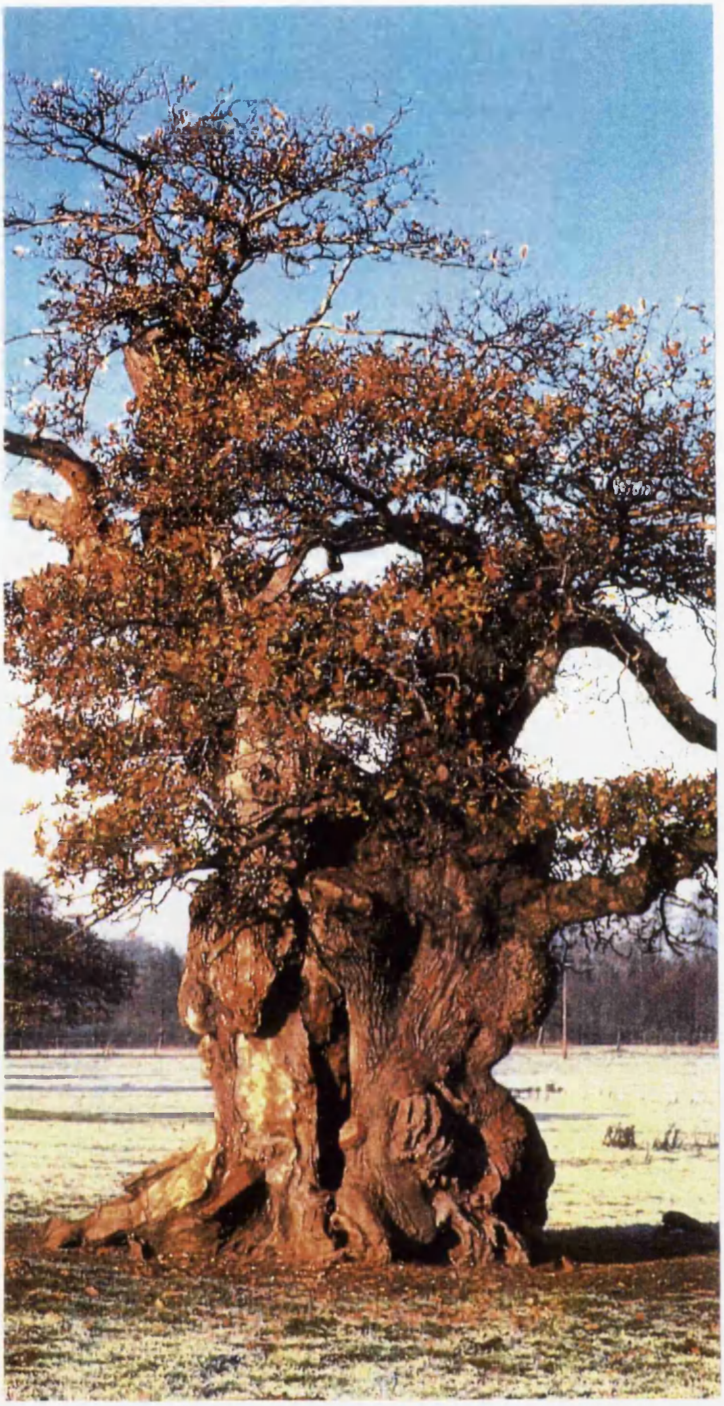
To my wife and my daughter



What is firmly established cannot be uprooted
What is firmly grasped cannot slip away.
It will be honoured from generation to generation

Lao Tsu (Sixth century B.C.)

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ABBREVIATIONS

A	The angle between the greatest strain and the horizontal plane
ANS	Anterior Nasal Spine
Cd	Condylion
D1	The principal deformation along the direction of greatest change
D2	The principal deformation along the direction of least change
EDM	Euclidean Distance Matrix
EDMA	Euclidean Distance Matrix Analysis
FE	Finite Element
FEA	Finite Element Analysis
Gn	Genion
Go	Gonion
Id	Infra-dentale
Me	Menton
MP	Mandibular Plane
N	Nasion
Pg	Pogonion
PNS	Posterior Nasal Spine
S	Sella
T1	Preoperative evaluation

T2	Surgical changes (Immediate postoperative cephalograph)
T3	Postsurgical changes at 6 months follow up
T4	Postsurgical changes at 1 year follow up.

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DECLARATION

This thesis is the original work of the author.

Ashraf Farouk Ayoub

SUMMARY

The improvement of diagnostic methods, treatment planning, orthodontic preparation of the patients and techniques of orthognathic surgeries within the last decade have evolved to allow optimal correction of the facial disproportion resulting from structural abnormalities of the jaws. Nevertheless, relapse has been a major problem. Multiple factors are associated with or contribute to postsurgical instability and the resulting relapse.

The results of recent investigations have shown that there is considerable relapse following surgical correction of mandibular retrognathia more than any other orthognathic surgical procedure. Therefore, the aim of this thesis was to evaluate skeletal stability following various orthognathic surgical procedures for correction of mandibular retrognathia. The following surgical procedures were assessed in this thesis; pedicled advancement genioplasty, sagittal split advancement osteotomy, bimaxillary osteotomy with internal rigid fixation and bimaxillary osteotomy with non-rigid fixation. Bimaxillary osteotomy cases had simultaneous maxillary impaction and sagittal split advancement osteotomy. The cases studied in this thesis were treated at either Canniesburn Hospital, West of Scotland Regional Plastic & Maxillofacial Unit, U.K. or at Michigan University Hospital, Ann Arbor U.S.A.

Lateral cephalometric radiographs were used to evaluate surgical and post-surgical changes. It has been shown in the literature that conventional cephalometry is inappropriate tool for morphometric analysis. The limitations of conventional cephalometric technique had induced stasis in the understanding of facial form and its

changes. The recently introduced methods of morphometric analysis, Finite Element and Euclidean Distance Matrix analyses have seemed to overcome most of the problems associated with cephalometric analysis. The methods allow assessment of surgical changes independently to any plane of orientation or registration e.g. Sella-Nasion or Frankfort plane and do not require any cephalometric superimposition. These methods in addition to conventional cephalometric analysis were used to evaluate surgical stability in the different group of cases considered in the thesis.

Advancement genioplasties were performed by horizontal osteotomy to provide chin prominence. Three inter-osseous wires were used for the stabilisation of the symphysis segments. This study has shown that the standard advancement genioplasty produced excellent results. Bone stability was generally very good irrespective of any other concomitant type of orthognathic surgery which was carried out.

In the group of cases who had bimaxillary osteotomy with rigid internal fixation at Canniesburn Hospital, the maxillray osteotomy was more stable when compared to mandibular advancement. The mandibular postsurgical changes at 6 month follow up demonstrated clockwise rotation with posterior settling. This was mainly secondary to the posterior condylar displacement during surgery. No further changes were detected at one year follow up.

The cases who had bimaxillary osteotomy at Michigan, with rigid internal fixation were more stable. At 6 months follow up, the mandible showed less posterior settling than Canniesburn cases.

The condyles were in their presurgical anatomical position which may have enhanced mandibular stability. However, in comparison with a similar group of cases treated at Canniesburn, the magnitude of mandibular advancement was smaller, with less presurgical facial deformity.

In cases who had bimaxillary osteotomy with non-rigid fixation, at Canniesburn Hospital, the maxilla was generally stable similar to other groups. However, mandibular stability was different in comparison with the rigid fixation group treated at the same centre. At 6 months follow up, the non-rigid fixation cases showed a clockwise rotation of the distal segment secondary to the supra-hyoid muscle pull. This resulted in opening of the gonial angle. The gonial angle remained stable in rigid fixation cases. At 1 year follow up, further clockwise mandibular rotation was observed in the non-rigid fixation cases with increase of the mandibular plane angle by 1 degree. No further changes were detected in the rigid fixation cases.

In cases who had sagittal split osteotomy only, at Canniesburn Hospital, the magnitude of mandibular postsurgical changes seen at 6 month follow up were similar to those seen in cases with bimaxillary osteotomy. At one year follow up, no changes were detected in bimaxillary osteotomy cases whereas different remodelling patterns were detected in sagittal split osteotomy cases. Cases of bimaxillary osteotomy treated at Canniesburn Hospital did not seem to gain an ultimate benefit of simultaneous maxillary impaction.

Finite Element and Euclidean Distance Matrix analyses provided definitive information on the individual changes at each osteotomy site. These methods are sensitive tools that aid in understanding surgical changes. Nevertheless, they appear to complement rather than replace conventional techniques of cephalometry.

Chapter 1

Introduction

1. Introduction

1.1 Relapse

The orthognathic surgical literature is dominated by reports and studies on changes and stability following different surgical procedures. However, there are wide individual variations of the concept of relapse. Relapse is a general term which is defined in Chambers Cambridge Dictionary as "a return or falling back to a former state". However, the term relapse following orthognathic surgery is used to cover most postoperative alterations in form. These consist of two components; remodelling and repositioning. The aetiology of these components and the mechanism by which they affect surgical stability are different. Remodelling is a physiological reshaping of the bony segments due to combined muscle pressure and tension. This combination of bone resorption and apposition causes shape change rather than positional change. Repositioning is a failure of maintenance of the relative position of bone segments, this occurs in any direction and may be unrelated to the direction of the movement occurring during surgery. Bone remodelling can be monitored by changes in the relationship of landmarks to each other in a given bony segment whereas repositioning is identified by changes detected between adjacent segments.

1.2 Conventional cephalometric analysis

Conventional cephalometric analysis is unable to separate the components of surgical relapse. Recently introduced mathematical models for cephalometric analysis should allow elucidation of the roles of these two forms of relapse. Separation of remodelling from repositioning should help in understanding how relapse occurs and thus lead to methods of improving surgical techniques.

1.3 Orthognathic surgery

Orthognathic surgical correction of dentofacial deformities has been widely used for more than a decade. Despite broad technical advancement and increasing usage, surgical correction of mandibular retrognathia has not been uniformly successful. Reports of the frequency, extent, and pattern of skeletal and dental changes have given rise to conflicting and diverse conclusions regarding the stability of its outcome. Unfortunately, advancements in surgical technique may be ahead of the understanding of the surgical changes and stability. The subjective nature of most postsurgical monitoring, the difficulty of assessing dynamic anatomic relationships, and the variety of surgical techniques employed are factors that contribute to the widely differing opinions. Emphasis needs to be placed on well documented longitudinal studies of homogeneous groups of cases from which valid conclusions can be made.

It would take more than the time available to most investigators to evaluate the changes and stability of all the currently used orthognathic surgical procedures. In the context of this thesis the investigation is limited to patients with class II skeletal deformity due to mandibular retrognathia with or without accompanying vertical maxillary excess.

1.4 Mandibular retrognathia

Mandibular retrognathia is quite common in both America and northern European populations. Data from recent large-scale U.S. Public Health Service surveys of the occlusion of the children ages 6 to 11, and youths ages 12 to 17, indicate that about 20 percent of the United States population have a distal relationship of the mandibular molars. A recent investigation in Glasgow found that 26% of nine year old school children have class II skeletal deformity.

Mandibular form and function are affected by many varied adverse genetic and environmental influences. Consequently, there are many possible causes for skeletal mandibular deficiency. Frequently, it is impossible to determine the pathogenesis or the exact nature of the processes affecting mandibular growth that clinically manifest as mandibular deficiency. In most instances, it appears that the deficiency is simply due to an inherited tendency. This inherited variation seems to account for the majority of the milder forms of mandibular deficiency. Trauma to the mandibular condyles at an early age, with resulting ankylosis or limitation of movement, is an environmental cause that can result in an extremely severe deformity, especially if the injury occurred during infancy.

Mandibular retrognathia with Angle's Class II malocclusion has been variously referred to as mandibular deficiency, mandibular micrognathia, mandibular retrusion, skeletal Class II or simply as Class II malocclusion. The term mandibular deficiency or micrognathia may be defined as a small size mandible in a relatively normal antero-posterior relation to the maxilla. Whereas mandibular retrusion is defined as a mandible usually of normal size in a posterior relationship to the maxilla. Mandibular deficiency syndrome can also be used to describe cases with idiopathic mandibular deficiency which have a constellation of abnormal aesthetic, skeletal, neuromuscular, occlusal, and growth characteristics. However mandibular deficiency syndrome does not include other well-recognised conditions with a deficient mandible, such as hemifacial microsomia, Pierre Robin anomalad, and Treacher Collins syndrome.

The expression mandibular retrognathia is used in this study to include mandibular micrognathia, mandibular deficiency and mandibular retrusion. It is a broad term which includes a wide variation of mandibular forms with an altered facial appearance.

1.5 Surgical correction of mandibular retrognathia

The commonest procedures for correction of mandibular retrognathia are advancement genioplasty, sagittal split mandibular advancement osteotomy and where there is vertical maxillary excess a simultaneous Le Fort I maxillary impaction. It is the stability of these surgical procedures which will be assessed in this study.

Chapter 2

Review of the literature

2.1 Methods of assessing surgical changes

2.1.1 Introduction

The application of morphometric analysis to oral surgical problems has been developing during the last decade. Many changes have occurred in the theory, rationale, methods and interpretation. Various methods have been used to assess facial form and the supporting dental and skeletal structures. These include the use of dental casts, photographs, computerised axial tomograms, stereo photometry, nuclear magnetic imaging and laser scanning. Dental casts can only provide information about the occlusion, they therefore cannot be used as the sole method for morphometric analysis. Photographs record facial appearance and can be used to measure facial proportions and relations, however, they do not show the skeletal and dental structures. Computerised tomography allows three dimensional modelling of skull structures (Gillespie *et al.*, 1987). The advantage of this method is that preoperative planning can be carried out using a 3 dimensional life-size model of the patient's skull. However, it is an expensive method, has high radiation dosage and is not in routine use.

Laser scanning is a simple non-invasive method of measuring three-dimensional surgical changes (McCance *et al.*, 1992). The patient is rotated under computer control and the distortion of the laser beam as it illuminates the face is recorded. Hence three dimensional computer visualisation of the face can be obtained. Landmarks can be identified and used for assessing facial changes. The main problem with this technique is that no clear statistical method has been established for comparing shapes. Laser scanning is an expensive method and is only available in one centre in the United Kingdom where it is used solely for studying surgical changes. It only records soft tissues unless combined with axial computer tomography. The lack of records of the general population does not allow for a comparison between patients and normal controls.

Cephalometric radiographs are the routinely used method for craniofacial morphometric analysis. They provide standardised measurements of the craniofacial skeleton from which skeletal and dental relationships may be obtained and they also can be used to supply limited information on the overlying soft tissues. Cephalographic measurements have played a major role in maxillofacial research and treatment planning. They are routinely used in all centres carrying out orthognathic surgery for planning and follow up purposes. Cephalometric analyses are also used extensively to define the degree by which a case deviates from accepted norms and to evaluate the changes occurring during and after orthognathic or orthodontic treatment. Cephalometric measurements have also been used in attempts to predict growth trends and assess aberrant growth.

2.1.2 DEVELOPMENT OF CEPHALOMETRY

In 1931, Broadbent developed the application of cephalometric methods to lateral skull radiographs in order to record and measure the changes in cranial and skull bones. His first problem was the design and construction of a headholder to keep the skull in a fixed position. His second problem was to find a means for recording precisely the cephalometric landmarks of the face and cranial bones. A specially designed craniostat was constructed to obtain a standardised skull position. Tests on a dry skull confirmed its stability. Broadbent also designed a head holder based on the working principles of the craniostat. This was the first step in the development of a cephalometer to hold the head in a reproducible position. Thus with standardised radiographic views Broadbent was able, with reasonable accuracy, to determine changes in the cranial and skull bones due to growth. He radiographed a group of children every three months during the mixed dentition period. These roentgenograms revealed areas in the cranial base that he believed to be relatively stable throughout growth. Sella Turcica and Nasion are examples of anatomical structures which he identified as possible stable end points of a base line for relating tracings and measuring the changes in the teeth, jaws, and face.

2.1.3 ASPECTS OF CEPHALOMETRIC METHODOLOGY

The greater problem of registering the internal landmarks of the face and cranial base was solved through the perfection of roentgenographic techniques to record these points accurately on the radiographic film. To use cephalographs as an analytical tool, landmarks and reference planes must be defined for measurements or for the superimposition of films in a serial study. Different types of error may arise and affect the validity of clinical use of cephalometric analysis. Various studies have been conducted to control the sources of error that affect cephalometric methodological reliability. Although technical advances have been made with computerised analysis of cephalometric radiographs, errors of interpretation are still possible, since human judgement remains a factor in taking head films, and identifying landmarks and structures. Automated cephalometric soft tissue analysis is a new approach that exploits the power of computers through image processing algorithms to eliminate manual landmark identification (Mostafa *et al.*, 1990). The method uses edge detection and image segmentation techniques. It requires large differences in contrast between adjacent structures and is only suitable for some landmarks. This system is not widely available and must be considered still to be experimental.

2.1.4 SOURCES OF CEPHALOMETRIC ERRORS

Regardless of the purpose for which head films are obtained, Baumrind & Frantz, (1971a) and Baumrind & Frantz, (1971b) showed there are inherent problems with cephalographs which may affect the validity of clinical usage. Two general classes of error arise in estimation of cranial dimensions from head films. Firstly errors of projection and secondly errors of landmark identification.

2.1.4.1 Projection Error

Projection errors arise because head films are two dimensional shadows of three dimensional objects. Since the rays which produce the shadow are non-parallel and originate from a very small source, head films are always distorted (enlarged). The enlargement factor varies with distances of the film and x-ray source from the landmark. Head films are further distorted by foreshortening of distances between points lying in different planes and by radial displacement of all points and structures not on the principal beam axis (Central ray).

Brodie, (1941), Hixon, (1956), Bjork & Solow, (1962), and Salzmann, (1964) reported these projection errors and explained the limitations of roentgenographic cephalometrics. Adams, (1940), Wylie & Elsasser, (1948), and Vogal, (1967) have attempted to introduce correction factors for this error. However, the cumbersome nature of the necessary computations has prevented the general use of these adjustments. Systematic corrections for projection errors have been obtained either by the use of stereo-head films or by the integration of the information from lateral and frontal films. Neither of these methods is considered practical for routine clinical use (Baumrind & Frantz, 1971a).

It would seem that complete control of projection errors is not possible, but attempts can be made to reduce the impact of this source of error. The distance between the film and the object should be maintained constant so that all the midsagittal landmarks will have a standardised enlargement factor. The true anatomic midsagittal plane should coincide with the midsagittal plane of the x-ray cephalostat. This will standardise the technique and prevent distortion due to rotation. The distance between the object and film should be minimised to increase image detail thus facilitating landmarks identification.

2.1.4.2 Error of Landmarks identification

The second source of error in head film measurement is "Error of identification". This is the error involved in the process of identifying specific anatomic landmarks on head film. Many investigators have shown that inconsistency in identification of cephalometric landmarks is an important source of error in cephalometry (Hatton & Grainger, 1958; Hixon, 1960; Miller, Savara & Singh, 1966; Richardson, 1966; Savara, Tracy & Miller, 1966; Baumrind & Frantz, 1971a).

Broadway, Healy & Poyton, (1962) investigated the accuracy of tracing lateral cephalographs. A random selection of 40 radiographs was made. These radiographs were traced by a professional tracer who marked a number of cephalometric landmarks, from which seven commonly used measurements were determined. The radiographs were retraced and measured by independent tracer, and the work was repeated by the original tracer who did not know that she had previously handled the same radiographs. The data was analysed using the mean and standard deviations of the differences between pairs of measurements. They showed that the apex of the lower incisor was particularly difficult to identify consistently. The differences between tracers averaged 2 degrees. There were some consistent differences (bias) between the measurements taken on two occasion by the same tracer. The authors made the following recommendations to achieve the necessary high quality of assessment: Increasing the focus-film distance to 9 feet, decreasing the distance between the sagittal plane and the film, and decreasing the kilo voltage. These factors improved landmark clarity as well as the film contrast. Nevertheless, these factors increased the radiation dosage and the scattered radiation and were incompatible with the need to minimise patients exposure to radiation. They suggested that the measurements should be carried out by single tracer to minimise the random error and to maintain consistency with landmark definition.

Baumrind & Frantz, (1971a), studied the reliability of landmark identification on a random sample of twenty lateral cephalographs. Each film was traced by each of the five members of a graduate class. They had all completed the same course of training in cephalometric diagnostics. Fifteen cephalometric landmarks were chosen for identification. The landmarks used were those most commonly employed in conventional cephalometric analyses. The magnitude of the error in landmark identification varied. For most of the landmarks, they found the distribution of the error was systematic. Each landmark had its own characteristic and showed non-circular envelope of error. The sharpness of the edge effect at the point to be identified, the confounding noise from adjacent structures and the individual interpretation of the definition of the landmarks were the three factors that these authors found to be the principal cause of identification error. Sella presented a unique problem among the points studied because it involved visual estimation of the centre of the structure. Gonion and lower incisor apex were the least reliable landmarks. The authors recommended that, in clinical application, the impact of the observed errors in landmark location can be reduced through the routine use of replicated estimates of each landmark position.

Richardson, (1966) investigated the reproducibility and identification errors of some structures, and lines used in cephalometric analysis. Ten lateral cephalographs were traced by two observers on two different occasions. Thus, for each landmark there were four estimations on each of the ten films, forty estimates in all. On each film an arbitrary horizontal line was defined by joining the upper most point of the image of the ear posts to the image of the lead spot which had been placed over the lowermost point on the rim of the right orbit. At the right hand edge of the film, a second line at right angle to the horizontal was defined. The coordinates of each point were measured in relation to these reference lines (Datum lines) to the nearest 0.5 mm, and the differences in the point locations between each tracing were calculated. To find the discrepancies in De Coster line, optic planes and ethmoidal triad, the tracings were superimposed for each of them. The intersection points of the datum lines, due to superimposition of the tracings, were recorded. In each case the mean of the ten estimations was calculated. The difference in mean of each of the four sets of the ten radiographic estimations were tested using Student t-test. The differences between the estimates of the two observers and between the same observer on separate occasions were calculated. The author concluded that the discrepancies between measurements made by different observers were more serious than those made by one observer on different occasions. However, the statistical method was simplistic and a more sophisticated approach may have allowed a better understanding. Despite De Coster's line having poor reproducibility, the author recommended this line as a reference plane for superimposition of two films rather than two tracings. By doing this, it is possible to register the small details of bone structure to improve reproducibility. Menton point ranked high in the order of reproducibility vertically but not horizontally. Nasion was more reproducible horizontally than vertically. Anterior Nasal Spine (ANS), Posterior Nasal Spine (PNS) were much more reproducible vertically than horizontally. The author concluded that the maxillary, mandibular and Sella-Nasion planes would show the smallest variation, since PNS, ANS, Gonion, Menton, Sella and

Nasion showed small vertical discrepancies. The number of cephalographs used in the study was insufficient to generate general conclusions about the reproducibility of cephalometric points and reference planes that could be applied to a wider range of patients. The author did not report either the time interval between the occasions of film tracings or whether there was any observer training which may have reduced the level of error.

On lateral cephalographs of twenty-five randomly chosen children, Midtgard, Bjork & Aronson, (1974) investigated the reproducibility of landmark location and cephalometric measurements. Two consecutive cephalographs were taken of each child during the same examination. The average age of the examined children was 11.1 years. For each case the lateral cephalographs were superimposed on the anterior and posterior base of the cranium. Tracing sheets were used, fifteen cephalometric landmarks and seven linear distances were studied. The pair of cephalographs were traced by one observer. In the second part of the study each cephalograph was traced twice by each of the two observers with an interval of one month between tracings. The differences between the observers on the location of the landmarks on the same cephalograph were evaluated. The statistical method used was Students t-test. The method error was examined using the ratio of the error variance from measurements of the same films to the between subject variance. The authors found there was uncertainty about identifying landmarks so that there was always a difference in location between the two films. The degree of uncertainty varied between landmarks. The greatest difference between recordings of the same landmark was for Orbitale, where the mean difference was more than 2 mm. The greatest degree of certainty was recorded for Sella, and

Articulare. The differences in the position of the landmarks on the same cephalograph when recorded twice one month apart by the same observer, were similar to the differences between observers, when tracing the two cephalographs of the same individual. The authors concluded that the interval between cephalograph measurements had not significantly affected the reproducibility. The greatest inaccuracy was reported in estimating the distances Nasion-Subspinale and Nasion-Supramentale. The authors did not discuss the possible effect of memory when the cephalographs were traced on the same occasion. This could influence point identification and increase the risk of bias. These observations are supported by the work of Richardson, (1966) and Baumrind & Frantz, (1971a).

To quantify the reproducibility of 14 landmarks used in cephalometric analysis and to examine inter- and intra-observer differences, one hundred lateral cephalographs were investigated by Staburn & Danielsen, (1982). Fifteen landmarks were registered using a digitizer and the two observers repeated the registration of the landmarks one month later. A major interest of this study was the lower incisor apex as it is difficult to identify but is considered to be an important landmark. For each registration the observers also reported the certainty or uncertainty they felt when they had localised this landmark. The difference between the means on each occasion for each observer were compared by a two-tailed Student t-test. Their data showed that each landmark had different degree of reproducibility. The coordinate of points Supramentale and Subspinale had a wide distribution along the Y-axis. The intra-observer data indicated that each observer held a definite opinion regarding the landmark definition and localisation which resulted in apparently improved individual precision. Despite prior calibration training, the inter-observer differences in landmark identification were high. They reported " uncertainty about locating the lower incisor apex in about 75% of the cases ".

So, the optimum method for precision of landmark identification and which minimises the effect of memory seems to be the use of a single observer carrying out replicated measurement with a two week period between occasions of recording. The reproducibility of cephalometric points should govern the selection of landmarks. The difference in the reliability of cephalometric landmarks needs to be considered when assessing shape changes.

2.1.4.3 Measurement Errors

The traditional approach to the measurement of lateral cephalographs is to trace the structure of interest on an acetate sheet, identify the landmarks and then measure the tracing. The development of digitizer equipment has simplified the measurement of such records. It allows position of anatomical landmarks to be recorded directly from radiographs without the need for an intervening tracing. Although digitizers were originally used for the analysis of maps, special versions have been developed for orthodontic purposes (Bondevik, Rosler & Slegsvold, 1981). They showed that direct digitization of radiographs is less time consuming, and it also eliminates the stage of tracing which could be a source of error. The digitizer records the coordinates of each point in relation to Cartesian axes. Given the coordinates, the computer can be programmed to calculate the length of lines, and angles between lines joining landmarks. It can be used to analyse individual cases as well as data from groups of subjects. The advantages of this system is the speed and facility of operation which is especially useful if large numbers of records are to be analysed.

The accuracy of the digitizer and its influence on measuring errors depends on the resolution of the digitizer and reliability with which the end points of the line can be identified (Houston, 1979). Resolution is the shortest distance which can be distinguished between two points. For cephalometric measurements resolution of 0.15 mm is desirable. This author also recommended repeated digitization, using fiducal points, to minimise the error that may arise from landmark identification. When cephalographs were superimposed on a base plane e.g. the anterior cranial base, the use of a pair of fiducal points was recommended. For superimposition on another plane e.g. the mandibular plane, a second pair of fiducals were recommended. For data analysis, it was shown that the records from each film could be aligned by the best fit on the appropriate pair of fiducals. The vectors of displacement of the points of interest could be calculated, their orientation being registered according to whatever base line is required. To avoid gross errors of location, it was also suggested that the digitization of each film should be carried out at least twice on the same occasion. This immediate replication should be undertaken without moving the radiograph. Using error checking is then possible to reject any point more than a predetermined distance from its previous digitization. To check the accuracy of landmark identification, Houston, (1983) recommended a second occasion of digitization. The data from the two occasions should be averaged, and stored.

The two sets of data providing a record of the digitization error of the operator and an estimate of the contribution of errors in point identification to the total error variance.

Richardson, (1981) compared the traditional and computerised methods for cephalometric analysis. On 50 lateral skull radiographs, 14 cephalometric points were digitized. The digitized coordinate were compared with those obtained by traditional cephalometric tracing. Each method was repeated on two separate occasions. Means and standard deviations of the discrepancies between occasions of digitization were derived and compared. For 12 of 14 points, the mean horizontal digitization discrepancy was smaller than that of the traditional method. When comparing standard deviations, digitization was superior for 9 of the 14 points. In the vertical direction, the mean discrepancy of the digitizer measurements was smaller than the traditional method for 12 out of 14 points. For 8 points the standard deviation of the digitizer measurement was less than the corresponding manual measurement. Subspinale, ANS and Supramentale were difficult to locate vertically but were more reproducible horizontally. It was suggested that the digitizer could be used to find and record points on a curved outline which are defined as the most anterior or posterior, highest or lowest. This can be done by running the digitizer cross-wires along the curve and watching the visual display of the coordinates. The extremes of the horizontal and vertical prominences or concavities can be readily identified provided that the film is oriented correctly. The digitizer appeared to offer enormous advantages in terms of speed and the preparation of the data for computer analysis. The time interval between the occasions of digitization was not reported.

It would have been useful if Hoteling's T2 test or multiple analysis of variance had been used to assess the combined effect of both axes together rather than separately. A multivariate approach would have allowed the comparison to be determined for both method and axis error effects.

Houston, (1982) investigated the reliability of cephalometric measurements with direct film digitization and tracing of the radiographs using 25 lateral skull films. On each film 13 points were identified. The landmarks were defined according to Solow, (1966). The cephalographs were traced on two occasions a week apart under optimum conditions on the light box of the digitizing table. On each occasion the tracings were digitized twice, the digitizations were averaged and the measurements of interest calculated. After 6 months, a replicate digitization was carried out directly on each film, with a one week interval between the two occasions. The images were superimposed using fiducal points to allow calculation of the differences in the landmark coordinates. The first and second tracings were compared as were the repeated digitizations. The possible effects of memory of landmarks affecting the immediate repeated digitization was also assessed. The differences between the repeated cephalometric measurements were calculated. For evaluating the error in landmark identification, the distances between the coordinates of the points after repeated digitization were calculated. Some points were more readily located than others. The errors from direct redigitization were greater than those of repeated tracings. The author explained the fact that the design of the cursor used for digitization, obscured the structures peripheral to the landmark of interest and sometimes the cross hairs of the cursor were not easy to see against darker parts of the radiographic image, this problem did not arise with tracings. Tracing an indistinct structure, such as incisor root also aids in the location of the landmark such as the root apex. The differences in the location of landmarks were less with immediate than delayed redigitization. The reproducibility of the calculated measurements between landmarks was better than that of landmark identification. Measurements were not necessarily affected by the total error in the identification of their landmarks. To obtain the highest precision, the author recommended immediate redigitization on each of two separate occasions, with error checking. This would improve reliability, both by reducing the risk of gross errors due to incorrect identification of landmarks and by reducing the size of random errors by averaging replicate measurements.

It seems reasonable to conclude that computer aided cephalometric analysis improves the reliability of identification of landmarks and the validity of the analysis. Digitization offers an important advantage in terms of speed and preparation of data for computer analysis. It should be also borne in mind that the traditional tracing of cephalometric radiographs involves additional factors that affect measurement precision. This is a potential source of error not applicable to the use of a digitizer.

2.1.4.4 Problems with registration of serial radiographs

One of the most frequently used registration lines for the superimposition of serial tracings of lateral skull radiographs is the Sella-Nasion line (Brodie, 1941; Bambha, 1961; Fishman, 1969) and it has been reported to be relatively stable (Wei, 1968).

Steiner, (1953) used the Sella-Nasion with a registration point at Sella and at Nasion to evaluate the position of the maxilla through changes in the SNA angle. Bjork, (1955) used Sella as a registration point to assess changes in position of both jaws. He advocated the use of Sella-Nasion as a particularly suitable reference line during adolescence because of the consistency (in 90% of his cases) in the relationship between Sella-Nasion and the deepest midsagittal contour of the anterior cranial fossa. Bjork, (1960) and Bjork & Skieller, (1983) reviewed the biologic origins of Sella and Nasion and concluded that these weakened the analysis when Sella-Nasion was used as reference plane for estimation of facial changes. They showed that an upward or downward displacement of Nasion may occur because of appositional growth at the fronto-nasal suture. Likewise, a posterior displacement of Sella may occur by the remodelling of dorsum Sella arising from increase in size of the pituitary gland.

Superimposition on Bolton-Nasion planes was introduced by Broadbent (1937). A perpendicular line is drawn from the Bolton-Nasion plane to Sella. The midpoint of this perpendicular line he called the registration point R. He superimposed tracings of successive cephalographs on R, keeping Bolton-Nasion planes of these radiographs parallel to each other. Broadbent based this method of superimposition on observations from dried skulls and a comparative study of cranial base planes (Bolton-Nasion, Porion-Nasion, Sella-Nasion) in individuals of 3 to 18 years of age. Although there was no statistical comparison of the different groups studied, the coefficient of variability was the smallest for Bolton-Nasion plane.

In 1952, De Coster suggested the use of the midsagittal outline of the anterior portion of the cranial base as a registration line (De Coster line). He based this idea on the belief that growth changes in this area are minimal after seven years of age. Hausser, (1959) found difficulty in following De Coster's line. Etter, (1959) also commented on the difficulty of interpretation of the anterior cranial fossa. Hopkin, (1962) investigated the stability of the anterior position of the cranial base through serial tracings of this area from lateral skull radiographs of nine children. The author showed that De Coster's line was better for superimposing tracings than Sella-Nasion line. Superimposition on Sella-Nasion line swung the profile upward and forwards. This is due to the change in Nasion position with growth that may give the appearance of more maxillary forward growth than what actually took place.

Baumrind & Frantz (1971b) suggested the usage of fiducal points for serial radiographic superimposition. During analysis, the data from different occasions of measurement of the same cephalograph were aligned by the mathematical best fit on a pair of fiducals. This enabled the error of locating the landmarks to be determined.

Baumrind, Miller & Molthen, (1976) investigated the reliability of different superimposition planes. This study was carried out on twenty five children in the late mixed dentition period. Two head films were taken for each child separated by an interval of two years. The films of each pair were traced and superimposed independently by each of four trained judges. Twenty two dental and skeletal landmarks were identified in each film. For each tracing the judges also outlined the contours of "anterior cranial base", "palatal plane", "mandibular plane", and "Sella-Nasion line". All the tracings were digitized, and to eliminate the effects of differences in landmark identification by the four judges, the four tracings were averaged to obtain the mean position of each landmark for each film. Each pair of tracings was superimposed mathematically four times, one for each anatomical plane of superimposition. The authors also discussed the possible sources of variation arising from computer superimposition rather than those arising from superimpositions carried out by a trained judge. The findings of this study showed that for most landmarks evaluated with respect to most superimpositions, there were rotation effects which formed a larger portion of the total error of superimposition than did the translation effect. The errors from translation are the same for all landmarks for any tracing or superimposition. Translation errors arise when a straight line connecting any two points, along the superimposition plane, remains parallel to its original position at all times. Whereas rotational error arises when the plane rotates due to a difference in orientation of the plane varying from one judge to another. The effect of this type of rotation depends on the particular landmark's distance from the centre of rotation.

Due to difficulties in locating point Nasion vertically, the primary rotation errors were larger when superimposition was on Sella-Nasion plane than on the anterior cranial base. The palatal plane superimposition was the least reliable of all the planes. The authors also analysed the effects of superimposition error upon the interpretation of the perceived movement of the teeth. The total errors were smallest for mandibular border superimposition, it was approximately 1 mm at each dental landmark. For each of the other superimpositions the average error exceeded 1 mm. To minimise the superimposition errors and increase the reliability of any measurements for research purposes, the authors recommended multiple tracings of each head film and multiple independent replications of each act of tracing superimposition.

The subtraction method for superimposing radiographs was investigated by Lee, (1980) and McWilliam, (1982). The superimposition errors were low and less with this technique than when using Sella-Nasion line as a reference plane. Houston & Lee, (1985) reported that there was an appreciable error in all methods of superimposition. They did not find that any method was more accurate than any other.

Ghafari, Engel & Laster, (1987) evaluated the following superimposition methods; best fit on anterior cranial base anatomy, Sella-Nasion, Bolton-Nasion, and Basion-Nasion planes. This study was conducted on twenty six patients (13 boys :13 girls) treated for class II division I malocclusion. Cephalographs were taken before and after treatment with the same cephalostat. These radiographs were traced by one operator. The post-treatment tracing were superimposed on the pre-treatment one by each of the superimposition methods. From each tracing and for each superimposition method, six landmarks were digitized before and after treatment: Posterior Nasal Spine, Anterior Nasal Spine, A point, B point, Pogonion, and Gonion. Pairs of methods were compared using Student t-test to assess the average difference in each comparison. Differences between all pairs of methods were statistically significant at $p<0.01$. No clinically significant differences of any of the landmarks were detected in girls. They considered a difference of less than 1 mm to be clinically insignificant. However, greater differences than this were detected between the methods of superimposition in boys. This sex difference was due to timing of treatment, and sex differences in absolute measurements and rate of facial growth. The authors concluded that interpretation of facial changes should be made only with reference to the superimposition method used.

Trenouth, (1989) assessed the variation in outlines of tracings using 60 fetal cephalograph and photographs. He compared between the centroid and skull anatomical points for superimposition to evaluate any statistically significant difference between the two methods of superimposition. The centroid was defined as a point around which a body hangs freely in equilibrium when it is suspended in a gravitational field. The centroid represented the mean point of a shape about which it varies and is subject to the least amount of variation in relation to anatomical points. The centroids for the 60 fetuses were plotted on the reference grid and their mean position determined. The spread of the fetus head outlines was related to a reference grid using centroid for superimposition and was compared statistically with that using anatomical points. There was a significant reduction in the spread of the outlines when the centroid point was used for superimposition instead of anatomical points. The author concluded that centroid points are the least variable among anatomical points. This finding agrees with the reports of Johnson, (1960, 1978, 1979 & 1982) who has shown that centroid was the most stable of the reference plane methods. However, the centroid point in common with all other coordinate methods involving superimposition of tracings is dependent on the concept of a local frame of reference which is assumed to be fixed. In all reference frame dependent methods, changes in form are plotted in relation to a reference system which should be independent of changes in form. None of the reference frames is absolutely constant and each one gives a different perception of shape change. Centroid points would not be the most stable point for superimposition when assessing surgical changes as surgery may deviate the centre of the skull and shift the location of the centroid which then becomes dependent on the change in form.

In conclusion, there is an appreciable error in all methods of superimposition, and this must be taken into account in studies involving cephalometric superimposition. None of the methods of superimposition tested emerged as being significantly more accurate than the others. De Coster' line seems to be the most stable cranial reference plane.

2.1.5 Methods of cephalometric analysis

2.1.5.1 Traditional Cephalometric Analysis

Many investigators have proposed a wide variety of cephalometric analysis systems. Each analysis comprising linear and angular measurements and ratios of these. Ricketts, Steinhauser, Witts, Sassouni and Down's analyses are examples. The basic units of analysis are angles in degrees and distances in millimetres. Measurements may be treated as absolute or relative, or they may be related to each other to express proportional correlation. In dimensional analysis various angles are considered in isolation and compared with average figures. Down's analysis is of this type. Proportional analysis is based on comparison of the various angles to establish significant relations between the separate parts of the facial skeleton. Angular measurements may also be used to determine the position of parts of the facial skeleton. The angles SNA and SNB, for example, give the relations between the maxillary and mandibular bases and cranial base. Angular measures have certain deficiencies if the lines defining them are drawn in relation to a primary reference plane, on the premise that this remains constant. If this plane shows deviations from the normal, the analysis becomes unreliable. Measurements are often related to particular norms of mean values. These norms are however subject to a number of factors, such as age, sex, hereditary and ethnic predisposition. The measured change in angle is a very complex function of the relative motions of the three landmarks involved, not just one or two as it is so often assumed.

For linear analysis, the facial skeleton is analysed by determining certain linear dimensions. Linear dimensional analysis determines the distances between certain reference points that have been projected onto a reference plane. Wylie, (1947) applied linear dimensional analysis by using the Frankfort horizontal plane as the reference plane. He projected a number of reference points perpendicularly onto this, and measured the distances between the points thus obtained on the plane. The analysis also gives an absolute value to the distance between two reference points which are compared with norms, e.g. upper and lower facial heights. These linear measurements can not separate size from shape changes. They do not explain the mode of change between the two reference points. In a similar way to angular measurements they are dependent upon cephalometric registration and orientation.

Rabey, (1978) used a recording machine called an Analytic Morphograph to analyse craniofacial morphology in three dimensions. The machine allows standardised radiographic, photographic, and lithographic (dental models) assessment of dentofacial forms. The radiographs and photographs and dental models obtained in frontal, lateral, and basal views. These were related to each other and had a three dimensional analytic validity. The radiographs were superimposed upon a standard morphoanalysis grid for interpretation. Each model was inserted into an orientation jig in an electronic cephalostat and photographed in three dimensions, the obtained photographs were called analytic lithograms. The radiographs, photographs and lithograms of the same and other patients were compared and had a three dimensional validity. It was claimed that there was analytical and statistical validity with ease in communication between centres. The technique was complex, needing extensive training and expensive equipment to conduct the analysis. The method did not find wide acceptance and is only available in a few maxillofacial centres making multi-centre comparisons difficult. Morphography is still dependent on an external frame of reference that camouflages the perception of shape change as explained by Moyers & Bookstein, (1979). Retrospective studies are not possible due to lack of records of treated cases.

Moyers & Bookstein, (1979) presented their reasons for believing that conventional cephalometry is an inappropriate tool for morphometric analysis. They argued that the limitations of conventional cephalometric technique had induced stasis in the understanding of facial form and its changes.

In conventional cephalometrics the face and the cranium are measured by locating landmarks on the projected images. These landmarks are either anatomically identified by some feature of the local morphology or on a bony shadow not differentiated by local proportions but defined implicitly by maximal or minimal geometric properties. Moyers & Bookstein, (1979) define these as external landmarks and for analytical purposes these points are related to a fixed orientation plane. All standard orientations are also defined in terms of landmarks the location of which may depend on the orientation of the subject in space. Moyers and Bookstein showed that an incorrect placement of the orientation plane may arise from faulty positioning of the subject. It also may arise from inappropriate landmarks for that subject or perhaps because of disproportionate growth or asymmetry. Cephalometry is thus susceptible to forms of mis-measurement in which error in the orientation is propagated affecting the positions of all orientation dependant landmarks. They also pointed out that point 'landmarks' do not define curved bony shapes but rather lie upon them. Landmarks cannot represent the shape or relative position of an entire curved feature. They explained that analysis of morphology and shape changes involving only landmarks lacks information about contour and is inadequate for describing shapes. Approaches that involve landmarks and straight lines will fail to capture curved forms and curved shape changes. It will also exclude proper measurements of size for non-straight line structures. Growth will be misrepresented by being portrayed as vector displacements rather than a generalised distortion.

Moyers & Bookstein, (1979) were able to demonstrate that conventional cephalometric procedures misinform by fabrication, camouflage, and confusion.
In super-imposition of successive cephalometric tracings, the motion of a corresponding landmark with time is called a track. Fabrication was explained as the change in these tracks as a result of changes in plane of orientations or any measurement error in the coordinate system. In addition, traditional cephalometric analyses amalgamate the changes at landmarks as a statistically unmanageable mixture of translation and remodelling. The methods of cephalometric superimposition each give a different perception of shape changes. The biological reality of morphological changes are camouflaged. There is no best registration and since the information content of alternative registrations is equivocal, the analysis becomes statistically fallacious. Some examples of this problem which have been presented in the literature are discussed in section 2.1.4.4 Moyers and Bookstein pointed out that it is very difficult to decide whether any registration is concealing or camouflaging crucial co-variation of the structures and all registrations share this fundamental statistical flaw.

Moyers & Bookstein, (1979) described three major sources of confusion affecting the explanation of the behaviour of geometric objects in the plane of the cephalograph. These confusions are:

1. The concept of rotation. They showed that the motion of a rotating object in a rotating coordinate system is not open to any simple interpretation in any third coordinate system. When measuring the growth rotation of the mandible, the position obtained by superimposition on the Frankfort plane or the palatal plane has no geometric relationship to similar rotation superimposed on the cranial base.

2. The concept of size measurements. They explained that the analysis of size and shape as separate quantities is necessarily confusing.

3. Measuring changes using angles. Any cephalometric angular measurement is a function of three points of two coordinates each, totalling six degrees of freedom. Measuring a change in an angle is a very complex function of the relative motions of the three landmarks involved, not just of one or two as it is often assumed. Translation caused by growth occurs in many planes and is not restricted to the straight line between a cephalometrician's favourite registration points. Remodelling accounts for further growth changes and is ignored by methods subtracting two distances with one common point of superimposition. (Moyers & Bookstein, 1979)

In an attempt to overcome the inherent deficiencies of traditional cephalometric procedures, they suggested two possible techniques to extend conventional cephalometrics:-

1. Tangent angles and curvatures. The tangent angle is the azimuth of a straight line lying on a curved outline at a landmark.

2. Blum's medial axis. The medial axis, or skeleton of a curving boundary is defined as the locus of centres of circles which touch the boundary at two distinct points. Landmarks are part of this form of analysis. In computing the skeleton, no points of the outline are treated differently from any others.

The authors have not reported their own use of these methods in clinical applications nor have these been adopted by others as a technique for clinical use. Their practicability and usefulness do not appear to have been tested and they remain theoretical ideas.

For the measurement of shape change, biorthogonal grids were suggested. This method had been developed from that of Thompson, (1917). It represents change in shape as changes in size along specific directions. Computer programs are needed to determine the distortion of the mesh of homologous points. All grid angles are 90 degrees. Changes are shown by the stretching or shrinking of parts of the lattice figure. These distortions represented bending of the grid into curves. These curves intersect at right angles {biorthogonal grids}. This method is descriptive only and is not amenable to statistical analysis.

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2.1.5.2 Tensor Analysis (Finite Element analysis)

Bookstein, (1982) introduced tensor analysis as a new method of evaluating shape changes. This is a simplification of the more widely recognised method of finite element analysis, a system of mathematical modelling best known from its applications in engineering. In Finite Element Analysis (FEA) the structure under investigation is subdivided by a series of imaginary lines into triangular elements, a process called discretization. In discretization the assumption is made that all the points within a given finite element share a common behaviour. This assumption becomes more accurate as the number of elements is increased and their size is decreased. The three points that define a finite element are called nodes, these may be common to adjacent elements. When applied to cephalographs anatomical landmarks can be used as nodes. An analysis of changes using a finite element method necessitates accurate location of each node on each occasion by the precise determination of their coordinates within a Cartesian framework. Elements are observed in matched pairs e.g. pre and postoperative. Inside the first triangular finite element a circle can be drawn so that it touches the three sides (Fig. 2.1A). Changes in the locations of the nodal points of the element will distort the circle into an ellipse (Fig. 2.1B). The ellipse has two axes that are 90 degrees to one another and these are called the principal axes of deformation. These principal deformation axes are drawn at the centroid of each element (Fig. 2.1C). If the deformation is greater than 1.00 it represents a stretching or dilatation; if less than 1.00 it represents a shrinkage or compression (Fig. 2.1D). Dilatations occurring are recorded as the percentage ratios of change of length. Uniform deformations were thereby described as a pair of percentage rates of change, along the principal directions. This comparison is entirely independent of the coordinate systems or any local frame of references. Bookstein explained that the product of the dilatations is the ratio by which the area of triangle has increased. The ratio of the dilatations is a measure of the directionality of this size change, a measure engineers call

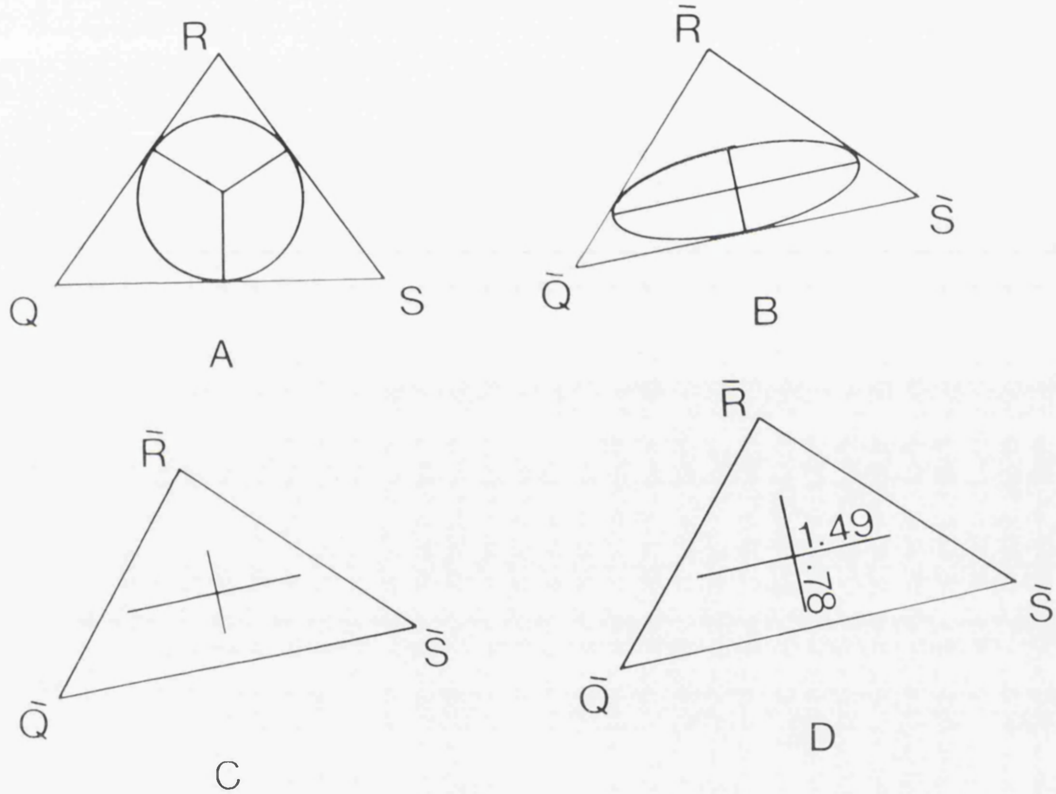


Figure 2.1 Finite Element Analysis. A, Undeformed element with a circle touching the three sides. B, The strain ellipse. C, The principal axes of deformation at the centroid of the element. D, The deformation values.

anisotropy. An isotropy is defined as a transformation which preserves shape i.e. takes the triangle to a similar triangle or takes circles to circles. For these transformations, dilatations are equal in all directions, and the principal axes can not be defined uniquely and any cross at 90 degrees will suffice. Tensor analysis is a coordinate free representation of a geometric change. Bookstein defined a tensor as a geometric machine regardless of the coordinate systems. The relation of a point to a line, if changing, is expressed not by the vector of displacement but by tensor of deformation, with two rates of change in two orthogonal directions. He also emphasised that this proposed analysis for a single pair of triangles is fully equivalent to the simplest case of the finite-element description with principal strains at exactly 90 degrees.

Bookstein & Moyers, (1982) also applied the tensor analysis method to cephalometry. They used various triangles linking the cranial base with the maxilla and mandible. The points on or near the cranial base that they used were Basion, Sella, Spheno-Ethmoidal Registration (S.E.R.), Fronto-Maxillary Suture (F.M.S.), and Nasion. In the maxilla they made use of Anterior Nasal Spine (ANS) and on the mandible Gonion and Menton. They used these points to analyse the growth directions of the facial skeleton. This study was carried out on two groups of patients. One with horizontal and the other with vertical direction of mandibular growth, 13 in each group, using films taken at age 8 years and 14 years. The following triangles were used to compare between the growth types. S.E.R.-Nasion-Menton, Sella-Nasion-Menton, Sella-ANS-Menton. They concluded that nearly half the observed differences between groups were due to local changes in remodelling at Nasion which were irrelevant to the repositioning of Menton. Instead of using two points along the cranial base and one in the mandible, they used two on the mandible and one on the cranial base. Using the following triangles, Gonion-Menton-ANS, Gonion-Menton-F.M.S., Gonion-Menton-S.E.R. they concluded that the vertical growers grew vertically at Nasion by an extra 0.4 per year. The horizontal growers were growing horizontally by an additional 0.6 per year. Also in the horizontal group Menton moved directly away from a point 25% of the way from Sella to Nasion, and in the vertical group from a point 50% of the way from Sella to Nasion, at the same rate of 0.5 per year.

They concluded that conventional cephalometric techniques are inadequate for precise analysis and practical prediction of craniofacial change and that cephalometrics should be carried out independently of any orientation or registration. The clinical implication of this is that the interpretation of surgical changes from conventional cephalometric measurements will depend on the choice of reference plane and superimposition method. Changing the choice of superimposition or reference plane will affect the interpretation of the changes and different methods may produce contradictory results. It is only by using new measuring techniques which are independent of orientation and registration that the problem can be over come.

To evaluate the craniofacial growth independent of any method of registration and superimposition, Moss *et al.* (1985) studied the two dimensional craniofacial growth of the rat skull using the finite element analysis method. The data consisted of the coordinates of a series of anatomical points obtained at different ages of the group of rats studied. A group of triangular finite elements were chosen to assess craniofacial growth. For each finite element the computer program determined the direction and amount of maximal and minimal growth changes (strains) in relation to the age. The authors concluded that "Finite element methods are able to provide absolute quantitative descriptions of the cranial skeletal shape and shape changes independent of any external local frame of references". By so doing, the principal sources of methodological error in traditional cephalometric analysis were eliminated. However, they recommended further research in this area of assessing shape changes to maкe the interpretation of the finite elements clearer and biologically meaningful.

Lavelle, (1989) studied the lateral cephalographs of two samples (each containing 40 subjects) of boys aged 12 years. The cases exhibited crowding of the maxillary anterior teeth. In one group the first premolars were extracted in both arches and cases had fixed appliance therapy to ensure teeth alignment. In the other group the overcrowding was corrected by fixed appliance therapy without teeth extraction. The study was based on the lateral cephalographs taken immediately prior to treatment and 2 years later at the end of treatment. The differences between the two groups were assessed using seven cephalometric points. These points were used to define 14 triangular finite elements. The deformations of these 14 finite elements were computed for the subjects after orthodontic treatment (target finite element) relative to pre-orthodontic treatment (reference finite element). Local size change was computed as the mean of the principal strain values (maximum and minimum principal strains divided by two). Shape change was defined as the absolute value of the arithmetic difference between the maximum and minimum principal strains values divided by two. Cephalometric shape changes due to orthodontic treatment were significantly greater in the non-extraction (22%) than extraction samples. The values for finite element (Condylion-ANS-Pogonion) and (Sella-ANS-Nasion) were 117% and 25%, respectively, greater in the non-extraction than extraction samples. The author concluded that the subdivision of cephalometric form into a number of component finite elements provided further understanding of morphological differences between the two samples. Lavelle did not comment on the method used to record the nodal points coordinate, he did not assess the possible sources of error in cephalometric measurement and its influence of finite element analysis. The angle of the principal strain in relation to the element's sides were not considered in the study.

Ngan, Scheick & Florman, (1993) used tensor analysis to analyse the cephalometric results of a group of patients treated with high-pull activator (HPA) to demonstrate the application of this research tool. Eight patients with Class II open bite malocclusions in the mixed dentition were treated with HPA. A control group consisting of eight untreated children with similar Class II malocclusions were used as a comparison group. Lateral cephalographs taken before and at the completion of treatment were traced, digitized, and analysed with both conventional cephalometric measures and tensor analysis. Tensor analysis was performed on triangular elements formed by joining triples of skeletal landmarks. Angles with reference to Sella-Nasion were calculated in an attempt to illustrate the direction of maximum and minimum strains. The authors concluded that the main advantage of the tensor analysis over the conventional cephalometric techniques is that the magnitude and the direction of the maximum and minimum strains do not depend on any reference line. This overcomes one of the deficiencies of conventional cephalometric analysis. The authors recommended further use of the tensor method as a sensitive tool for morphometric analysis.

2.1.5.3 Fourier Analysis

Fourier analysis is a widely utilised technique employed primarily in engineering and physics for the characterisation of wave forms. More recently, the method has been applied in the geological and biological sciences (Lestrel, 1974). The Fourier technique represents a different approach to circumvent the deficiencies of conventional cephalometric analysis. Fourier analysis provides a decomposition of a form into a series of components with a potentially meaningful interpretation. The elliptical Fourier representation is based on decomposing a closed curve into a sum of harmonically defined ellipses (Kuhl & Giardina, 1982; Rohlf & Archie, 1984). An implicit orientation arises through the use of the major and minor axes of the initial ellipse as the basis for a new coordinate system. The coefficients of the decomposition are defined with respect to this coordinate system, hence, the orientation of the initial ellipse with respect to the original shape is critical. The orientation is given by the single ellipse that best fits the original shape. Lestrel *et al.* (1977) when using Fourier analysis for evaluating size and shape of the Hominoid distal femur, explained that the accuracy of the Fourier series as a curve-fitting procedure is limited by the presence of irregularities in the shape, and the number of terms taken in the series. As the number of terms in the series are increased, the fit becomes more accurate and the residual fit becomes minimal. The computer output of a Fourier program consists of a set of Fourier coefficients (a0, a1,a2,a3.......an). The first term in the series a0 is known as a constant, which represents a circle and is defined as the mean of all observations for a given specimen. The first few harmonics describe gross differences in the morphology, while the higher harmonics describe the more detailed structure of the shape. Moreover, because each harmonic has a predetermined shape, so unique individual forms can be readily compared by looking at the numerical differences between coefficients.

Three particular advantages characterise Fourier series and make the analysis widely usable. The technique does not depend on homologous points, although it can contain this information. The coefficients can be treated as independent variables which makes it possible to separately analyse the contributions that each harmonic makes to the total form. Size and shape components can be separated.

Lestrel & Roche, (1976) compared individuals exhibiting Down's syndrome with normal controls to try to ascertain whether the cranial thickness from Nasion to the occipital bone in the mid-sagittal plane was affected. This study was carried out on 160 lateral cephalometric radiographs of which 80 were confirmed trisomy 21 cases and 80 were normal controls. The outer and inner margins of each cranial vault were traced onto acetate sheets and the vectors were submitted as data to a specially written Fourier analysis program. The output from this program consisted of Fourier coefficients which for each individual described the cranial vault from Nasion to the occipital region in the mid-sagittal plane. Two separate sets of Fourier equations were produced to describe the vault, one for the ectocranium and one for the endocranium. A Student t-test was used to test for any statistically significant differences in cranial thickness between the two groups. The results indicated that the cranial thickness in adult trisomics was thinner than that of normal controls.

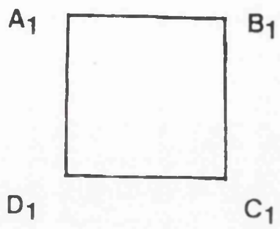
In the same year Lestrel & Brown, (1976) evaluated the adolescent growth of the cranial vault also using Fourier analysis. This study was conducted on lateral cephalographs in a sample of 15 males and 15 females, ages four through to eighteen. The Fourier coefficients were not equally sensitive to the pubertal spurt. Of the 9 harmonics used in the study the first four accounted for over 96% of the variability in the human cranial vault. The results of this study demonstrated the presence of an adolescent growth spurt in the cranial bone which was both more pronounced in males and lasted longer than in females.

2.1.5.4 Euclidean Distance Matrix Analysis (EDMA)

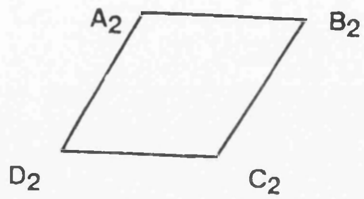
This method for the comparison of shapes was proposed by Lele, (1991) and has been applied in several studies of craniofacial morphology (Grausz, 1990; Richtsmeier & Lele, 1990; Corner and Richtsmeier, 1991). Euclidean Distance Matrix Analysis can be used to describe the shape of anything that has recognisable landmarks. EDMA uses all the possible linear distances between the landmarks to define the shape, as in Figure 2.2a & 2.2b. The relative locations of the landmarks can be completely reconstructed from these distances. The distances are stored as a two dimensional array called an Euclidean distance matrix (Fig. 2.2c, 2.2d). When using EDMA for comparing shapes, there are two Euclidean distance matrices. One represents the initial morphology, the other represents the second shape. This analysis compares the Euclidean distance matrices using the ratios of each pair of corresponding distances. The matrix of these ratios is called a difference matrix (Fig. 2.2e). This matrix allows determination of the way the two shapes differ by identifying those linear distances that are most and least different between the shapes being compared. If all ratios of the difference matrix are equal to one then there is no difference between the shapes. A ratio less than one suggests that the linear distance is smaller in the second shape while ratio greater than one indicates a larger distance in the second shape. If the ratios are equal, but not equal to one, then the difference between the shapes is only due to a change in size. When the ratios are not equal, the differences between the shapes are due to both size and shape. The ratio of greatest to least change is an index of shape difference (Fig. 2.2f), the statistical significance of which can be tested using the non-parametric "Bootstrap" technique in the manner described by Lele & Richtsmeier, (1991).

2.1.5.5 Appropriateness of methods for assessing surgical changes

EDMA, Finite element and Fourier analyses eliminate superimpostion problems as they do not require cephalometric superimposition. The description of shape changes does not depend



1a



1b

	B_1	C_1	D_1
A_1	1	1.414	1
B_1		1	1.414
C_1			1

1c

	B_2	C_2	D_2
A_2	1	1	1
B_2		1	1.732
C_2			1

1d

	B	C	D
A	1	0.707	1
B		1	1.225
C			1

1e

1.225/0.707=1.733

1f

Figure 2.2 A simple illustrative example of Euclidean Distance Matrix Analysis.

a. The initial shape - A square A_1 B_1, C_1, D_1 with sides of unit length.
b. The second shape - A rhombus A_2,B_2,C_2,D_2, with sides of unit length.
c. The Euclidean distance matrix of the initial shape.
d. The Euclidean distance matrix of the second shape.
e. The difference matrix.
f. The index of shape difference - the ratio of maximum increase to maximum decrease (from 1e).

on any local frame of references or an orientation plane. The Fourier method describes only the outline of the shape, and can not be used to assess internal changes or the rotational changes that are demonstrable with a finite element method. However, this method is the best for analysing curved or irregular outlines but can not provide information on how the changes in outline are brought about by movements of component parts.

EDMA and FEA seem to be more useful in describing internal shape changes. The interpretation of surgical changes shown by finite element analysis requires both surgical and biological understanding as has been explained by Moss *et al.* (1985). EDMA is an easier method to understand and apply. It provides a quantitative description of shape changes and lends itself to statistical manipulation more readily than finite element analysis. However, it cannot be used to assess the rotational changes that are demonstrable with finite element analysis. Therefore, it seems that a combination of finite element and Euclidean distance matrix methods may be the optimum method to evaluate orthognathic surgical changes.

2.2 ORTHOGNATHIC SURGICAL PROCEDURES

2.2.1 Introduction

As orthognathic surgery has become more sophisticated, it has allowed the surgeon to address deformities that were previously untreatable. The stability of changes resulting from these surgical procedures has been an area of concern since both the aesthetic and functional improvement are directly related to the degree of postsurgical stability.

2.2.2 Mandibular surgery

2.2.2.1 Historical background

The first recorded orthognathic surgical procedure was for treatment of a prognathic mandible and utilised an intra-oral approach. The procedure, a subapical osteotomy of the anterior mandible was performed by Hullihen in 1849. After this, only a few intra-oral procedures of any kind were reported for almost one hundred years. Subsequently, Moose, (1945, 1964) began to describe, in details, subcondylar, subapical, and vertical ramus osteotomies.

Surgical procedures to correct mandibular skeletal deformity were described early in this century by Blair, (1907, 1909). Probably because of the ease of access and the prevalence of missing mandibular teeth, body ostectomy became the first popular surgical procedure for shortening the mandible (Dingman, 1944; Burch, Bowden & Woodward, 1961). Following Caldwell & Lettermann's paper in 1954 on vertical subcondylar osteotomy via an extra-oral approach to the ramus of the mandible, this surgical approach tended to replace the body ostectomy for correcting mandibular skeletal excess. Winstanly, (1968) reported the first intra-oral vertical subcondylar osteotomy. A significant improvement in the technique was reported by Herbert, Kent & Hinds (1970); their osteotomy technique utilised a Stryker oscillating power unit.

2.2.3 Correction of mandibular retrognathia

Surgical treatment of the underdeveloped mandible was first reported in the literature by Blair in 1909. He presented two cases of retrognathia in which a horizontal ramus osteotomy was performed at the neck of the condyle with a Gigli saw. Limberg, (1928) presented an alternative procedure for correction of retrognathia. The site of his operation was either the ramus or the body of the mandible. Robinson, (1957) reported the extra-oral approach for the vertical osteotomy of the ascending ramus inserting an iliac crest graft into the osteotomy defect. Surgical procedures to lengthen the mandible did not become common until after the European surgeons Trauner & Obwegeser, (1957a) & (1957b) described the sagittal split ramus osteotomy and its historic development. Hawkinson, (1968) reported the arcing osteotomy of the ascending ramus and body of the mandible. The arcing osteotomy improved bone to bone contact for mandibular advancement procedures. This osteotomy was recommended for procedures in which rotations of the mandible were necessary in contrast to straight or linear movements. Caldwell, Hayward & Lister, (1968) presented a "vertical-L" osteotomy, which was modified to a "C-osteotomy".

Subapical osteotomy of the mandible has been advocated to allow movement of the dental base independent of the basal bone (Proffit & Bell, 1980). In cases where mandibular retrognathia is associated with a deep bite, a subapical osteotomy may be combined with the sagittal split procedure to produce a complete subapical osteotomy. The technique was designed to correct Class II malocclusions, reduce the labiomental fold, maintain Pogonion in the desired antero-posterior position, and increase lower-face height in selected individuals with deep bites of skeletal origin.

The sagittal split osteotomy, C-osteotomy, complete subapical osteotomy, combined sagittal split osteotomy and advancement genioplasty, and the step sliding osteotomy of the mandible constitute the basic surgical approaches in current use.

2.2.3.1 Genioplasty

Dentofacial deformities may be associated with excessive protrusion or retrusion of the chin. Surgical changes in chin position are often required to improve overall harmony of the face. Surgery may augment or reduce the symphysis antero-posteriorly, vertically or laterally or any combination of them.

Due to excessive resorption and low predictability, augmentation with autogenous, homogeneous, or heterogeneous bone grafts is no longer routinely performed (Heiple, Chase & Herndon, 1963; Thompson & Casson, 1970; Ellis, *et al.*, 1984).

A number of methods are currently used for chin correction. Anterior augmentation (Epker & Wolford, 1980), Vertical correction (Wessberg, Wolford & Epker, 1980; Precious & Delaire, 1985) or reduction in a posterior direction (McBride & Bell, 1980; Kerkmanov & Kahnberg, 1987) have been described as solitary procedures or in a combination with sagittal splitting of the mandible. Both extra-oral (Turvey & Epker, 1974) and intra-oral (Bell *et al.*, 1980; Epker & Wolford, 1980; Wessberg *et al.*, 1980; Precious & Delaire, 1985) approaches have been used. Periosteum has usually been reflected from the anterior and inferior surfaces of the osteotomized segment (Epker & Wolford, 1980; Wessberg *et al.*, 1980; Precious & Delair, 1985).

Since the architecture and position of the soft tissue chin reflect the shape and position of the underlying bone, many studies have been performed to quantify both the bony changes and that of the overlying soft tissue response. Most of the measuring methods used in these studies were based on cranial base superimpositions of cephalometric radiographs of the patients. The ratio of the hard /soft tissue changes noted varied from 1:1 to 1:0.6 (Bell & Dann, 1973; Bell, 1981; Scheideman, Legan & Bell, 1981).

In an attempt to evaluate relapse following genioplasty, McDonnell, McNeill & West, (1977) studied a sample of 15 patients who received advancement genioplasty in conjunction with other orthognathic surgery and orthodontic therapy. In addition to the advancement genioplasties, nine patients received mandibular advancement by means of bilateral sagittal osteotomies, six had maxillary or combined mandibular and maxillary osseous surgery. Twelve patients received one-step horizontal advancement of the symphysis, the other three had multistep advancements. The cases were evaluated by means of a retrospective cephalometric analysis of superimposed mandibular tracings. The antero-posterior position of the hard tissue chin was assessed preoperatively, immediate postoperatively and at a minimum of one year follow up. Changes during these time intervals were measured to the nearest millimetre using a coordinate system based on the Frankfort Horizontal. The change in the horizontal position of Pogonion from immediately after surgery until the time of follow up was measured. This method of evaluation did not account for any vertical changes at Pogonion. The influence of the other concomitant surgery and any changes of orientation of the mandible to the Frankfort plane were not considered. The authors concluded that there was a general osseous remodelling with resorption at Pogonion and apposition at the superior aspect of the symphysis. This conclusion is unsupportable since the method used for evaluation was not able to differentiate between positional change and a remodelling resorption at Pogonion. The problems of the inherently flawed measurement techniques were compounded by the heterogenicity of the surgical techniques.

Davis, Davis & Dally, (1988) studied long term stability following advancement genioplasty. Twenty three patients who had undergone advancement genioplasty were evaluated for an average of three years postsurgically for bone and soft tissue changes. All except two had concomitant orthodontics and maxillary orthognathic surgical procedures. Measurements were made of the angle of the osteotomy cut to an arbitrary constructed horizontal line (7 degree to Sella-Nasion line). The amount of advancement was measured along the osteotomy plane from the anterior aspect of the symphysis to the antero-superior edge of the advanced segment. Traced serial cephalometric radiographs revealed no discernible bone remodelling between Gnathion and Menton. Six cases showed minor posterior shifting of the inferior border segment. The appropriateness of using the osteotomy plane as a reference plane is debatable. Alteration in this plane may be either due to local remodelling in the osteotomized segment or due to change in the spatial mandibular position secondary to maxillary surgery. Remodelling of the detailed bony structure at the osteotomy site would change the location of end point landmarks.

Park *et al.* (1989) used another measuring method to evaluate the immediate and postsurgical changes in hard and soft tissues of the chin after advancement genioplasty of twenty-three patients. Seventeen patients were treated by bimaxillary surgery and six patients were treated by single jaw surgery, in addition to the genioplasties. All the patients were evaluated cephalometrically for a minimum of 6 months after surgery. The occlusal plane and the Menton horizontal plane {a horizontal plane parallel to the occlusal plane and tangent to hard tissue Menton} were used as reference planes. The occlusal plane was defined as a horizontal line tangent to the upper most convex area of a definite radio-opaque body (dental filling, orthodontic band or bracket) of the most posterior tooth and of the orthodontic bracket of the most anterior tooth of the mandible.

The horizontal position of the chin was measured as a distance from Pogonion parallel to occlusal plane to a point P. Point P was defined as the most posterior aspect of the inner lingual cortex. The perpendicular distance from the occlusal plane to Pogonion was the measure of the vertical position of the chin. The perpendicular distance between the horizontal plane tangent to Menton and the occlusal plane was the measure of the vertical position of inferior aspect of the hard tissue chin. All tracings and measurements were performed by one author and repeated four times to assure maximum accuracy. The results indicated that the position of the genial segment was stable after advancement. The authors explained that reference planes based on cranial base superimposition, such as the Frankfort Horizontal plane are not accurate when determining horizontal dimensional differences in the chin area unless the mandible maintained the same position after surgery as before. In this study about 74% of the patients were treated by surgery that changed the orientation of the occlusal plane. The sources of error that could arise using a cranial reference plane may also happen when using the occlusal plane as a base for assessment. The occlusal plane may alter if there are changes in the position of the teeth that determine this plane. Whether such changes occur or not will depend on the quality of the occlusal result and the stability of the changed incisor/soft tissue relationship and this may be affected by any previous orthodontic treatment. Thus the stability of the reference plane must be suspect. The author's claim that the method used is highly reliable takes account only of the accuracy of locating the points and measuring the distances. What also should have been taken into consideration is the error that could develop from using the occlusal plane as a reference and its influence on the reliability of the method. The radio-opaque objects (brackets) used to define the occlusal plane may allow accurate superimposition of radiographs, nevertheless, it would be impossible to use the same method to evaluate long term changes following surgery after removal of the orthodontic appliance.

Many investigators have attempted to establish criteria for predicting changes following genioplasty by means of cephalometric tracings. To obtain reliable results, it is imperative to use reference planes or landmarks that are not altered by surgery. In the literature several methods have been described that depend on reference planes of doubtful reliability. Cranial base superimposition is a method used to determine and predict overall surgical changes of the jaws. However, this method creates problems in the study of dimensional changes of the hard and soft tissue of the chin, because concomitant jaw surgery can affect mandibular position. Therefore superimpositions based on cranial reference planes such as the Frankfort or Sella-Nasion planes are not suitable for determining dimensional differences in the chin area unless the rest of the mandible maintains its position in spite of surgery. These methods are not sensitive enough to separate changes at the chin points due to alterations in position or due to local remodelling. They would also camouflage the changes at the chin as an intractable mixture of chin repositioning, due to concomitant maxillary or mandibular surgery, and local changes due to genioplasty.

In reviewing the literature there are no reports of a measurement method that was able to evaluate changes related to genioplasty independent of other adjunctive orthognathic surgery. Further studies are needed to assess the stability of advancement genioplasty independent of other concomitant surgery. Descriptive analysis of surgical changes and post-operative stability is required, which does not depend on a frame of reference affected by change in the spatial position of the mandible.

2.2.3.2 Sagittal split ramus osteotomy for mandibular advancement

2.2.3.2.1 Historical background

Trauner & Obwegeser, (1957a) & (1957b) introduced the sagittal split ramus osteotomy for the correction of prognathism and retrognathia. The initial report described sagittal splitting performed on the vertical portion of the ramus. Dal Pont, (1961), modified Obwegeser's sagittal splitting osteotomy technique by moving the lateral cut forward onto the body of the mandible thereby increasing the area of bone-to bone contact during the healing period. Hunsuck, (1968) suggested a short lingual bone cut, as far as the area immediately above and behind the lingula, to facilitate ramus splitting and to avoid displacement of the muscle attachments of the ramus. The sagittal split osteotomy has been modified in several other ways since first being described (Bell & Schendel, 1977; Epker, 1977). Modifications in osteotomy design, the evolution of special instrumentation, and the versatility of the procedure make the sagittal split osteotomy of the mandibular ramus the most frequently performed surgical procedure to correct mandibular prognathism as well as retrognathia. The broad bony contact, which allows rapid osseous healing, is another merit of the procedure.

The set back sagittal split osteotomy for correction of mandibular prognathism is a fairly stable procedure. Several studies have reported the surgical changes and the long term stability (Pepersack & Chausse, 1979; Kobayashi *et al.*, 1986). There is general agreement in the literature concerning the surgical changes following mandibular set-back and its post-operative stability.

On the other hand, several investigations have shown that skeletal relapse is a frequent sequel of mandibular advancement surgery. It still remains a major concern in the surgical correction of mandibular retrognathism.

2.2.3.2.2 Theories of relapse following mandibular advancement

Although skeletal relapse seems to be a multifactorial phenomenon, numerous theories have been advocated to explain the reasons for relapse in these types of surgeries: (1) condylar distraction during surgery (Epker, Wolford & Fish, 1978; Schendel & Epker, 1980; Worms *et al.*, 1980; Ellis & Gallo, 1986). (2) Stretching of the muscles of mastication and suprahyoid musculature (Wolford *et al.* 1978; Wessberg, Schendel & Epker, 1982; Ellis & Carlson, 1983). (3) The magnitude of pre-surgical mandibular plane angle and posterior facial height (Poulton & Ware, 1971; Lake *et al.*, 1981). (4) The magnitude of mandibular advancement (Ive, McNeill & West, 1977; Van Sickels, Larsen & Thrash, 1986; Gassmann, Van Sickels & Thrash, 1990). (5) Methods of fixation (Sandor *et al.*, 1984; Singer & Bays, 1985; Ellis & Gallo, 1986; Moenning *et al.*, 1990).

2.2.3.2.2.1 Condylar position

Several authors found positional change of the proximal segment to be the most important parameter in determining stability of the advanced mandible. Intra-operative distraction of the mandibular condyles from their functional position in the glenoid fossae results in a dramatic mandibular relapse immediately on release of intermaxillary fixation (Schendel & Epker, 1980; Booth, 1981; Ellis & Gallo, 1986; Epker & Wessberg, 1982; Jeter, Van Sickels & Dolwick, 1984). The relapse occurs because a large discrepancy is created between the functional occlusal position and the terminal hinge position.

Condylar position following mandibular surgical advancement has been evaluated by a few investigators (Freihofer & Petresevic, 1975; Kundert & Hadjianghelou, 1980; Will *et al.*, 1984).

Freihofer & Petresevic, (1975) studied 38 patients who had bilateral sagittal osteotomies for mandibular advancement. Temporomandibular joint radiographs and lateral cephalographs were taken preoperatively, postoperatively, and a minimum of two years following surgery. Although ten of 26 condyles appeared to be positioned anteriorly in the glenoid fossa, the difference in projection angle made direct comparison with preoperative films impossible.

Kundert & Hadjianghelou, (1980) studied 35 patients who had received bilateral sagittal osteotomies, 14 of which were mandibular advancement. Temporomandibular joint tomograms, lateral oblique ramus films, and postero-anterior skull films were taken prior to and five weeks following surgery. They noted that in 75% of the cases the condyles were posteriorly displaced. Fifty percent of the condyles exhibited changes in axial inclination as well.

Will *et al.* (1984) studied the condylar position of 41 patients who had had a bilateral sagittal split osteotomy to advance the mandible. The advancement was stabilised by interosseous wires, which were fixed after manipulation of the proximal segments into what were felt to be the optimal anatomic position of the condyles in their fossae. This survey used submento-vertex films, lateral cephalographs and right and left temporomandibular joint tomograms for assessment. No significant condylar displacement was detected during surgery. No changes in condylar position were noted following release of maxillo-mandibular fixation. Eighteen patients, who had had no preoperative symptoms, complained of temporomandibular joint pain or noise postoperatively. The authors concluded that the 37% relapse detected in these cases in the absence of significant condylar distraction implied the action of other factors in the relapse process.

Condylar displacement during surgery appears to play an important role in the stability of mandibular advancement. More information about these changes are needed to ascertain the frequency, direction, and amount of condylar displacement in patients receiving a bilateral sagittal split osteotomy for mandibular advancement. Further studies are needed to determine whether a significant relationship exists between any observed alteration in condylar position during surgery and postoperative skeletal changes.

2.2.3.2.2.2 Muscular Adaptation

According to many surgeons, tension produced by the elongated and stretched suprahyoid muscles and associated tissues is one of the most significant factors contributing to the relapse of the surgically advanced mandible (Poulton & Ware, 1971; Kohn, 1978; Schendel & Epker, 1980; Lake *et al.*, 1981). The primary mechanism causing this relapse may be the tendency of soft tissues to resume their original lengths when stretched. This is particularly true of skeletal muscles. Striated muscles, when stretched, may exhibit active contraction in response to the myotic stretch reflex as well as passive contraction as a result of stretching of interstitial connective tissues within the muscle (Yemm & Nordstrom, 1974).

Lengthening of the mandible results in a stretching of the associated soft tissues, including the skin and subcutaneous tissue and presumably, depending on the amount of advancement, the suprahyoid muscle complex. Because of the unique anatomy of the suprahyoid-hyoid-infrahyoid region, there probably is not a simple relationship between mandibular lengthening and the amount of suprahyoid muscle stretching is not simple. Mandibular lengthening of any significant amount results in some stretching of the suprahyoid muscles. The major unresolved issue in this regard is how much mandibular lengthening can be accommodated before the suprahyoid muscles become sufficiently stretched to cause a problem.

Epker *et al.* (1978) suggested that suprahyoid muscles can be stretched up to 15% of their resting length and still function physiologically. When mandibular advancement lengthens the suprahyoid muscles more than 15% of their resting length, the authors recommended that the muscles should be surgically detached from the mandible as part of the mandibular advancement procedure. To measure this, they used the distance from the mid-body of the hyoid to the inferior-posterior cortical border of the mandibular symphysis on the cephalometric radiograph. Using cephalometric prediction tracing, the estimated advancement of the lingual cortical border of the symphysis was measured. This distance was used to calculate the approximate percentage of the muscle lengthening. This postulation was only based on the authors experience of using surgical techniques to correct the deficient mandible. They commented on neither the number of cases studied nor the method used to analyse their data.

On the other hand, it has been also suggested that suprahyoid myotomy is not essential to skeletal stability following surgical advancement of the mandible (Wessberg *et al.*, 1982). These authors investigated the mandibular stability of 16 patients who had undergone a sagittal split advancement osteotomy. The cases were divided equally into control and myotomy groups. The cases of the control group had six weeks of maxillo-mandibular fixation. The myotomy group had similar skeletal deformities and underwent a comparable surgical advancement supplemented by surgical detachment of the geniohyoid and digastric muscles, in addition to six weeks of intermaxillary fixation. The mean presurgical facial configuration and mandibular deformity were similar in both of these groups. Lateral cephalometric radiographs obtained immediately before surgical advancement of the mandible, during the first week after surgery and at 24 months follow up period, were used in the assessment. The stretch percentage of the suprahyoid musculature was calculated by measuring the linear distance between the hyoid bone and Menton before surgery and comparing it with the immediate postsurgical position. Changes in B point position was used to calculate skeletal relapse. In the control group the mean suprahyoid stretch was 18.5% with a mean skeletal relapse of 43.1%. In the myotomy group the mean suprahyoid stretch was 21.3% with a mean skeletal relapse of 48.5%. The authors did not comment on the direction of rotation of the advancement of the distal segment. This may have been a significant factor since Epker *et al.* (1978) had pointed out the potential for relapse due to stretching of the pterygo-masseteric sling following anti-clockwise rotation of the advanced distal segment. Rotation of the proximal segment and condylar position were also not assessed, which is surprising since it has been commented on the importance of condylar position in influencing the pattern of mandibular relapse. B point was used to assess mandibular position and this is a landmark which is little changed by mandibular rotation.

Ellis & Carlson, (1983) showed experimentally that the supra-hyoid musculature remains attached to the distal mandibular segment and may be stretched by the advancement procedure. The effect of this tension is to cause posterior and inferior displacement of the distal segment. The study was carried out on 10 adult monkeys who underwent mandibular advancement surgery of 4-6 mm with and without suprahyoid myotomy. Lateral cephalographs of each animal were obtained immediately before surgery, immediately after surgery, at the release of fixation, at six, 24, 48 and 96 weeks follow up. The non-myotomy group exhibited a significant reduction in the length of the advanced mandible during the fixation period, but showed no significant change in mandibular length after release of fixation. The myotomy group exhibited no relapse either during fixation period or after release of fixation. The authors believed this study supported the hypothesis that stretching of the suprahyoid musculature, as a result of mandibular advancement surgery, is a major factor leading to skeletal relapse. However it is debatable whether that mandibular advancement was enough to stretch the suprahyoid muscles in the monkeys in an amount comparable to that normally occurring in such surgery in humans. The osteotomies in the monkeys may have produced a malocclusion, which is another factor potentially affecting mandibular stability.

Epker *et al.* (1978) put forward an explanation of the role of muscles of mastication in mandibular relapse. They described three types of mandibular movements in advancement cases. Type I-clockwise and forward movement; Type II-straight forward movement; Type III-anti-clockwise and anterior movement. The clockwise description applies to patients facing to the right. Type III mandibular movement usually occurs when treating high angle cases and they believe it is less stable than the other two types of mandibular advancement. Due to the anti-clockwise rotation, the muscles of mastication are lengthened in the ramus area. As these muscles attempt to return to their original positions, they rotate the mandible in a clockwise direction. The authors recommended that high mandibular plane angle cases are best treated by simultaneous maxillary impaction. Repositioning the maxilla superiorly, with the consequent auto-rotation of the mandible, produces a more aesthetic result with improved stability.

There is a considerable uncertainty in the literature regarding the effect of suprahyoid muscle stretch on mandibular relapse. None of the studies considered the proximal segment and condylar position as contributory factors in relapse after mandibular advancement with or without myotomy. Further studies are needed to assess the relationship between the rigidity of internal fixation and suprahyoid muscle pull following mandibular advancement.

2.2.3.2.2.3 Presurgical Facial Form

Various authors have hypothesised that patients with low mandibular plane angles have much more stable results after mandibular advancement surgery (Poulton & Ware, 1971; Epker *et al.*, 1978; 3 authors
Wolford *et al.* 1978; Schendel & Epker, 1980) .

Twenty one patients treated by surgical advancement of the mandible were analysed by Ive *et al.* (1977) to assess mandibular 3 authors
stability during the fixation period. The mandibular plane angle varied from 21 degrees to 46 degrees. These values were correlated to the magnitude of mandibular relapse measured at B point. The data presented did not support the assumption that the pre-surgical form influenced the pattern or magnitude of relapse. This finding is in agreement with the results of Kohn, (1978).

Kohn, (1978) analysed the relapse in 17 cases of mandibular advancement surgery, 9 had sagittal ramus splits and 8 had C-osteotomies. Cephalographs were taken immediately before surgery, 48 hours after surgery and at the end of intermaxillary fixation. Six month postoperative cephalographs were only available for 12 patients. The cephalographs were superimposed on the palatal plane and fronto-nasal suture. Six parameters were selected to assess the changes in the mandibular skeletal segments. A condyle point was recorded only on the preoperative cephalometric tracing and represented the centre of the head of the condylar process. Surgical advancement of the mandible was measured by the forward movement of Gnathion and was associated with the movement of Gonion. The authors suggested that movement of the Gonion was associated with the displacement of the condyle. During intermaxillary fixation posterior relapse of Gnathion was detected. There was no significant relationship between the preoperative mandibular plane angle and the amount of posterior relapse. The authors concluded that the inferior movement of the proximal segment, recorded at Gonion, was the cause of the skeletal relapse of the distal segment. The study did not actually assess the condylar position since the condyle landmark was only traced on the preoperative cephalographs. Inferior displacement of Gonion may not necessarily be associated with condylar displacement. The location of Gonion is dependent on the distal segment position. Anti-clockwise rotation of the segment may transpose Gonion below the preoperative inferior border of the mandible. Local remodelling at Gonion may then be misinterpreted as displacement of the proximal segment. The measuring method used in the study can not separate remodelling of Pogonion from changes due to movement of the osteotomy segments. The patients were treated by two different surgical techniques which further confuses the result and prevents the drawing of firm conclusions.

Lake *et al.* (1981) evaluated 52 cases who underwent surgical mandibular advancement by sagittal split osteotomy. Immediate preoperative, immediate postsurgery, at release of fixation and 2 years follow up cephalographs were used in the assessment. Linear and angular measurements were conducted on the cephalometric tracings prepared and assessed by a single investigator. Postsurgical relapse was compared between cases with high (>37 degrees), normal (27 to 37 degrees), and low (<27 degrees) preoperative mandibular plane angles. Significantly greater skeletal relapse occurred in the high angle cases (-3.2 mm) than in the normal (-1.4 mm) and low angle cases (-0.3 mm). The authors concluded that there is a positive correlation between increasing mandibular plane angle and relapse tendencies. However, in their sample, the patients with high mandibular plane angle underwent the greater advancements. Therefore, higher mandibular plane angle cases may relapse more than low angle cases due to either one or both, of the necessity for larger advancements and of the greater need for anti-clockwise rotation of the distal segment. Both of these changes increase the tension in the suprahyoid muscles.

Kirkpatrick *et al.* (1987) evaluated skeletal stability following mandibular advancement and rigid fixation in 21 subjects who had sagittal split advancement osteotomy. Cephalographs were analysed before surgery, immediately after surgery and at 6 months follow up. A mean horizontal posterior relapse of 8%, a mean vertical increase in lower face height of 0.2 mm, with a backward rotation of 0.5 degree were observed six months after surgery. The authors found no correlation between presurgical facial form and postsurgical mandibular change. However, the average presurgical mandibular plane angle of their sample was 30.7 degrees, which is within the normal range. It is unlikely that the study had a sufficient range or number of extreme cases that could have provided adequate data to be able to draw these conclusion about relapse. However, the finding is in agreement with Smith, Maloney & West, (1985) whose study was restricted to the postoperative period of intermaxillary fixation only. Hiranaka & Kelly (1987) similarly, did not find any association between preoperative facial form and mandibular relapse in a longer term study.

So, despite many of the studies failing to prove any relationship between presurgical facial form and mandibular relapse, it is still considered an important factor in mandibular stability and should be carefully evaluated before surgery. It has been suggested that the magnitude of anti-clockwise rotation of the distal segment during surgery may have more influence on mandibular ~~relapse than~~ the magnitude of presurgical deformity (Epker *et al.*, 1978). Most 3 authors studies have flawed measurement methods which were unable to separate local bone remodelling from positional changes, most used changes at B point and these are poor measures of mandibular relapse.

2.2.3.2.2.4 Magnitude of Mandibular Advancement

One of the major factors suggested as contributing to skeletal changes after correction of mandibular retrognathia is the magnitude of mandibular advancement. This is because of many factors including the adverse tension arising within the skin, subcutaneous tissue, and periosteum, as well as muscles of maxillofacial region (Iye *et al.*, 1977; Epker *et al.*, 1978).

3 authors

Lake *et al.* (1981) found a moderate association between the magnitude of absolute horizontal advancement and mandibular relapse. As the magnitude of advancement increased, the tendency toward relapse increased. However, the authors contradicted themselves concerning the influence of mandibular advancement in relapse. They concluded that "the magnitude of mandibular advancement was a reliable surgical predictor of postsurgical relapse", whereas, in their results section, they reported that "relapse was less predictable as it related to the magnitude of mandibular advancement".

Van Sickels *et al.* (1986) studied the stability following sagittal split osteotomy in 51 patients who underwent mandibular advancement with or without genioplasties where rigid internal fixation was used. Thirty one subjects underwent advancement of the mandible only, 12 had mandibular advancement with genial advancement, and eight had mandibular advancement with genial set-backs. Radiographs were traced and digitized pre-operatively, immediately post-operatively, and at 6 months follow up. Relapse was assessed by the change in location of Pogonion. The position of Pogonion measured perpendicular to a vertical reference line drawn at Nasion, was used to assess mandibular relapse over different time intervals. Relapse was observed once the mandible was advanced more than 6 mm. They concluded that the magnitude of mandibular advancement was the single factor that could be used as a predictor of relapse. The finding that magnitude of mandibular advancement correlates well with relapse had been noted previously (Will *et al.*, 1984). However, distraction of the condyle from the fossa was not evaluated in this study and can not be excluded as a factor in mandibular relapse. Pogonion is liable to repositioning and remodelling due to concomitant genioplasty and its position should not be used as the sole measurement to assess mandibular relapse. The cephalometric analysis used could not separate changes at Pogonion that were secondary to sagittal split osteotomy from those due to genioplasties alone. The heterogenicity of the direction of movement of the genioplasties within the sample would confuse the interpretation of the results.

It appears that with large advancement (more than 6 mm) relapse may be correlated to the magnitude of mandibular advancement. However, this can not be used as a sole predictor for relapse. The adaptation of the circum-mandibular musculature to the advanced distal segment varies from one individual to another. The potential for muscle stretch to influence mandibular relapse should be considered for each case separately.

2.2.3.2.2.5 Methods of fixation

An analogy can be drawn between repair process following injury to soft tissues and bone cuts in an osteotomy. In both cases healing may occur by either primary or secondary intention. Secondary bone healing occurs with the use of semi-rigid fixation i.e interosseous wiring and maxillo-mandibular fixation when some inter-fragmentary movement still occurs with muscle activity. Primary bone healing occurs with rigid internal fixation (Reitzik & Schoorl, 1983). Perren, (1979) reported that "No external callus is formed as it appears in secondary bone healing, and all the classic early stages of bone repair are circumvented". This type of healing will not occur if a gap exists between the fractured segments or if the fixation is not rigid. Function in the osteotomy patient also plays a significant role in healing process. There is evidence that actively functioning bone segments heal faster and better than immobilised ones (Sarmiento *et al.*, 1977; White, Punjabi & Southwick, 1977).

long bones

It seems, therefore, that the ideal conditions for the healing following osteotomy involves rigid fixation across the bone cuts but without inter maxillary fixation.

To guard against suprahyoid muscle pull and to avoid distraction of the condyles from their fossae various techniques for sagittal split osteotomy fixation have been suggested. These techniques have evolved from maxillo-mandibular fixation alone, through maxillo-mandibular fixation with superior border or inferior border wiring, with or without anterior skeletal fixation to rigid internal fixation.

Isaacson *et al.* (1978) investigated movement of the proximal and distal segments of 27 patients. Six of them had an advancement sagittal split osteotomy, the rest of the patients had a C-osteotomy and vertical subcondylar osteotomies to correct mandibular prognathism. In a group of cases the proximal and distal segments were wired inter-osseously whereas in the rest of them no inter-osseous fixation was placed. The authors did not specify the number of the patients in each group. They reported that with mandibular advancement surgery, the condyles were displaced inferiorly by average of 2.2 mm and anteriorly by an average of 1.2 mm. After removal of maxillo-mandibular fixation, the condyles showed a mean superior and posterior positional change equal in

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magnitude but opposite in direction to the mean surgical displacement. They concluded that in cases where the proximal segments were not secured in their displaced position by interosseous fixation, they frequently return to a stable position during fixation. Thus eliminating a potential factor in mandibular relapse. There was no mention of the analytical method used to assess the proximal segment position. The number of cases that had sagittal split osteotomy was too small to draw firm conclusions. Long term follow up may have shown some movement between the proximal and distal segments, especially when no internal fixation was used. A larger homogenous group of patients is needed to test the validity of their theory.

In an effort to prevent inter-segmental movement and to promote primary bone healing, techniques for rigid approximation of the bony segments have evolved. Reitzik & Schoorl, (1983) investigated histologically and biochemically the bone repair in the mandible at the osteotomy site. The study was undertaken to compare the influence of rigid and semi-rigid fixation on bone healing of experimental mandibular fractures in monkeys. The fractured site was examined clinically to determine the extent of external callus formation. The strength of the formed callus was assessed by biometrical testing. The healed fractured areas were decalcified for histological examination. They concluded that rigid fixation produced a primary bone healing that was denser and stronger than with non-rigid fixation. A number of researchers have advocated rigid fixation with lag screws to promote primary bone healing and thus eliminate any space between the osteotomy segments. They suggested that when rigid osseous fixation is employed, it is possible to check condylar function prior to bone segment fixation. Several other investigations agree with this finding (Reitzik, Low & Schmidt, 1981; Rittersma *et al.*, 1981; Paulus and Steinhauser, 1982; Steinhauser, 1982; Leonard, 1985; Van Sickels & Flanary, 1985; Thomas *et al.*, 1986).

Sandor *et al.* (1984) investigated 40 patients who were treated for mandibular hypoplasia by surgical lengthening of the mandible using bilateral sagittal split ramus osteotomy. In half of the patients the proximal segments were left unwired; segments in the other half were internally fixed with a superior border osteosynthesis wire. The gonial arc, which is the radius of an arc passing through Gonion with Articulare as the centre of rotation, was used to assess rotation of the proximal segment. When no inter-osseous wire was used, skeletal relapse ranged from 46% to 100%, but with inter-osseous wire skeletal relapse range was from 0% to 54%. They explained that the absence of osteosynthesis may have allowed the unrestrained pull of the lateral pterygoid muscle to displace the condyle from its anatomical position in the glenoid fossa. The remaining muscle attachments to the proximal segment i.e the pterygomasseteric sling, would tend to pull the condyle back in the fossa. However, it would also encourage an anti-clockwise rotation of this segment, particularly if there were no superior border osteosynthesis. The authors recommended interosseous fixation during mandibular advancement. This study highlighted the importance of internal fixation to improve mandibular stability. The gonial arc used to assess the proximal segment is affected by local remodelling at Gonion and this may be misinterpreted as rotation of the proximal segment. It would have been useful if the relationship between the proximal and distal segment had been evaluated. This would have clarified any difference in the bone healing between the two groups. The relapse pattern described in this study is quite similar to that in several other reports (Behrman, 1972; McNeill, Hooley & Sundberg, 1973; Ive *et al.*, 1977; Schendel & Epker, 1980; Lake *et al.*, 1981)

Singer & Bays, (1985) compared inferior border wire and superior border wire techniques in 35 patients who had mandibular advancement. Nineteen patients received an inferior border wire and 16 patients received a superior border wire. Twenty-five patients had a single jaw procedure and 10 patients had bimaxillary procedures. Only preoperative and postoperative cephalographs were used in the study. Gonial, and ramus angles were used to assess surgical changes. The linear measurement Condylion-Gonion was used to evaluate condylar displacement. The angles formed by Sella-Nasion to Articulare, Gonion and Sella-Nasion to mandibular ramus Line were used to measure proximal segment rotation. The mandibular ramus line is formed by two points. One is the centre of a circle, the borders of which are tangent to the inner cortices of the narrowest part of the neck of the condyle. The second is the centre of the circle, the borders of which are tangent to the borders of the mandible at the mid-most and inferior-most aspects of the ascending ramus. They found that the condyle was displaced by 0.7 mm for inferior border wiring and by 1.5 mm for the superior border wire. The antero-posterior rotation of the proximal segment, shown by the increase in the gonial angle, was less in cases with inferior border wiring. The authors concluded that inferior border wiring techniques produced less displacement of the proximal segment.

The use of Condylion-Gonion measurement as indicator for condylar displacement is not appropriate. This length may increase due to inferior transpositioning of Gonion, secondary to anti-clockwise rotation of the distal segment during surgery. This may be then misinterpreted as displacement of the condyle. Further explanation and illustration of this anatomical transpositioning of Gonion will be considered in the discussion section 5.6.1. The mandibular ramus line used to assess proximal segment rotation is dependent on the inferior part of the ramus at the angle which is liable to change during surgery. The mandibular position may have been altered secondary to maxillary surgery. The measuring methods used were incapable of separating mandibular changes due to sagittal split osteotomy from those secondary to maxillary surgery.

Ellis & Gallo, (1986) studied 20 patients who underwent bilateral sagittal split osteotomies for mandibular advancement and who were stabilised with maxillo-mandibular fixation and anterior skeletal fixation. The skeletal fixation consisted of circum-mandibular wires placed bilaterally, distally to the canines and secured with either anterior nasal spine or bilateral piriform aperture wires. The study was concerned only with the period of maxillo-mandibular fixation. A reference line was drawn parallel to the preoperative occlusal plane through Sella. This line was transferred to succeeding cephalographs of the same individual by the computer. The horizontal and vertical positions of Pogonion were measured relative to the constructed reference line, the mandibular plane angle and ramus angle were used to assess mandibular relapse. Pogonion was advanced of an average 6.2 mm. During the period of maxillo-mandibular fixation a mean relapse of 0.56 mm occurred. The authors concluded that the use of skeletal suspension is advantageous in prevention of horizontal skeletal relapse. The horizontal relapse found in this study was lower than that reported in other studies of mandibular advancement in which non-rigid fixation was used (Lake *et al.*, 1981; Will *et al.*, 1984; Smith *et al.*, 1985). 3 authors However, longer term follow up is required to assess the validity of the claim that skeletal fixation reduces the overall relapse.

Moenning *et al.* (1990) investigated stability following sagittal split osteotomy of 28 patients (14 patients had inferior border wiring and skeletal fixation and 14 patients had rigid internal fixation). Preoperative, immediate postoperative and at least 6 months follow up cephalographs were analysed for each case. B point and Pogonion were used to assess mandibular stability. The Indiana horizontal reference plane (a line 7 degrees below Sella-Nasion plane) and the perpendicular to this plane at Nasion were used as reference lines. No statistically significant differences in vertical relapse between the inferior border wire and rigid fixation group were detected. However, the rigid fixation group was horizontally more stable than the inferior border wire group. The authors concluded from the long term results that rigid fixation is more stable than wire fixation. No correlation was found between the magnitude of mandibular advancement and the amount of relapse. The condylar position was not analysed in the study. The relationship between the proximal and distal segments, was also not investigated.

Watzke *et al.* (1990) studied the stability and clinical results in 70 patients (35 had wire fixation and 35 had screw fixation) who underwent bilateral sagittal split ramus osteotomy for mandibular advancement. Of the 35 patients in the screw fixation group, 21 received 2 mm positional screws, whereas the other 14 patients were secured with 2 mm screws placed with a lagging technique which allowed some compression between the segments. Of the 35 patients in the wire fixation group, 27 were fixed with superior border figure of eight wires, two received circum-mandibular wires and six received horizontal mattress superior border wires. The mean changes of 11 cephalometric landmarks were evaluated. Both groups demonstrated the same average direction and magnitude of mandibular advancement. During fixation, in the screw fixation group, Gonion showed almost no vertical change as the mandible advanced, but moved downward and forward in the wire group. At 6 weeks post-surgery in the screw fixation group, the mandibular plane angle increased in nearly half of the patients. This was explained by the authors as due to movement at Gonion. In the wire fixation group the mandibular plane angle increased in 75% of the sample because Gonion moved upward more than 2 mm. No statistically significant difference between the two groups at 1 year post-surgery was detected except at the Gonial area, which had moved superiorly and anteriorly a greater distance in the wire group. The authors suggested that in the wire group, the ramus tended to incline forward immediately after surgery, with Gonion moving forward 3 mm and the non-rigid fixation was not enough to prevent this displacement. In the screw fixation group ramus inclination and the position of Gonion were better maintained.

This is the only article in the literature that showed results following the use of wire fixation having comparable stability with rigid fixation. However, the authors were not careful about choosing their sample, since two different screws were used (position and lag). In addition there were three different techniques of wire fixation which could have affected proximal segment rotation and mandibular stability differently. The authors claimed that the magnitude and direction of mandibular advancement in both groups were similar. However Gonion moved downward and forward in the wire group. This anatomical displacement at Gonion may be due to anti-clockwise rotation of the distal segment that carried the lower posterior corner of the lingual plate below the inferior border of the mandible. The relationship between the proximal and distal segments was not assessed which may have been the reason for the increase in mandibular plane angle at the six month period. The cephalometric analysis used could not separate repositioning from remodelling changes at Gonion. Local bone resorption in this area may explain part of the difference seen between the two groups at the one year follow up.

2.2.3.2.2.6 Summary

Although numerous etiologic factors have been proposed, postoperative relapse following sagittal split osteotomy still appears to have many causes and shows a great deal of individual variation. Further studies are needed with more homogeneous samples to investigate the factors that may influence stability following sagittal split osteotomy. The influence of maxillary Le Fort I impaction on mandibular stability also needs to be investigated. A measuring method that can separate bone remodelling from bone apposition is required if meaningful conclusions are to be drawn.

2.2.4 Bimaxillary osteotomy

2.2.4.1 Correction of Class II Skeletal Deformities

During the 1970s, rapid progress in maxillary surgery led to the widespread adoption of the Le Fort I down-fracture technique, (Obwegeser, 1969; Willmar, 1974; Bell, 1975; Araujo *et al.*, 1978). This allowed the maxilla to be repositioned in all three planes of space. From the early reports of maxillary advancement surgery, it was recognised that there was a tendency for the maxilla to relapse posteriorly and the use of bone grafts was recommended to reduce this tendency (Araujo *et al.*, 1978). Relapse superiorly also was recognised as a problem when the maxilla was moved downward, and a number of suggestions to improve stability have been offered (Wessberg & Epker, 1981). More recently, several investigators have suggested that rigid internal fixation (RIF) in the form of bone plates and pins which are particularly helpful when the maxilla is to be moved downward (Bennett & Wolford, 1985; Luyk & Ward-Booth, 1985; Bays, 1986).

Advances in the surgical techniques have permitted simultaneous mobilisation of both the maxilla and mandible. Early studies of the stability of double jaw surgery reported less mandibular relapse but more maxillary relapse than for the same procedures performed independently (Hiranaka & Kelly, 1987; Brammer *et al.*, 1980). While others have reported relapse comparable to that found in single-jaw surgery (Hennes *et al.*, 1988; Turvey *et al.*, 1988)

Whilst many studies have evaluated stability after single jaw surgery, studies on stability after simultaneous bimaxillary surgery are few (Brammer *et al.*, 1980; LaBanc, Turvey & Epker, 1982; Turvey, 1982; Satrom, Sinclair & Wolford, 1991)

Brammer *et al.* (1980) evaluated 12 patients for postoperative stability eight month after combined maxillary and mandibular osteotomies. Inter-osseous wire fixation was used. The results showed minimal maxillary changes and a strong correlation between the amount of mandibular advancement and its relapse. The direction of the surgical movement varied greatly between the patients, and four had not received concurrent orthodontics.

In a preliminary study by LaBanc *et al.* (1982) 100 cases of simultaneous surgical repositioning of the maxilla and mandible were reviewed. The authors observed more relapse, than with single jaw procedures, but neither cephalometric measurements nor the review intervals were reported. Ninety seven percent of the patients underwent Le Fort I osteotomy, and 82% had adjunctive sagittal split ramus osteotomy. Fixation techniques varied between patients. This study is subjective and not quantitative.

In 1982, Turvey reviewed 31 patients who had undergone simultaneous Le Fort I and sagittal split ramus osteotomies. All had superior repositioning of the maxilla, 16 with a mandibular set-back and 15 with mandibular advancement. The author reported, without quantification, that relapse had occurred in some patients but that all currently had acceptable results.

Hiranaka & Kelly, (1987) studied the short term stability (during inter-maxillary fixation) in 18 patients who underwent simultaneous bimaxillary orthognathic surgery. Seven patients had a class II, six patients had a class III, and four patients had a class I malocclusion, and one patient had had facial asymmetry. Patients were treated by different mandibular surgical techniques and the maxilla was repositioned in different directions. Using routine cephalometric analysis, they concluded that overall stability of the mandibular surgery was improved by concomitant maxillary impaction. They also found a positive correlation between the magnitude of the mandibular advancement and the amount of postsurgical relapse. Mandibular advancement showed greater relapse than mandibular set back. There was great variability in the patient deformities and the corrective surgical procedures. The analysis used in this study would was unable to differentiate between mandibular changes and effect of the maxillary changes on the mandibular postoperative position. This study only assessed short term stability up to six months postoperatively.

Hennes *et al.* (1988) investigated 24 patients who had undergone osteotomies for maxillary impaction and mandibular advancement where internal rigid fixation was used. Nine patients had concomitant advancement genioplasty, surgical elastic bands were applied as inter-maxillary fixation for two days and Class II elastics were worn for about three weeks. The cephalometric radiographs were traced and measured by a single investigator. Cephalometric superimpositions were constructed according to the best fit technique on the ethmoid triad. Thirteen anatomical landmarks and 13 parameters were located in each tracing. Frankfort horizontal plane from the preoperative cephalograph was used as the X-axis. The Y-axis was constructed by scribing a line perpendicular to the

X-axis at the cranial base registration point. The position of the Condylion and Gonion were recorded only in the preoperative tracing and then transferred to each successive tracing to serve as a reference point from which the position of the proximal segment was measured. The results showed that the maxilla was stable vertically. However, the antero-posterior change measured at point A was significant (-0.7 mm +/-1.4). The mandibular distal segment showed continued auto-rotation (anti-clockwise rotation) with insignificant antero-posterior changes. The proximal segment showed upward movement with a decrease in posterior facial height. No significant correlation was detected between the amount of mandibular relapse and the magnitude of advancement or the presurgical mandibular plane angle. There were no significant differences in mandibular stability between cases with or without concurrent advancement genioplasty. The authors claimed that maxillary impaction did not contribute to mandibular stability when they compared their results with the other group of cases who had isolated mandibular advancement surgery. The authors did not comment on either the presurgical facial form of the other group of cases used for comparison or the methods used to assess the differences between the two groups. Hennes *et al.* (1988) did not explain the reasons for the postoperative anti-clockwise rotation of the distal segment and the upward movement of the proximal segment. Removal of the occlusal splint at the follow up period may be the cause of these changes. Moreover, local bone resorption at Gonion may be misinterpreted as upward displacement of the proximal segment with decrease of posterior facial height. The measuring methods used would not allow the separation of remodelling from repositioning changes.

The findings of Hennes *et al.* (1988), are similar to these reported by LaBanc *et al.* (1982) but are contrary to those of Brammer *et al.* (1980) who have shown that cases with mandibular advancement in conjunction with maxillary impaction tend to show more stable results. They demonstrated that as the amount of maxillary impaction increased with auto-rotation of the mandible, the absolute amount of mandibular advancement that was necessary decreased.

Skoczylas *et al.* (1988) compared the short term stability between rigid and non-rigid fixation techniques following Le Fort I impaction with simultaneous bilateral sagittal split advancement osteotomies Thirty patients were studied and divided equally between the two groups. Lateral cephalographs were taken for each patient preoperatively, immediate postoperatively, and prior to the release of fixation at 8 weeks in the wire fixation group or immediately prior to splint removal at 4 weeks in the rigid fixation group. Cephalographs were traced by one examiner for each of the three occasions and superimposed on the cranial base. Cephalographs were traced and a best fit superimposition of the cranial base was used to obtain all tracings of each case on a single acetate sheet. The tracings were digitized and landmark location recorded on an X-Y coordinate system. In the non-rigid fixation group the magnitude of mandibular advancement was 5 mm as a horizontal movement of point B and the average postsurgical change was 0.9 mm in a posterior direction. In the rigid fixation group, the average mandibular advancement was 7.8 mm with 0.4 mm posterior relapse. The authors found no statistically significant differences in post-surgical stability between cases with rigid fixation and cases with non-rigid fixation. The study was concerned with short term stability during the first two months postsurgery. Longer term follow up may have shown a difference in the stability between the two groups. The authors did not comment on the number of cases which had had concomitant genioplasty and how they were distributed between the two groups. Condylar position, changes at Gonion, rotation of the proximal segment, the relationship between the proximal and distal segment, preoperative facial form and the mandibular plane angle were not evaluated in this study. Full evaluation would have also required a longer assessment period. Digitization of cephalometric tracings adds another source of measurement error which were not evaluated in the study. Since the sample size was small, the failure to show statistical significance was not surprising.

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Satrom *et al.* (1991) studied the stability of rigid versus non-rigid fixation techniques in patients who underwent simultaneous surgery for superior repositioning of the maxilla and advancement of the mandible. Thirty-five patients (26 with rigid fixation and 9 with wire fixation) were selected for the study. Both groups were evaluated over an average period of 13 months after surgery. Twenty-eight points were identified in each cephalograph and 27 cephalometric linear and angular measurements were used for the analysis. No significant differences were found in the stability of the maxilla between the two groups, the maxilla stayed within 1 mm of its postsurgical position. During mandibular surgery, the rigid fixation sample tended to show an anti-clockwise rotation of the distal segment, whereas the wire fixation sample underwent a clockwise rotation. During the follow up period, the rigid fixation group underwent less relapse than the wire fixation group. The wire fixation sample had a greater opening of the mandibular plane angle (rigid 0.8 degree, wire, 2 degrees). Mandibular changes were evaluated using SNB and ANB angles. These are insensitive measures for this purpose as the mandible may rotate superiorly or inferiorly with little change in B point antero-posteriorly. Primary mandibular changes cannot be separated from the secondary effects of maxillary repositioning when the ANB angle is used.

There have been no studies that have quantitatively assessed the stability of bimaxillary surgery and were able to separate maxillary and mandibular changes. There is still a need for further studies comparing the stability of similar samples that have undergone the same double jaw procedure, varying only in whether they had rigid or non-rigid fixation. The possibility of increased postoperative skeletal stability in bimaxillary surgery when using internal rigid fixation needs to be investigated. The influence of maxillary impaction on mandibular stability also has to be adequately assessed.

2.3 Aims of the study

The overall aim of this thesis is to improve the surgical techniques for correction of mandibular retrognathia to obtain stable results. The subsidiary aims to achieve this goal were:

1. Orthognathic Surgery

Firstly, to study surgical and postsurgical changes following various orthognathic surgical procedures for the correction of mandibular retrognathia.

The goals of this study were considered in the following order:

1. Assessment of surgical changes and long term stability following various orthognathic surgical procedures using conventional cephalometric method as well as FE and EDM analyses.

2. To match and contrast the data obtained by the three methods of morphometric analysis.

3. To evaluate the applicability of FE and EDM analyses in assessing surgical changes from lateral cephalographs.

4. To compare the stability of the different methods used to correct mandibular retrognathia.

5. To determine if any relationship exists between the amount of postsurgical skeletal change and factors existing before surgery, or occurring as a consequence of surgery.

Secondly, to analyse the effect of the different factors which contribute to postsurgical skeletal changes.

Thirdly, to draw conclusions on the interactions and the roles played by these factors when analysing postsurgical stability.

2. Cephalometric Analysis

Firstly, to address as far as possible the problems associated with conventional cephalometric analysis.

Secondly, to study the applicability of Finite Element and Euclidean Distance Matrix analyses in evaluating surgical and postsurgical changes.

Finally, to compare and contrast the results obtained by the three methods of morphometric analysis and so achieve a greater understanding of the surgical and postsurgical changes. This should allow the aims of the first part to be achieved

Chapter 3

Methods and Materials

3.1 Scope of the study

The cases included in the study were classified according to the surgical technique used to correct the mandibular retrognathia. The cases had orthognathic surgical correction at either Canniesburn Hospital, West of Scotland Regional Plastic and Maxillofacial Surgery Unit , Glasgow, Britain or the Department of Oral Surgery, Michigan University Hospital, Ann Arbor, U.S.A. Most of the cases had presurgical orthodontic preparation and postsurgical orthodontic final adjustment. The surgical changes and the stability of the following surgical procedures were investigated in the study.

1. Nineteen patients who had had pedicled advancement genioplasty were treated at Canniesburn Hospital;

2. Ten patients who had had sagittal split advancement osteotomy with rigid internal fixation were treated at Canniesburn Hospital;

3. Twelve patients who had had simultaneous maxillary impaction and sagittal split advancement osteotomy using wire fixation were treated at Canniesburn Hospital;

4. Fifteen patients who had had simultaneous maxillary impaction and sagittal split advancement osteotomy using screws and bone plates for rigid internal fixation were treated at Canniesburn Hospital;

5. Fifteen patients who had had simultaneous maxillary impaction and sagittal split advancement osteotomy using screws and bone

plates for rigid internal fixation were treated at Michigan University Hospital.

3.2. General METHODS

3.2.1 ASSESSMENT AND TREATMENT PLANNING

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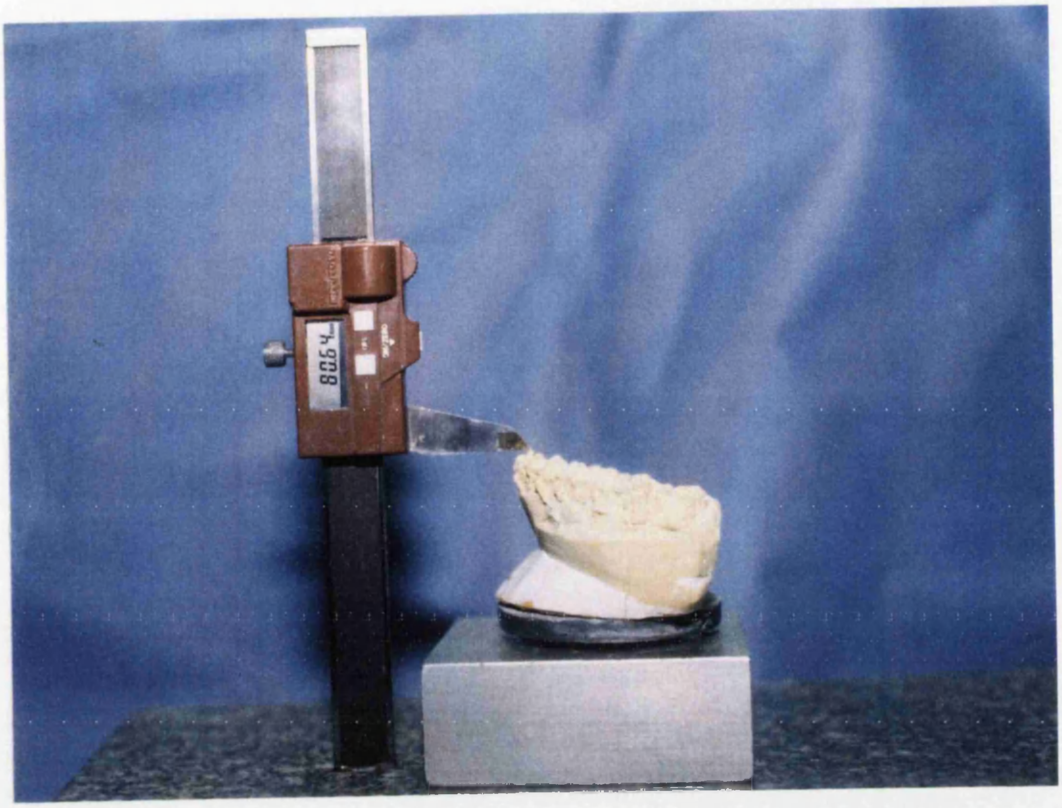
The patients were examined clinically to assess their deformities. From a frontal view, any transverse asymmetry was noted, the relationship of the dental midline to the skeletal midline was recorded. The heights of the mid face from the supraorbital ridges to the base of the nose and from the base of the nose to the undersurface of the chin were measured. The relationship between the upper incisal edge and the lowest point of the vermilion border of the upper lip was assessed at rest and during smiling. From the lateral view, profile convexity or concavity and jaws disproportion were analysed. The chin position in relation to the tip of the nose and soft tissue Nasion was investigated. The accentuation of nasolabial and mentolabial sulci were noted. Upper anterior and lower anterior facial heights were measured. The ratio of the upper and lower lip lengths in relation to the lower facial height were calculated. The face was also examined from a submento-vertex position to assess any differences between the right and left malar bones prominence.

Cephalographs (lateral and frontal), dental casts, profile and frontal photographs were prepared for each patient. They were used for diagnosis and treatment planning. Conventional cephalometric analysis (Steiner's analysis) was applied to assess skeletal deformities and occlusal derangement. The ratio of lower anterior facial height to total anterior facial height was calculated to separate cases of vertical maxillary excess from those of deficient vertical height. The relationship of the maxilla to the base of the skull was assessed by SNA and the Maxillary plane angle. The inclination of the upper anterior teeth in relation to the maxillary and Sella-Nasion planes were also evaluated. The maxillo-mandibular relationship and the mandibular position in relation to the base of the skull were assessed.

Plaster models of the teeth were prepared and mounted on a semi-adjustable articulator using a face bow transfer and bite registration. Facebow transfer was needed to orient the maxillary cast to the glenoid fossa and to the Frankfort horizontal plane. The dental models were used to evaluate the occlusion, determine the need of presurgical orthodontic treatment, and to decide the exact amount and the direction of movement of the arches to obtain the desired occlusion. This was guided by the cephalometric and photocephalometric planning, and in turn it also led to modification of that planning. The models were sectioned and placed in their planned position by either a free hand method using a ruler for measurement or using Erickson Model Surgery Platform (Great Lakes Orthodontic Ltd, Tonawanda, MY) (Fig. 3.1). This machine was only utilised for cases treated at Michigan University Hospital. The machine contains an electronic sliding ruler to measure the distances, in tenth of millimetres, from maxillary incisal and occlusal edges to the model surgery platform. This platform is a device that allows mounting of the models, after removal from the articulator, on a square model-block for measurement before, during, and after model surgery (Fig. 3.2). Measurements of the cast are made using the electronic digital calliper that is mounted in the base of the model surgery platform. In this manner, all the



Figures 3.1 & 3.2 Erickson Model Surgery Platform (Great Lakes Orthodontic Ltd, Tonawanda, NY) showing the method of measuring the vertical & antero-posterior position of the maxillary incisors.

measurements were made either perpendicular or parallel to the platform, therefore, parallel or perpendicular to Frankfort horizontal. The models were cut and placed in the optimum position which was guided by cephalometric analysis and photocephalometric planning. Antero-posterior, vertical and horizontal movements to be accomplished at surgery were recorded after model surgery was performed. A horseshoe-shaped acrylic splint was constructed. It covered the occlusal and lingual aspect of the posterior teeth and the incisal and lingual aspect of the anterior teeth. In case of a bimaxillary osteotomy, an intermediate occlusal splint was constructed to relate the maxilla in its new position to the mandible. A final splint was also prepared to orientate the distal mandibular segment after sagittal split osteotomy to the repositioned maxillary segment.

For each case a profile transparency was produced. This was a positive photographic image printed on a transparent base and enlarged to allow accurate superimposition on the soft tissue profile of the cephalograph. The patients were photographed in the "teeth together" position with the lips in repose. Both cephalograph and photograph were thus taken in the same pose for a true lateral view. The photographic negative was enlarged so that the photograph fitted the same line as the cephalometric profile. After superimposition the maxilla, mandible and teeth were traced from the cephalograph to the transparency. The maxilla and mandible were cut and placed in the desired position. This helped to assess, to some extent, the expected postoperative appearance of the patients (Fig. 3.3).

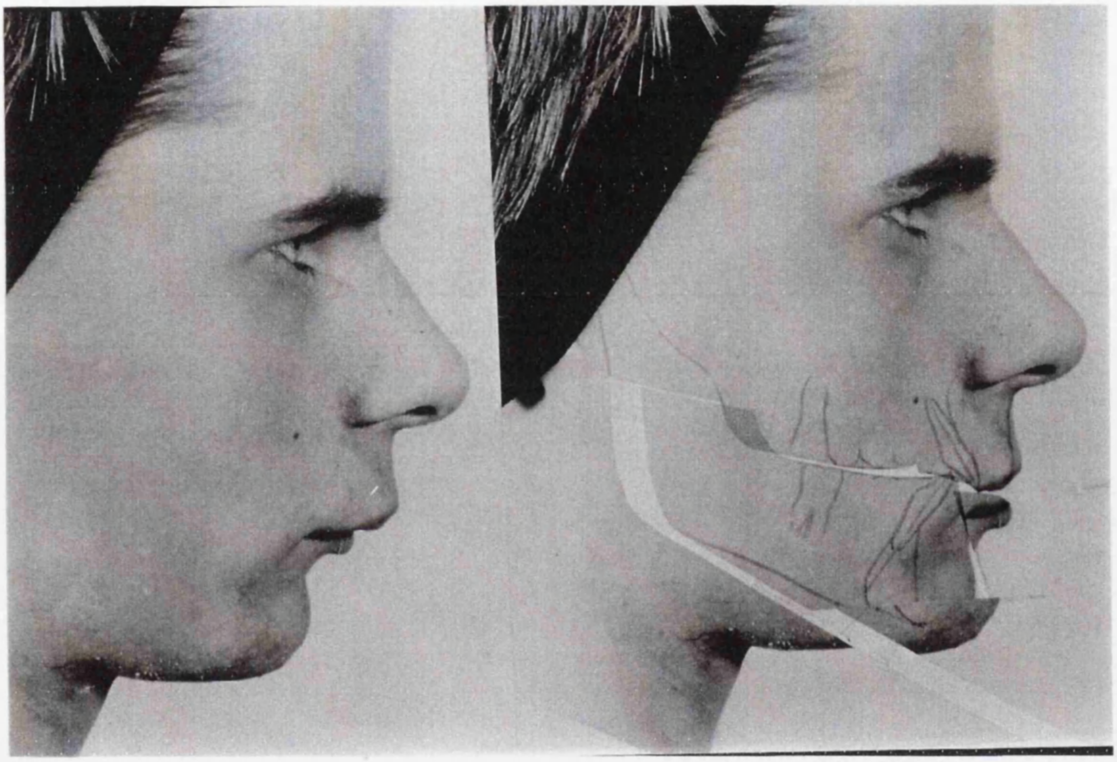


Figure 3.3 Cephalometric prediction of post operative changes. The transparent profile photography of the patient is superimposed on his cephalograph to trace maxillary and mandibular teeth and bony landmarks. The mandible is cut and placed in its desired position. The soft tissue profile is also modified according to the expected soft tissue change in response to surgery.

3.2.2 Cephalometric Analysis

3.2.2.1 Introduction

The assessment of surgical changes and stability following surgery was carried out using lateral cephalographs. For each patient four cephalographs were analysed, the immediate preoperative cephalograph (T1), immediate postoperative cephalograph (T2) (within a week from the date of surgery), six months (T3) and one year follow up cephalographs (T4). These were taken in the natural head position using a cephalometric head holder. All cephalometric radiographs were taken at an film-anode distance of 150 cm. Because of the inherent difficulty and lack of reliability in identification of soft tissue landmarks in cephalographs, only skeletal landmarks were used in the analysis. Dental points were not considered in the study. The digitization of the dental points was difficult due to superimposition of the orthodontic brackets and tubes, surgical arch bars, and occlusal splints that covered the occlusal and incisal surfaces.

3.2.2.2 Data from Cephalographs

Twenty cephalometric landmarks were digitized from each radiograph. The X and Y coordinates of every digitized point were automatically recorded onto a computer disc. Each radiograph had 2 pin holes punched in the margin to be used as fiducal points. One fiducal point was punched approximately 2 cm above the Sella-Nasion line, the other was punched approximately 2 cm below the angle of the mandible. These fiducal points were digitized so that the separate digitization on different occasions of each radiograph could be related to one another. In addition to the fiducal points, each cephalograph was punched by another two pin holes at the other side of the film, one in the upper half and the other in the lower half. The line joining them represented the natural head position, vertical.

Under optimal conditions on the light box of the digitization table the radiographs were digitized directly. Landmarks, fiducal and natural head position points were digitized twice using a high resolution digitizer, on a line to a microcomputer. A custom written computer program was used to allow each point to be digitized twice. When the difference in the coordinates between the first and second time of digitization was more than 0.5 mm the point was redigitized twice until satisfactory accuracy was obtained. The whole procedure was repeated not less than two weeks after the first occasion. One operator carried out all the digitization. The averaged coordinates from the two occasions of the digitization were used in the study. This is recognised in the orthodontic literature as the best method to minimise cephalometric measurement error (Houston, 1983).

The coordinates of the landmarks from each occasion were compared by mathematical superimposition using fiducal points, the averaged coordinates were used in the study. Where gross discrepancies (more than 2 mm) were noted then the process of replicate digitization was repeated until there was a reasonable consistency of landmark location. The error of recording the landmarks as measured by the differences in the coordinates between the first and second occasion of digitization was calculated. The influence of the residual landmark location error on the methods used to analyse the cephalographs was determined. A one sample Student t-test for each pair of replicates was used to test for systematic error and the index of reliability to measure random error.

3.2.2.3 Conventional Cephalometric Analysis

A custom written computer program in Q. Basic was used to calculate the cephalometric parameters using the averaged landmarks coordinate. The parameters used were dependent on the type of surgery applied. The mean and standard deviation of the measurements were calculated for each set of cephalographs for every group of cases having the same surgical procedure. The conventional cephalometric measurements were selected to allow comparison of the findings of this study with similar investigations. The use of conventional methods of cephalometry will aid in understanding for those unfamiliar with the new cephalometric techniques.

3.2.2.4 Application of Finite Element Analysis

A custom finite element analysis (FEA) computer program, was developed for the study. Cephalometric landmarks were used to define the nodes of the selected finite elements. The program allows the selection of any three cephalometric points to be used as nodes for the elements. The nodal points and finite elements used were selected for each type of surgery so as to examine the areas of surgical change. The finite element computer program provided numeric and graphic representations of morphological differences between reference and comparison forms at the centroid of each element

// by whom?

The deformations of these elements were computed for the subjects after surgical treatment (target finite element) relative to before surgery (reference finite element), and at different follow up intervals. For each group of cases the coordinates of the cephalometric points were averaged to calculate the finite element variables. The average principal strains and the direction of the principal deformation of each element was calculated. The principal strains are the maximum and minimum strains. The maximum strain is defined as the magnitude of maximum distortion among all possible directions local to the element. Minimum principal strain is defined as the minimum magnitude of distortion of all directions local to the element. Theta was the name given to the angle that defines the direction of maximum strain. To aid visualisation of the changes the elements were arbitrarily oriented to the natural head position vertical of the second film, before being plotted. The elements can be drawn in any orientation and the natural head position was used only to plot the nodal points in a similar orientation to their corresponding cephalometric landmarks.

The influence of the landmark recording error on finite element analysis was assessed. The residual landmark location error was calculated as the difference in landmark coordinates between the first and second occasion of digitization. The differences between the values of the finite element variables (Maximum strain, Minimum strain and Theta) on the first and second occasion were assessed. The influence of landmark recording error on the finite element method was determined. A one sample t-test for each pair of replicates was used to test for systematic error and the index of reliability to measure random error.

3.2.2.5 Euclidean Distance Matrix Analysis (EDMA)

A custom written Euclidean distance matrix analysis computer program was developed for the study. The program allowed a choice of the points to be included in the evaluation. The selected points were dependent on the type of surgery and the bone segments to be evaluated. Distances between each of the selected points were calculated from averaged coordinate data.

The corresponding linear distances between the points for pairs of occasions (preoperative to post-operative or postsurgery to the follow up occasions) were compared as ratios of the later to the earlier distances. These ratios comprise the difference matrices between the pairs of occasions. The statistical significance of differences in shape was tested by the "Bootstrap" method described by Lele and Richtsmeier (1991) using a customised computer program.

3.2.3 Surgical Procedures

3.2.3.1 Introduction

The advent of orthognathic surgery has given the oral surgeon, in conjunction with the orthodontists, the ability to correct skeletal deformities. Numerous operative approaches for correction of the deficient mandible have been advocated. The surgical correction of certain cases can be satisfactorily accomplished with single jaw surgery, however, for others double jaw surgery has been advocated.

3.2.3.2 Genioplasty

The operation was performed in the operating room with the patient under nasotracheal anaesthesia. Local anaesthesia with a vasoconstrictor was infiltrated into the labial vestibule to aid in haemostasis. The incision was designed to maintain circulation to the mobilised portion of the inferior border of the mandible by means of an intact soft-tissue pedicle of genial and digastric muscles and periosteum. In the anterior region of the mandible, the incision was made through the lower labial mucosa, midway between the depth of the labial vestibule and the vermilion border of the lower lip (Fig. 3.4). It was extended posteriorly to gain exposure of the planned osteotomy sites and mental nerves. In the premolar region the incision was made through the mucosa only, to prevent damage to branches of the mental nerve. The anterior portion of the incision was carried sharply through the mucosa only. The mucosa was then raised from the underlying submucosa and orbicularis oris muscle. The dissection was then directed posteriorly and inferiorly onto the mentalis muscle which was cut with the soft tissue and periosteum. These were elevated inferiorly from the underlying bone. The mental foramen and mental nerve were identified and were carefully protected (Fig. 3.5).

The osteotomy site was exposed from the mental foramen of one side to the contralateral mental foramen. The lateral parts of the body of the mandible posterior to the foramina were also exposed. The bone segment was cut using a Stryker saw or a surgical bur, leaving a broad lingual and inferior border muscle attachment (Fig. 3.6). The mobilised segment was grasped with a bone holding clamp and moved into the pre-planned position. The segments were

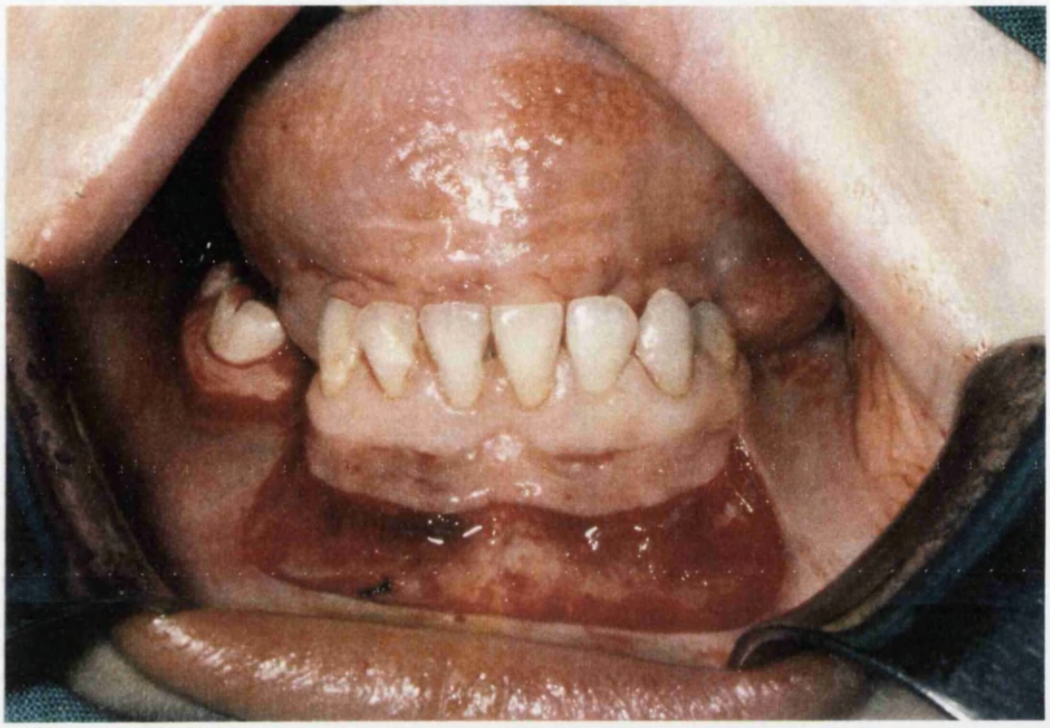


Figure 3.4 Lower lip incision midway between the vermilion border and muco-labial fold for exposure of the chin.

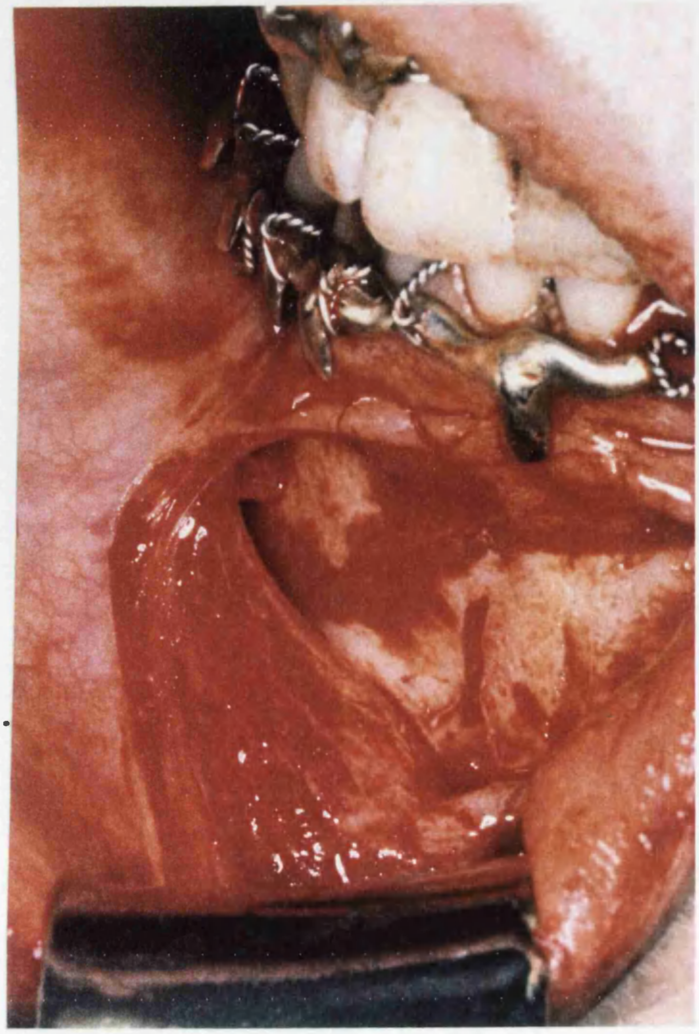


Figure 3.5 Identification and protection of the mental nerve while the genioplasty bone cut is extended inferiorly and posteriorly to the nerve.

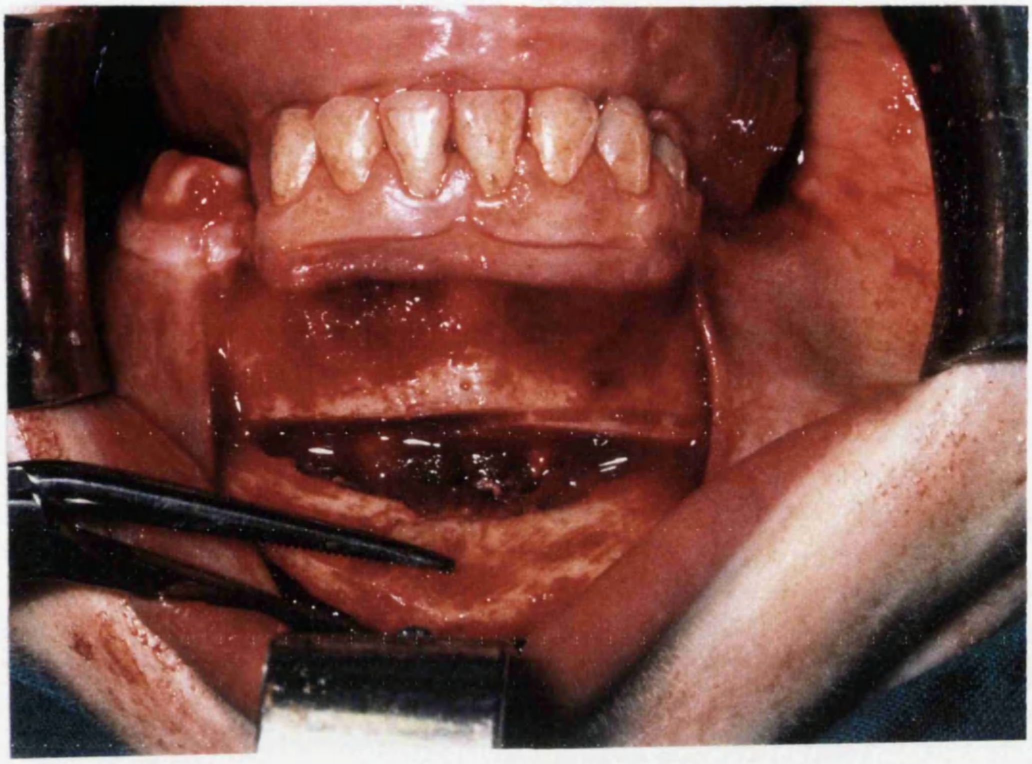


Figure 3.6 the inferior genial segment pedicled to geniohyoid and digastric muscle.

Figure 3.7 Fixation of the advanced genial segments using inter-osseus wiring.

fixed in the new position using three or four direct inter-osseous wires (Fig. 3.7). A long fissure bur was used to drill obliquely through the labial cortex and through the margins of the sectioned distal segment and out through the lingual cortex. The wires were attached to the lateral surface of the anterior mandible and the lingual cortical plate of the advanced segment. Placement of the bone holes and wires was determined by the direction and magnitude of osseous movement. The soft tissues were closed in two layers. A small pressure dressing was applied and left in position for up to five days.

3.2.3.3 Sagittal Split Osteotomy

The patient was positioned on the operating table and the oropharynx was packed, the mouth was stabilised in an open position with a prop. Local anaesthesia (2% Lidocaine) with adrenalin 1:200,000 was infiltrated along the external oblique ridge, along the medial aspect of the ramus and into the molar region of the mandible to provide some haemostasis. An incision was made over the anterior aspect of the ramus of the mandible beginning mid-ramus and continuing down onto the external oblique ridge and then curving into the lower vestibule, ending approximately at the first molar region. The soft tissue was retracted over the ascending border of the ramus with minimal subperiosteal dissection on the lateral aspect of mandibular ramus. The dissection on the medial side of the ramus was carried out beneath periosteum from above the lingula downward and almost to the posterior border of the mandible. The sigmoid notch was located by dental curette for the purpose of anatomical orientation. Periosteal dissection was then extended laterally, reflecting the thinner tissue over the body of the mandible, extending around the inferior border just below the second molar

A channel retractor was placed along the lingual aspect of the mandible to protect the neurovascular bundle and to provide adequate visualisation and accessibility for the lingual osteotomy (Fig. 3.8). The lingual horizontal medial bone cut was made just above the level of the lingula using Lindemann bur or reciprocating saw. The depth of the cut was equivalent to half the medial-lateral thickness of the ramus. Multiple small holes were drilled into the cancellous bone along the anterior border of the ramus. The holes were connected using a fissure bur, this cut was carried anteriorly and inferiorly to connect with a vertical bone cut on the lateral aspect of the body of the mandible. The vertical bone cut was made opposite to the second molar tooth. The cortex of the inferior border was also cut. The depth of the bone cut was extended into the cancellous bone. The bleeding marrow vascular spaces were noted throughout the entire course of the osteotomy (Fig. 3.9). A thin spatula osteotome was malleted into the osteotomy sites to define the cuts.

? avoid nerve damage during splitting

A thin osteotome was directed parallel to the lateral cortex of the ramus and was malleted to section the outer plate of the body of the mandible at the junction of the buccal cortical plate and the intermedullary bone. A Smith splitter was also used in some cases to facilitate sectioning of the inferior border of the mandible. Once the mandible was split the track of the neurovascular bundle was identified (Fig. 3.10). In some occasions the neurovascular bundle,

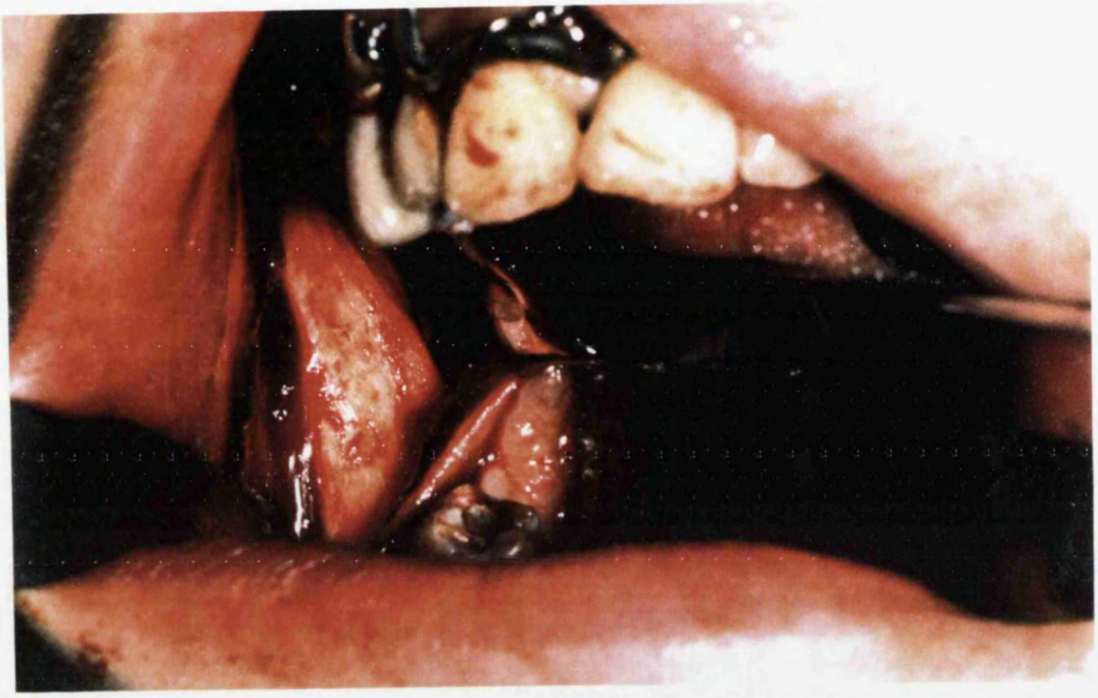


Figure 3.8 Channel retractor is positioned immediately superior and posterior to the neurovascular bundle to protect the nerves and facilitate the visualisation of the medial surface of the ramus of the mandible.

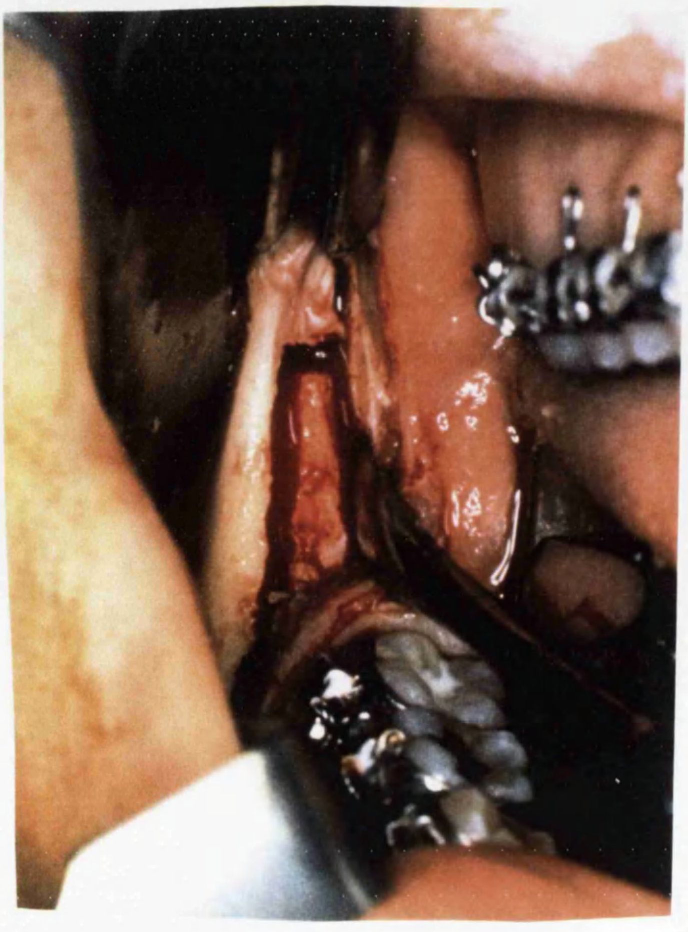


Figure 3.9 Sagittal split osteotomy, a horizontal bone incision immediately above the mandibular foramen, vertical bone cut distally to the lower second molar and the two cuts are connected along the anterior border of the ramus and superior surface of the body of the mandible.

Figure 3.10 The neurovascular bundle is dissected from the proximal segment and kept adherent to the distal segment.

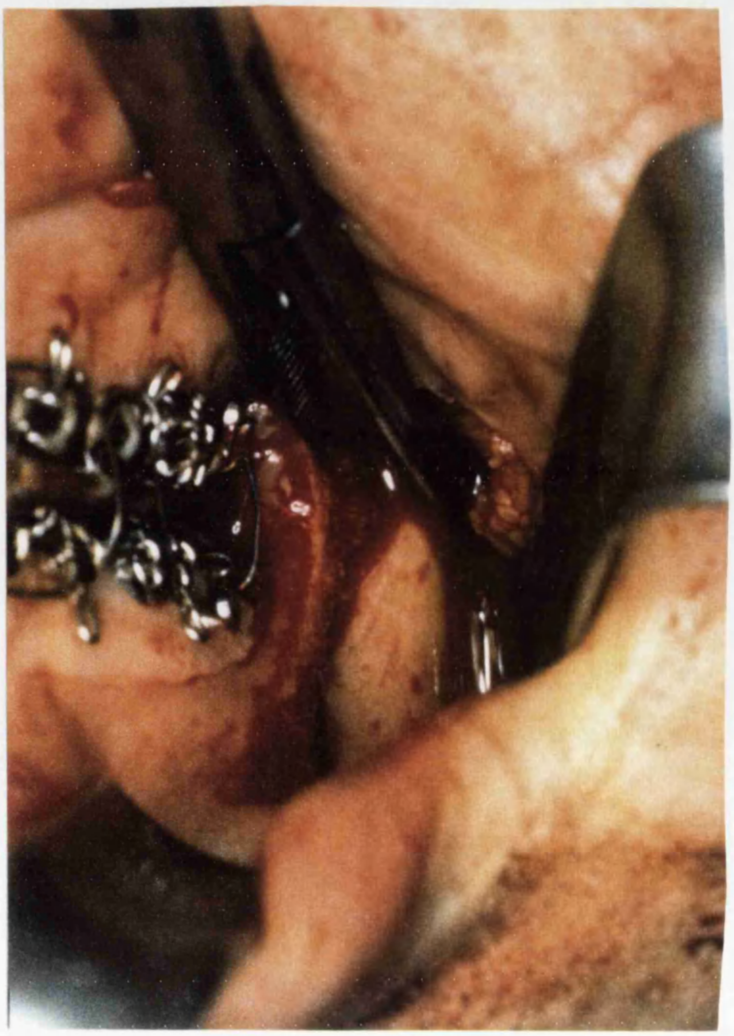


Figure 3.11 Shows bone clamp holding the proximal segment in position prior to fixation.

was attached to the proximal bone segment, the covering bone was removed and the nerve freed with an instrument, such as a Mitchell's trimmer.

The osteotomy was repeated on the opposite side of the patient's mandible. The distal mandibular segment was advanced and placed in its predicted position using an occlusal splint. The teeth were secured into maxillo- mandibular fixation with 25-gauge wire.

To establish an anatomical condylar position, the proximal segment was gently manipulated and placed in a position considered to be the most anatomical one. A ramus clamp was applied to hold the proximal and distal segment in the desired position before fixation (Fig. 3.11).

In the non-rigid fixation case, the proximal and distal segments were stabilised by an upper border wiring. An upper border wire was placed by drilling a hole through the cortex of the proximal as well as the distal segment. The hole at the distal segment was slightly higher and posterior to that of the proximal segment. A direct upper border wire was applied through these two holes and tightened after maxillo-mandibular fixation was in place. When the wire was tightened, the proximal segment and condyle were properly seated. ? why important

In rigid fixation cases, positional screws were applied either intraorally or extraorally (percutaneous) depending on the accessibility. When intraoral access was limited or when more perpendicular orientation of the screws to bone was desired, a percutaneous approach was the option of choice. Access was gained

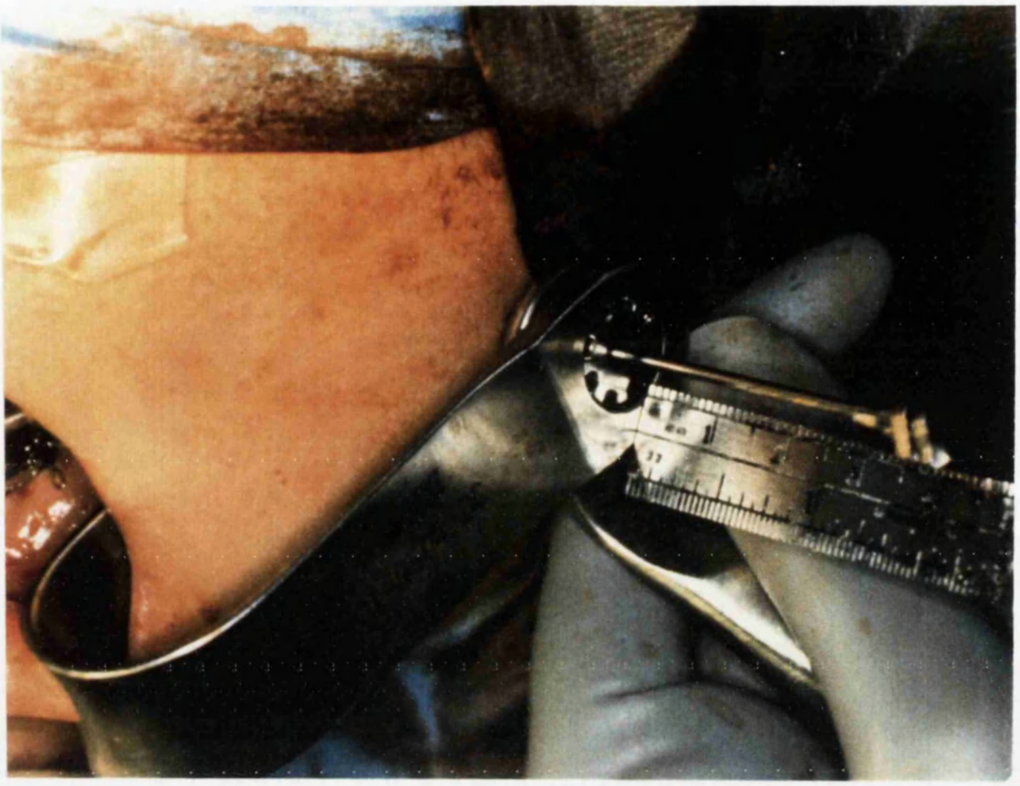


Figure 3.12 Screw fixation through extra-oral approach. The screw holes are drilled, their depths are measured and the screws placed through a skin penetration using a pointed trocar.

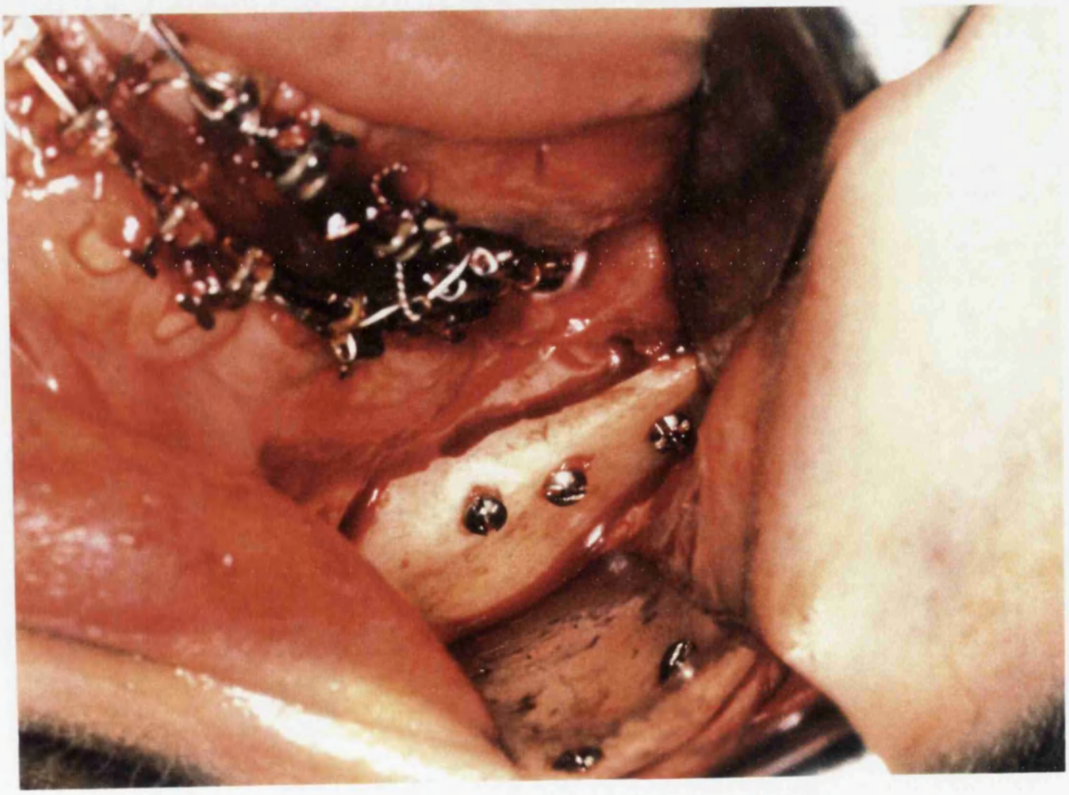


Figure 3.13 Three bicortical screws or fixation of the sagittal split osteotomy.

by placing a small stab incision in the skin beneath the angle of the mandible. Then a trocar was inserted through the incision allowing instrumentation through its cannula. The cannula was also used to measure the depth of the drilled holes to chose the proper screw (Fig. 3.12). Three bicortical position osteosynthesis screws were used per side (Fig. 3.13). The wound was closed using chromic gut. The occlusal splint is usually left fixed to the maxilla to guide the mandible into the new occlusion.

3.2.3.4 Bimaxillary osteotomy

In bimaxillary cases, the maxillary osteotomy was performed, just before mandibular osteotomy, and the maxilla was fixed in its preplaned position. The maxilla was down-fractured at the Le Fort I level and orientated to the mandible using an intermediate splint prepared at the time of model surgery.

The operation was performed under general anaesthesia. Antibiotics were routinely used preoperatively and postoperatively to protect against infection. Steroids were also used to reduce soft tissue swelling. Local anaesthesia with a vasoconstrictor (Adrenaline 1:200.000) was infiltrated into the labiobuccal vestibule for haemostasis. K wire was inserted at the "Glabella" to be used as an external reference mark. The distance from the wire to the incisal edge of the upper anterior tooth was measured. The alar width was measured to assess any change in the alar position following surgery (Fig. 3.14). A horizontal incision was made through the mucoperiosteum in the depth of the buccal vestibule extended from the zygomatic buttress above the first molar of one side to that of the opposite side. A buccal superior flap was raised to expose the

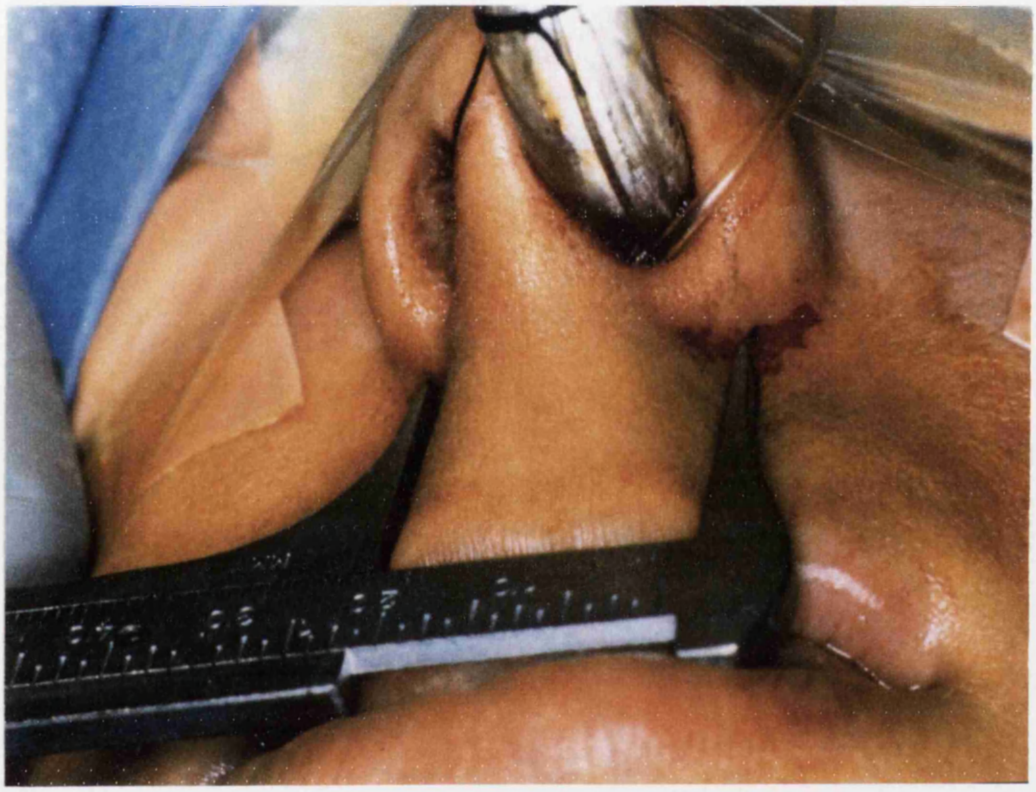


Figure 3.14 Measuring of the alar base width before Le Fort I osteotomy.

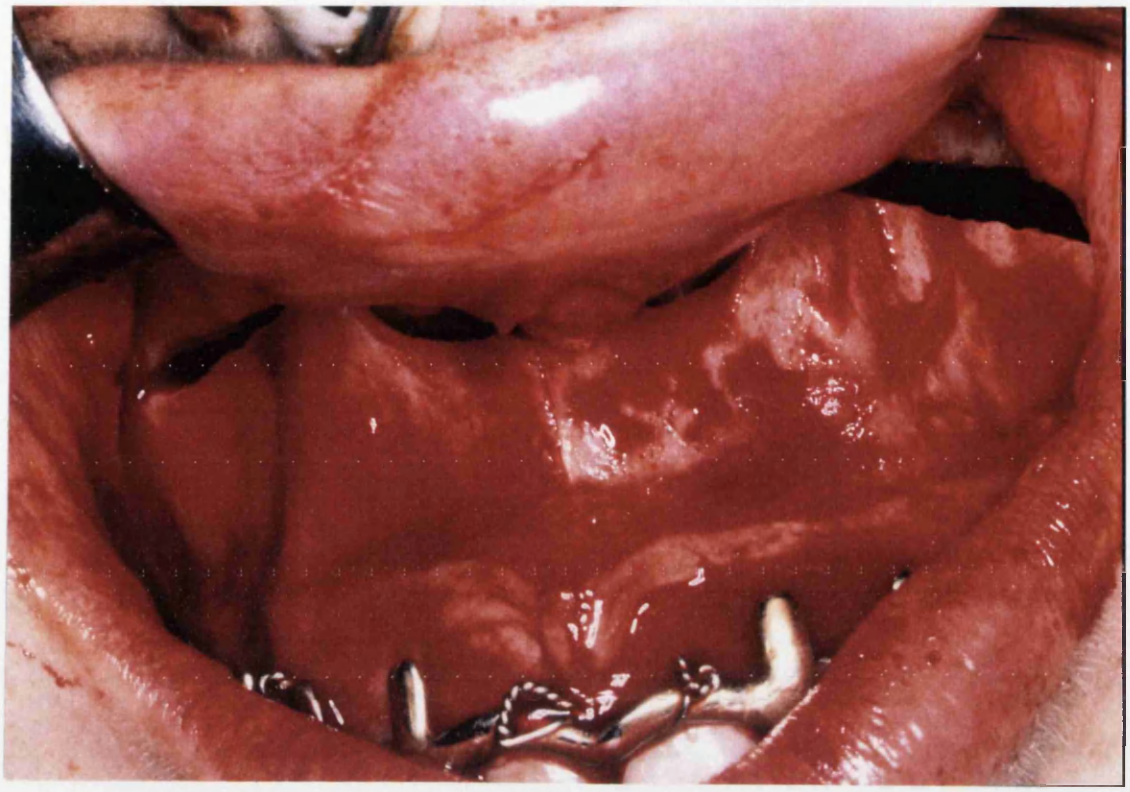


Figure 3.15 Le Fort I maxillary bone cuts extended from the piriform rim posteriorly to the ptergomaxillary suture.

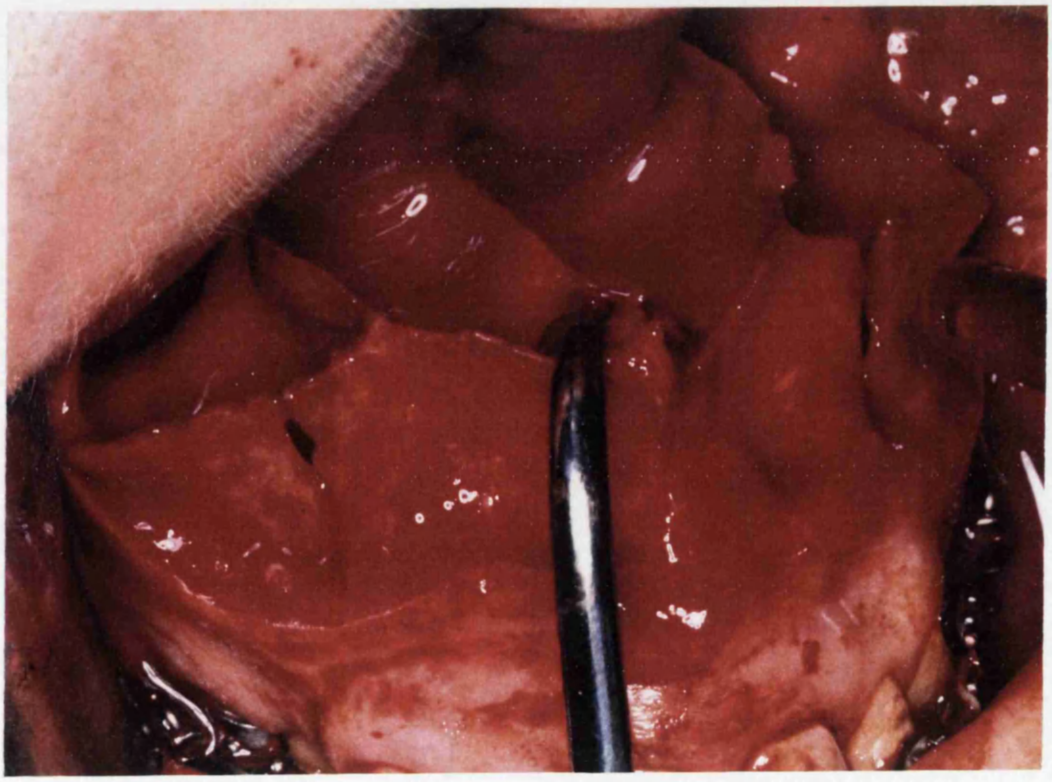


Figure 3.16 The maxilla is in downfractured position.

lateral walls of the maxilla, zygomatic buttress, anterior nasal floor, and piriform apertures. The infraorbital neurovascular bundles were identified and protected. The mucoperiosteum was detached from the floor of the nose, base of the nasal septum, and lateral nasal walls superiorly to the base of inferior turbinate. The posterolateral portion of the maxilla and the ptrygo-maxillary suture area were visualised by subperiosteal tunnelling and positioning the tip of a curved channel retractor at the suture.

Two horizontal osteotomy lines were made about 5 mm above the apices of the teeth from the lateral aspect of the piriform rim posteriorly across the canine fossa to the ptergomaxillary fissure with a fissure bur (Fig. 3.15). The vertical distance between the lines was dependant on the desired magnitude of maxillary impaction. Osteotomy lines were cut using a reciprocating saw, the nasal mucosa was protected by a periosteal elevator during the bone cutting. The lateral antral wall was sectioned using a nasal osteotome until contact was made with the dense perpendicular plate of palatine bone. A nasal septal osteotome was inserted above the anterior nasal spine parallel to the hard palate and malleted to separate the nasal septum from the maxilla. Pterygo-maxillary dysjunction was achieved by using a Tessier chisel to separate the maxilla from the pterygoid plates. Digital pressure was applied on the palatal mucosa in the region of the hamulus to feel the osteotome as it passed through the ptergomaxillary suture to ensure it did not traumatise the underlying mucosa. nasal

Firm inferior pressure was applied on the anterior portion of the maxilla to downfracture it (Fig. 3.16). As the maxilla was downfractured, the nasal mucosa which has not been yet separated from the nasal surface of the maxilla and horizontal plate of palatine bone was elevated. Maxillary disimpaction forceps were sometimes used to manipulate the downfractured maxilla to separate it from its remaining bony attachments. Tessier mobilizers were placed bilaterally on the buccal side at the posterior aspect of the maxilla, and under direct vision the maxilla was brought forward, fracturing any remaining posterior bone attachment. Bone was removed from the posterior maxilla and from around the descending palatine vessels using a rongeurs or a round bur (Fig. 3.17).

An occlusal wafer (intermediate splint) was then inserted and the maxilla and mandible were held together by utilising 25 gauge wire for temporary maxillo-mandibular fixation (Fig. 3.18). The distance between the K wire and the incisal edge of the upper tooth was measured to check the desired magnitude of maxillary impaction had occurred. By incremental removal of bone, the planned magnitude of impaction and good bone contact were obtained.

Stabilisation of the maxilla following superior repositioning was accomplished with either inter-osseous wire or bone plates. When wire fixation was used, holes were drilled in the thick areas of the piriform region and the zygomatico-maxillary buttress areas. In rigid fixation cases four Champy plates (two in each side) were placed in the anterior and posterolateral surfaces of the maxilla (Fig. 3.19). The plates were bent to conform as closely as possible to the walls of the maxilla. The plates were secured by two screws on either side of the osteotomy site. The alar width was measured again

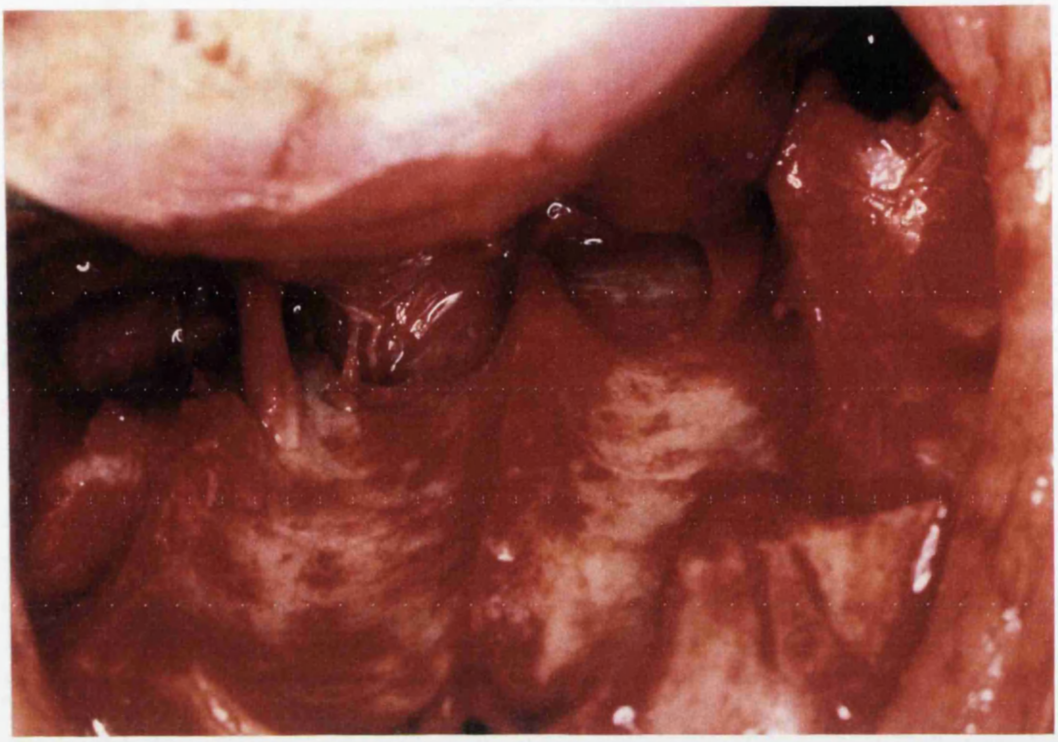


Figure 3.17 Intact descending palatine neurovascular bundle to enhance blood supply to the maxilla through the soft tissue pedicle on the palate.

Figure 3.18 Temporary maxillo - mandibular fixation using occlusal splint to guide the maxilla into its planned position.

Figure 3.19 Two Champy plates, on each side, for maxillary fixation, one at the piriform aperture and the other at the root of the malar bone.

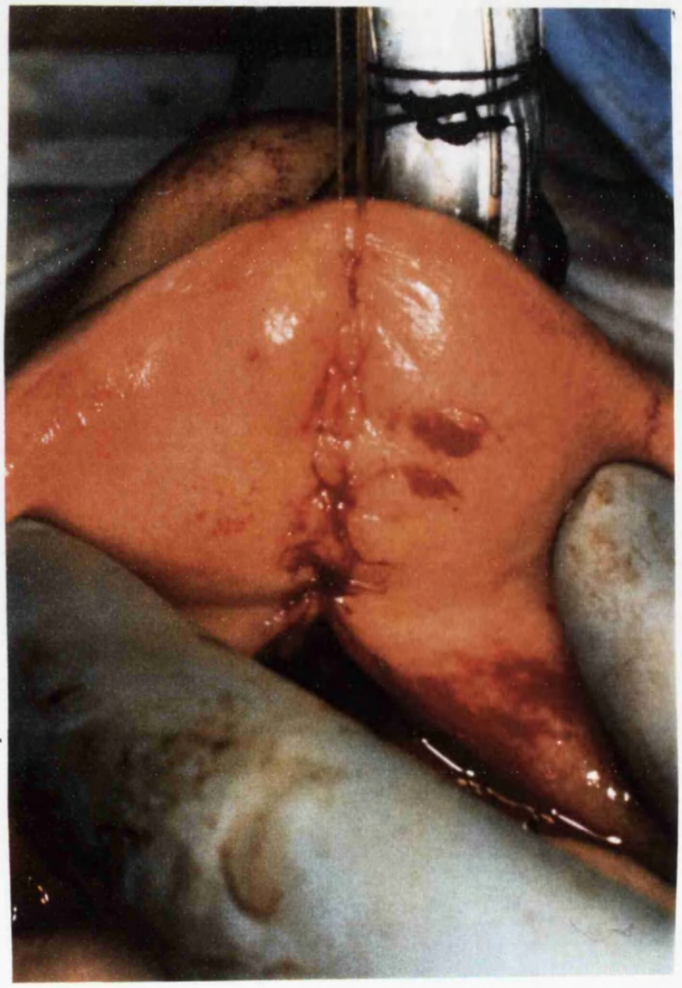


Figure 3.20 The V-Y closure; it maintains the amount of vermilion lip at the expense of the labial mucosa.
The closure begins posteriorly with retraction of closure pulling the superior mucosal edge anteriorly.

and suturing of the alar bases, using non-resorbable vicryl sutures, was indicated in cases of alar flaring. V-Y closure was applied in cases where lengthening of the lip was desirable (Fig. 3.20). The incision was closed and the occlusal splint removed prior to starting the mandibular osteotomy.

The mandible was advanced by a sagittal split ramus osteotomy. The technique used is the same as explained in section 3.2.3.3 In cases which had non-rigid fixation, maxillo-mandibular fixation was applied for six weeks. In cases where rigid fixation was used, the maxilla and mandible were held together using light elastics for two weeks. The final occlusal wafer was then left fixed to the maxilla to guide the teeth into the new occlusion.

Selection criteria for genioplasty:

1. Patients should have pedicled advancement genioplasty with inter-osseous wire for fixation.

2. The magnitude of genial segment advancement is between 2mm to 4 mm.

3. Cases which had suprahyoid myotomy were not considered in the study.

4. Cases of vertical augmentation of the chin and set back genioplasties were excluded.

5. Cases of cranio-facial syndromes and mandibular dysystosis were not included in this thesis.

3.3 MATERIALS

3.3.1 Advancement genioplasty

This study was carried out on 19 patients (14 females and 5 males) with mandibular retrogenia. Their age ranged from 16 to 35 years, with an overall mean of 24 years at the time of surgery. The patients had pedicled advancement genioplasty by means of horizontal sliding osteotomy of the symphysis with broad soft tissue pedicle. All the cases were treated at Department of Maxillofacial surgery, Canniesburn Hospital, West of Scotland regional Plastic and Maxillofacial Surgery Unit. Those excluded from the study were patients who were treated by wedge vertical augmentation using alloplastic materials. The changes following surgery were evaluated by comparing the immediate preoperative cephalograph (T1), immediate postoperative (T2), six months (T3) and one year postoperative (T4) cephalographs. Cases included had no significant preoperative asymmetry and were not secondary to temporomandibular ankylosis or associated with craniofacial syndromes.

The patients underwent traditional advancement genioplasty using a broad pedicled flap from an intra- oral incision. The bone segment was fixed in the new position using a triple or four wire osteosynthesis.

The following cephalometric landmarks were used to evaluate changes at the chin region

Infra dentale (Id): The most superior and anterior point of the bony lamella covering the lower central incisors.

Point B (Supramentale): The most posterior position of the concavity on the labial surface of the mandible in the mid line superior to Pogonion.

Pogonion (Pg): The most anterior point of the bony chin.

Menton (Me): The most inferior point on the lower border of the mandible.

Genion (Gn): The most superior point of the genial tubercles. This point should not be misinterpreted as Gnathion point which is not used in this thesis.

Conventional Cephalometric Analysis

The following group of angular measurements were used to assess the changes and stability following advancement genioplasty.

1. S-N/Pg (the angle between Sella-Nasion and Pogonion point)
2. S-N/B (The angle between Sella-Nasion and B point)
3. S-N/MP (Mandibular plane angle, the angle between Sella-Nasion and Menton-Gonion)

The Application of Finite Element Analysis:

In this study the mandible was subdivided into 4 triangular finite elements, with 5 anatomical points used as nodes for the selected finite elements (Fig. 3.21). The finite elements were defined as follows:

Element 1. Gn-Pg-Me

Element 2. Gn-B-Pg

Element 3. Gn-Id-B

Element 4. Id-Me-Gn

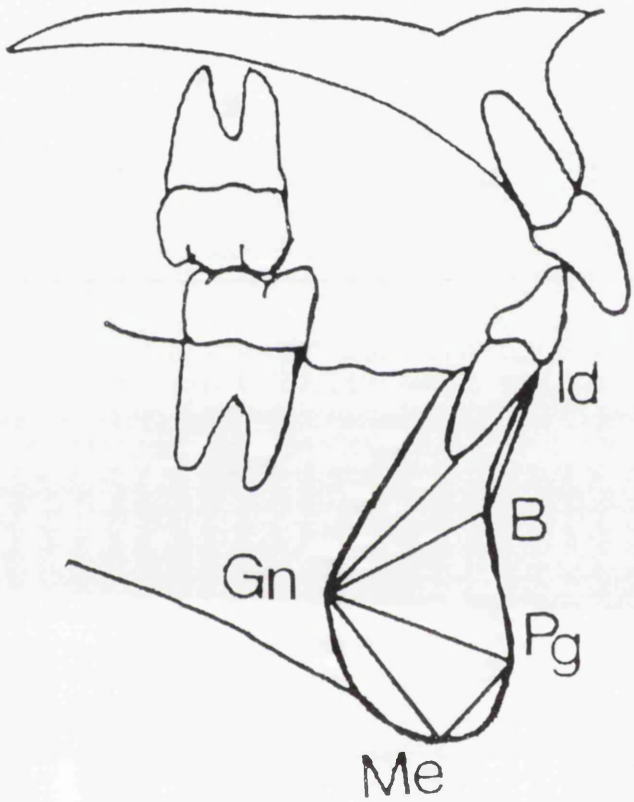


Figure 3.21 Subdivision of the anterior part of the mandible for the finite element analysis method.

Selection criteria for sagittal split mandibular advancement cases:

1. Cases which had bilateral sgaittal split advancement osteotomy with three bicortical screws in each side were evaluated.

2. Patients which had simultaneous advancement genioplasty were also considered in this study.

3. Each patient underwent sagittal split mandibular advancement had an intermediate splint at the time of taking the immediate postoperative cephalograph.

4. Patient which had any other concomitant surgery at the time of sagittal split advancement osteotomy or during the first year following surgery were excluded.

5. Cases of segmental osteotomy, hemifacial microsomia, mandibular dysystosis and cranio-facial syndromes were not considered

Application of Euclidean Distance Matrix Method

A custom written Euclidean distance matrix analysis computer program was developed for the study. The distances between each of the five points were calculated from averaged coordinate data. The Euclidean distance matrices were formed for the following occasions; preoperative (T1), immediate (T2), 6 month (T3) and final morphology at 1 year follow up (T4) of the anterior part of the mandible. The corresponding linear distances for T1/T2 and T2/T3 were compared as ratios of the later to the earlier distances. These ratios comprise the difference matrices between the pairs of occasions. The statistical significance of differences in shape was tested by the "Bootstrap" method described by Lele and Richtsmeier (1991) using a custom written computer program.

3.3.2 Sagittal split osteotomy (Canniesburn cases)

This study was carried out on 10 cases(7 female and 3 male) who had skeletal class II deformities. Two cases had had [illegible] advancement genioplasty. The patients had sagittal split mandibular advancement with rigid internal fixation using three bicortical screws in each side. The screws were consistently placed through an extraoral approach. Light interdental fixation using light elastics with an occlusal splint in place was used for up to 2 weeks. Seven patients had retrogenia in addition to mandibular retrognathia. Concomitant pedicled advancement genioplasty was also performed for those group of cases. The patient average age was 28 years (range 17 to 42). Cephalometric radiographs were obtained before surgery (T1), within one week following surgery (T2), at six months (T3), and one year (T4) following surgery. The cephalographs were taken in *norma lateralis* in the same cephalometer.

Selection criteria for bimaxillary osteotomy cases (Non-rigid fixation):

1. all the patients must had a presurgical diagnosis of vertical maxillary excess and mandibular deficiency.

2. Cases had bilateral sgaittal split advancement osteotomy with wire osteosynthesis for fixation. Simultaneously, the maxilla was impacted and kept in place using wire osteosynthesis. Maxillomandibular fixation for six weeks.

3. Patients with additional skeletal fixation were excluded.

4. Patient which had any other concomitant surgery, except advancement genioplasty, at the time of surgery or during the first year follow up were excluded.

5. Cases of segmental osteotomy, hemifacial microsomia, mandibular dysystosis, cleft lip or palate and cranio-facial syndromes were not considered

Table 3.1 shows the points digitized from each cephalograph to evaluate surgical changes and stability. Table 3.2 shows the linear and angular measurements used to assess surgical changes and stability up to one year following surgery.

Application of Finite Element Analysis:
Euclidean Distance Matrix analysis was carried out using a custom written computer program to calculate all the possible distances between the 20 points digitized. Each entire matrix has 19 by 19 components and there are four distances (one for each occasion) and three difference matrices (ratios between occasions). The statistical significance of differences in shape was tested by the method described by Lele and Richtsmeier (1991)

3.3.3 Bimaxillary osteotomy (Non-rigid fixation)

This study was carried out on 12 patients (8 females and 4 males) who had simultaneous Le Fort I maxillary impaction and mandibular advancement via a sagittal split ramus osteotomy. Their ages ranged from 28 to 44 years with an average age of 33 years. Five patients had concomitant advancement genioplasty. Lateral cephalometric radiographs were obtained preoperatively (T1), immediately after surgery (T2) when the patients were still in maxillo-mandibular fixation, at six months (T3), and one year (T4) postoperative intervals. The patients were treated at Canniesburn Hospital.

The following points were used in the evaluation and were defined according to Rakosi, (1982) Sella, Nasion, Anterior Nasal Spine, A point, Supradentale, Upper Incisal Edge, Upper Anterior Root Apex, Upper Mesial Cusp Tip, Posterior Nasal Spine, Lower Incisal Edge, Lower Anterior Root apex, Infra-dentale, Point B, Pogonion (Pg), Menton (Me), Genion (Gn), Cemento-enamel Junction of Lower Molar Mesial Cusp Tip, Gonion, Condylion.

In addition to the linear and angular measurements shown in table 3.2, Maxillary plane angle was also used in the assessment. Maxillary plane angle is the angle between Sella-Nasion and the maxillary plane (The line connecting Anterior Nasal Spine with Posterior Nasal Spine).

Application of Finite Element Analysis:

The following elements were used for the finite element analysis.

Element 1. S-ANS-PNS

Element 2. S-N-Gn

Element 3. S-N-Cd

Element 4. S-N-Go

Element 5. N-Cd-Go

Element 6. Cd-Go-Gn

Euclidean Distance Matrix analysis was carried out using a custom written computer program to calculate all the possible distances between the 20 points digitized. Each entire matrix has 19 by 19 components and there are four distances (one for each occasion) and three difference matrices (ratios between occasions). The statistical significance of differences in shape was tested by the method described by Lele and Richtsmeier (1991)

POINT	DEFINITION
Anterior Nasal Spine (ANS)	The most anterior point of the nasal floor, tip of the maxilla on the midsagittal plane.
A point	The deepest concavity below the anterior nasal spine
Posterior Nasal Spine (PNS)	The most posterior point on the conture of the bony palate.

Table 3.1 Shows the cephalometric points used to assess surgical and post-surgical changes.

POINTS	DEFINITION
Sella:	The midpoint of the sella.
Nasion:	The most anterior point of the nasofrontal suture in the median plane.
Lower Incisal Edge:	The incisal edge of the most anterior mandibular central incisor.
Lower anterior	The root apex of the most anterior mandibular central incisor.
Infra dentale:	The most superior and anterior point of the bony lamella covering the lower central incisors.
Point B:	The most posterior position of the concavity on the labial surface of the mandible in the mid line superior to Pogonion.
Pogonion (Pg):	The most anterior point of the bony chin.
Menton (Me):	The most inferior point on the lower border of the mandible.
Genion (Gn):	The most superior point of the genial tubercles.
Cemento-enamel:	The most mesial point of the cemento-enamel junction of the lower first molar.
Lower Molar Mesial Cusp Tip:	The mesiobuccal cusp tip of the lower first or second molar.
Gonion:	The intersection of the lines tangent to the posterior margin of the ascending ramus and the mandibular base.
Condylion:	Most superior point on the condyle.

Table 3.2 Shows angular and linear maesurements used to assess surgical and postsurgical changes following sagittal split osteotomy.

MEASUREMENTS	DEFINITION
ANGULAR:	
SNA	The angle between Sella-Nasion line and A point
S-N/Pg	The angle between Sella-Nasion Line and Pogonion.
SNB	The angle between Sella-Nasion line and B point.
SN/MP	Mandibular plane angle, the angle between Sella-Nasion plane and Menton-Gonion.
GONIAL	Gonial angle, the angle between Condylion-Gonion and Gonion-Menton.
RAMUS	Ramus angle, the angle between Sella-Nasion and Condylion-Gonion.
LINEAR:	
UAFH	Upper anterior facial height, the distance from Nasion to Anterior Nasal Spine.
LAFH	lower anterior facial height, the distance from Anterior Nasal Spine to Menton.
UPFU	Upper posterior facial height, the distance from Sella to Posterior Nasal Spine.
LPFH	Lower posterior facial height, the distance from Posterior Nasal Spine to Gonion.

Selection criteria for bimaxillary osteotomy cases (Rigid fixation) Canniesburn and Michigan cases:

1. All the patients must have had a presurgical diagnosis of vertical maxillary excess and mandibular deficiency.

2. The surgical procedure must have consisted of double jaw surgery with a Le Fort I maxillary impaction to correct the vertical maxillary excess and a bilateral, sagittal split ramus osteotomy to correct mandibular deficiency using rigid internal fixation.

3. Orthodontic treatment to prepare the patient for surgery and complete the correction of the occlusion following surgery is not an exclusion criteria

4. Patient which had any other concomitant segmental osteotomy at the time of surgery or during the first year follow up were excluded.

5. Cases of hemifacial microsomia, mandibular dysystosis, cleft lip or palate and cranio-facial syndromes were not considered

3.3.4 Bimaxillary osteotomy using rigid fixation (Canniesburn cases)

Fifteen patients (3 males and 12 females), with a mean age of 23 years received bimaxillary osteotomy to correct class II skeletal disproportion. The cases underwent simultaneous mobilisation of the maxilla and mandible. The maxilla was impacted about 4 mm anteriorly (range 3 to 5 mm) and 2 mm posteriorly (range 1 to 3 mm). Twelve patients had simultaneous advancement genioplasty of an average 3 mm (range 2 to 4 mm). Standard lateral cephalometric radiographs were obtained using the same cephalometer with the same magnification for each patient. The preoperative cephalograph (T1), immediate postoperative (T2), six month (T3), and one year (T4) postoperative cephalographs were used in the analysis. Cases of segmental osteotomy, cleft lip or palate and craniofacial syndrome patients were excluded from this study. All the patients had presurgical orthodontic preparation and postsurgical orthodontic adjustments to obtain maximum occlusal interdigitation.

Each patient underwent bimaxillary surgery with rigid internal fixation. The maxilla was down-fractured at the Le Fort I level and orientated to the mandible using an intermediate splint prepared at the time of model surgery. Intermaxillary wire fixation was applied temporarily to position the maxilla in a predetermined relation to the mandible. The mobilised maxilla was then repositioned and stabilised with Champy plates, two on each side at the piriform apertures and the zygomatico-maxillary buttresses. Once the maxilla was stabilised, the intermaxillary fixation and intermediate splint were removed. Intra-oral sagittal split ramus osteotomies were then carried out. The distal segment was stabilised with maxillo-mandibular fixation to a final inter-occlusal splint. The proximal mandibular segment was left in its preoperative position. Proximal and distal segment were then rigidly fixed using three bicortical position osteosynthesis screws per side. The occlusal splint is usually left fixed to the maxilla to guide the mandible into the new occlusion.

The cephalometric points selected and analyses carried out to assess surgical changes and stability were similar to those used with similar cases with non-rigid internal fixation.

3.3.5 Bimaxillary osteotomy using rigid fixation (Michigan cases)

This study was carried out on 15 patients who had simultaneous Le Fort I maxillary impaction sagittal split mandibular advancement. The cases were treated at Michigan University Hospital, Ann Arbor, Michigan, U.S.A. Nine patients had a concomitant advancement genioplasty of an average of 3.2 mm (range 2.5 to 4 mm). The average mandibular plane angle was 44.4 degrees with 89.7 mm total posterior facial height. Cephalometric radiographs were obtained before surgery (T1), within the first two weeks following surgery (T2), and at six months following surgery (T3).

The patients had the same cephalometric analysis similar to other bimaxillary osteotomy samples.

The cephalometric points selected and analyses carried out to assess surgical changes and stability were similar to those used with similar group of cases treated at Canniesburn Hospital.

Chapter 4

Results

4.1 Methodological Errors

In this study fiducal points were only used to relate the coordinates of the cephalometric points (Landmarks) on the two occasions of digitization. The error in locating fiducal points was assessed by measuring the distance between each pair on the two occasions of digitization. The group of cephalometric points used for genioplasty was used to assess methodological errors. The difference in this distance was never greater than 0.5 mm and at the limits of the accuracy of the digitizer. The residual landmark location error was calculated as the difference between coordinates of the landmarks on the first and second occasions of digitization.

Table 4.1 shows the statistical evaluation of the absolute distances between replicated digitization of the landmarks when superimposed using fiducal points.

The reproducibility of all the landmarks was high. The non-significance of Student t-tests shows there was no bias or systematic error. The high index or reliability shows that the random errors were small. The average distances between repeated digitization of points Infra-dentale and Genion were higher than for the other points. The superimposition of the overlying structures; e.g. arch bar fixation for Infra-dentale and the bone structure for Genion point, may have affected the accuracy of their identification. No systematic error in the location of the points was detected at the 90 percent confidence level (Table 4.1).

Figure 4.1 shows the relationship between replicate values of X coordinates of the digitized points. Figure 4.2 shows the same for

Error analysis for landmark coordinates

Point	X	Y	Standard Error	"t" Value	"p" Value	Index of Reliability
S	0.5*	0.7*	1.1	0.211	0.510	0.99
N	0.6	0.8	1.2	0.180	0.550	0.99
ANS	0.6	0.9	1.3	0.208	0.581	0.98
PNS	0.9	1.2	1.4	0.200	0.681	0.99
A	1.4	1.1	1.1	0.186	0.573	0.99
Go	0.9	1.2	1.3	0.298	0.582	0.99
Cd	0.8	1.1	1.2	0.180	0.560	0.99

* Differences in mm of the landmark coordinates between the first and second occasions of digitizations.

All Student t-tests were not significant at the 90% level of confidence.

Table 4.1 Error analysis for landmark coordinates

Point	X	Y	Standard Error	"t" Value	"p" Value	Index of Reliability
Id	1.1*	0.9*	1.3	0.209	0.282	0.99
B	0.9	0.7	1.4	0.180	0.570	0.99
Pg	0.8	0.6	1.3	0.208	0.581	0.98
Me	0.9	0.6	1.3	0.200	0.581	0.99
Gn	1.4	1.1	1.4	0.186	0.573	0.99

* Differences in mm of the landmark coordinates between the first and second occasions of digitizations.

All Student t-tests were not significant at the 90% level of confidence.

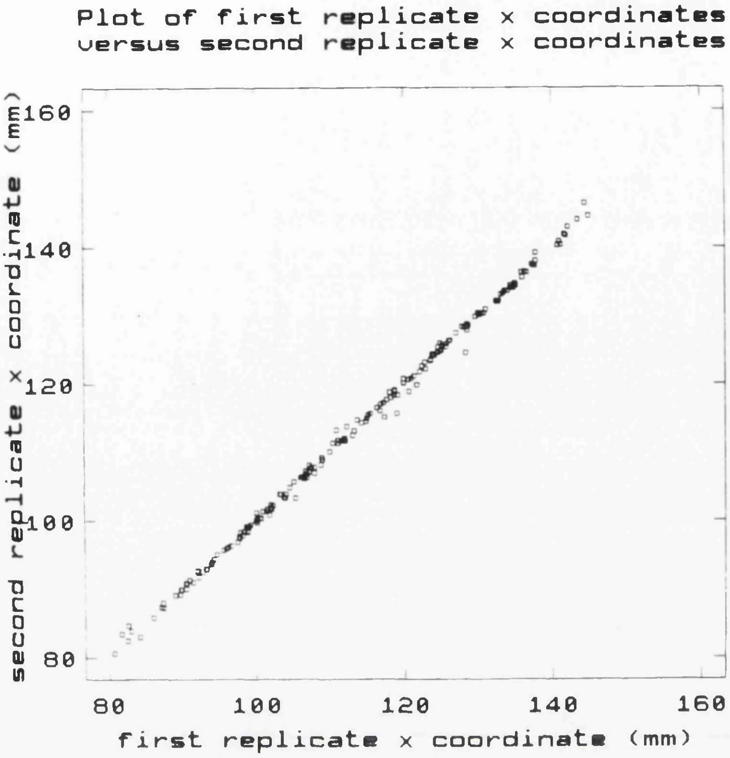


Figure 4.1 Combined scatter plot, for all landmarks used to assess genioplasty, of the first and second replicate values of X coordinates

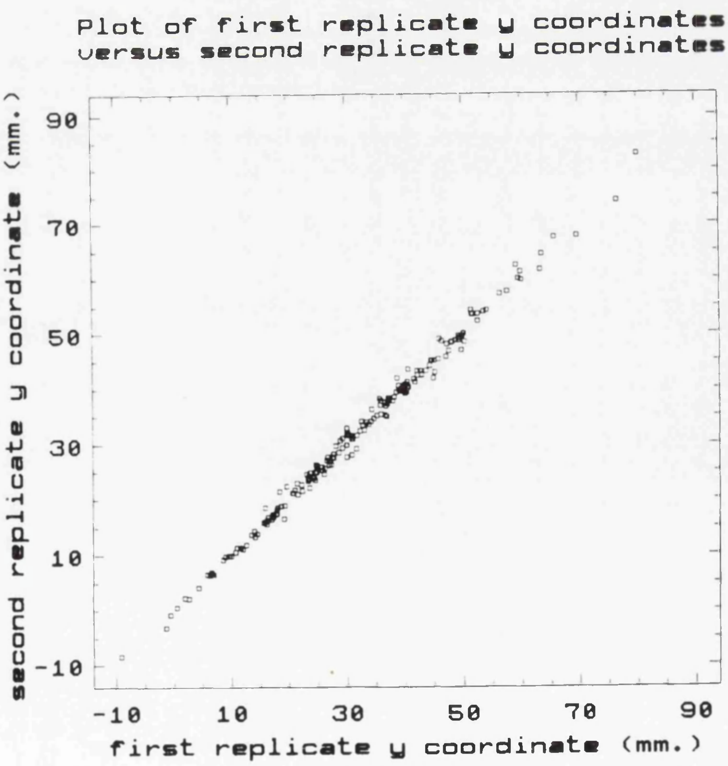


Figure 4.2 Combined scatter plot, for all landmarks used to assess genioplasty, of the first and second replicate values of Y coordinates

the Y coordinates. Both scatter plots were formed from pooling data from all subjects and for all landmarks. The scatter graphs show high consistency of successive recordings of the same landmarks from the cephalographs. This gives a visual indication of the reliability of landmark coordinates and of the validity of measuring method used.

Table 4.2 Shows the finite element analysis error assessment. For each element the variables are the maximum and minimum strains which are directed along the fulcrum of minimum and maximum deformations. A third variable "Theta", the angle between the direction of maximum strain and the natural head position, was determined in relation to the horizontal plane of the second film. Theta is derived from the direction of maximum strain with respect to one side of the element and is thus not dependent on any superimposition. However, to aid visualisation of the changes the elements were arbitrarily oriented to the natural head position vertical of the second film before being plotted.

There was no systematic error for the finite element components at 90 percent confidence level except for minimum strain of the element Pg-Me-Gn. However, the random errors were very large. The calculation of the minimum and maximum strains for finite elements is very sensitive to small changes in landmark location. Despite the indices of reliability were at least 0.98 the precision of recording the cephalometric landmarks was not sufficient for reproducible calculation of the strain components on an individual basis. However, when the cases were averaged and the strains calculated accordingly, the results were reasonably reproducible. ?

Table 4.2 The difference in components of FEA for each of the three genioplasty elements between the first and second occasions of digitization of pre and post operative films.

Finite Element	Mean Difference	"t" Value	"p" Value	Index of Reliability
Id-B-Gn				
Maximum Strain	-1.52	0.959	0.350	0.296
Minimum Strain	-0.01	1.049	0.308	0.043
Theta	-1.03	0.161	0.874	0.473
B-Pg-Gn				
Maximum Strain	-3.60	0.949	0.355	0.298
Minimum Strain	0.01	0.223	0.826	0.102
Theta	-13.20	1.263	0.222	0.470
Pg-Me-Gn				
Maximum Strain	7,66	0.918	0.371	0.156
Minimum Strain	0.01	0.100	0.922	0.667
Theta	14.79	1.498	0.151	0.125

The differences between the finite element results after averaging the 19 first and 19 second occasions of digitization were small. Table 4.3 showed that results were relatively stable on the two occasions of digitization.

Error analysis for Euclidean Distance Matrix method was assessed by analysing the indices of shape change that arise from the genioplasty surgery for each individual patient. The before and after surgery radiographs were digitized on four separate occasions. The first with the second and the third with the fourth occasions were averaged to produce two sets of coordinates. Each set being produced in the same manner as the sets of averaged coordinates used subsequently in this study for the assessment of surgical changes. From these sets of data, matched pairs of indices of shape change were calculated for each of the 19 patients. The differences between these were tested for bias using Student t-test. The mean difference in the indices was 0.021 with a t value of 0.659 which is not significant at the 10% level of confidence and it is therefore reasonable to assume no systematic error. The level of random error was examined using the index of reliability, the value of this was 0.97 which indicates acceptable low level of random error.

4.2 Advancement Genioplasty

It is quite difficult to interpret surgical changes and stability of the genial segment using conventional cephalometric measurements when concomitant maxillo-mandibular surgery is carried out. The changes in mandibular spatial position secondary to maxillary or mandibular osteotomy camouflage other changes due to genioplasty when an external reference plane is used for the assessment. Sella-

Table 4.3 Error analysis for the Finite Element Components.

Finite Element	First occasion of Digitization	Second occasion of Digitization
Id-B-Gn		
Maximum Strain	2.14	2.16
Minimum Strain	0.09	0.09
Theta	62.6	62.1
B-Pg-Gn		
Maximum Strain	3.09	2.87
Minimum Strain	0.03	0.027
Theta	70.1	67.5
Pg-Me-Gn		
Maximum Strain	2.29	3.1
Minimum Strain	0.04	0.042
Theta	14.4	15.2

Nasion line, Frankfort plane or any other external reference plane would not allow separation of changes at the chin area due to genioplasty from those secondary to the concomitant maxillary or mandibular surgery. Le Fort I maxillary osteotomy and/ or sagittal splitting of the mandible will change the horizontal and vertical positions of the mandible. Therefore, conventional cephalometric analysis using linear and angular measurements would not be useful to assess surgical and postsurgical changes due to genioplasty. Even the linear distances from Pogonion and Menton to occlusal plane are not useful measurements as both horizontal and vertical changes in the genial segment position occur and measurements in just the vertical plane can not reflect this bi-directional movement. Moreover, the reliability of dental points that defined the occlusal plane are also doubtful. These points are often masked by arch bars and occlusal splints which affect the precision of their recording and consequently their reproducibility. Orthodontic tooth movements during the course of treatment also jeopardise the value of the occlusal plane as a reference plane.

Nevertheless, conventional cephalometric analysis was included to compare the results of this investigation with previous studies. It will also help those who are unfamiliar with the recent techniques of morphometric analysis to interpret the results (Table 4.4).

The averaged coordinates of the five points (Infra-dentale, B point, Pogonion, Menton, Genion) from the 19 subjects who had advancement genioplasties were used in the analysis. The five points were employed as nodes for the finite elements. Genion is used as an anchor node, it is not affected by surgery, thus the

Table 4.4 Surgical changes (T1-T2) following advancement genioplasty using linear and angular measurements.

Angular measurements	T1 Mean	SD	T2 Mean	SD	Differences
SNPg	77.3	5.9	78.7	4.1	1.4
SNB	77.1	5.3	75.9	4.3	-1.2
SN/MP	43.5	8.3	40.7	6.3	-2.8
Ramus	133.8	16.1	121.2	12.1	-12.6
Linear measurements					
Pg/Occ	38.7	5.4	35.6	4.1	-3.1
Pg/S-N	123.3	12.4	121.8	9.7	-1.5
Me/Occ	44.8	3.9	42.7	3.8	-2.1
Me/S-N	127.9	11.4	127.6	9.5	-0.3

MP (Mandibular Plane Angle)

T1 Preoperative assessment

T2 Immediate postoperative evaluation

principal strains can be interpreted in relation to the other two nodes of the triangular elements.

4.2.1 Surgical Changes (T1-T2)

4.2.1.1 Finite Element Analysis

Figures 4.3 a & b show the elements used to evaluate surgical changes following advancement genioplasty.

A. Element Gn-Pg-Me:

The maximum principal strain is parallel to the Genion-Pogonion line which represents the direction of surgical advancement of the genial segment. The minimum strain is within the measurements error. The strains of these elements should be interpreted with caution, the elements sides are short with very obtuse angles which may cause exaggeration of the strains values.

B. Element Gn-B-Pg:

The maximum principal strain is almost parallel to Pogonion-Genion line due to surgical advancement of the genial segment. The minimum strain is due to vertical changes in the element. Its orientation is at right angle to the direction of the genial segment advancement which resulted from the anti-clockwise rotation of the advanced segment that shortened the distance between B point and Pogonion.

C. Element Gn-Id-B:

The changes in this element are within digitization error.

Figure 4.3a

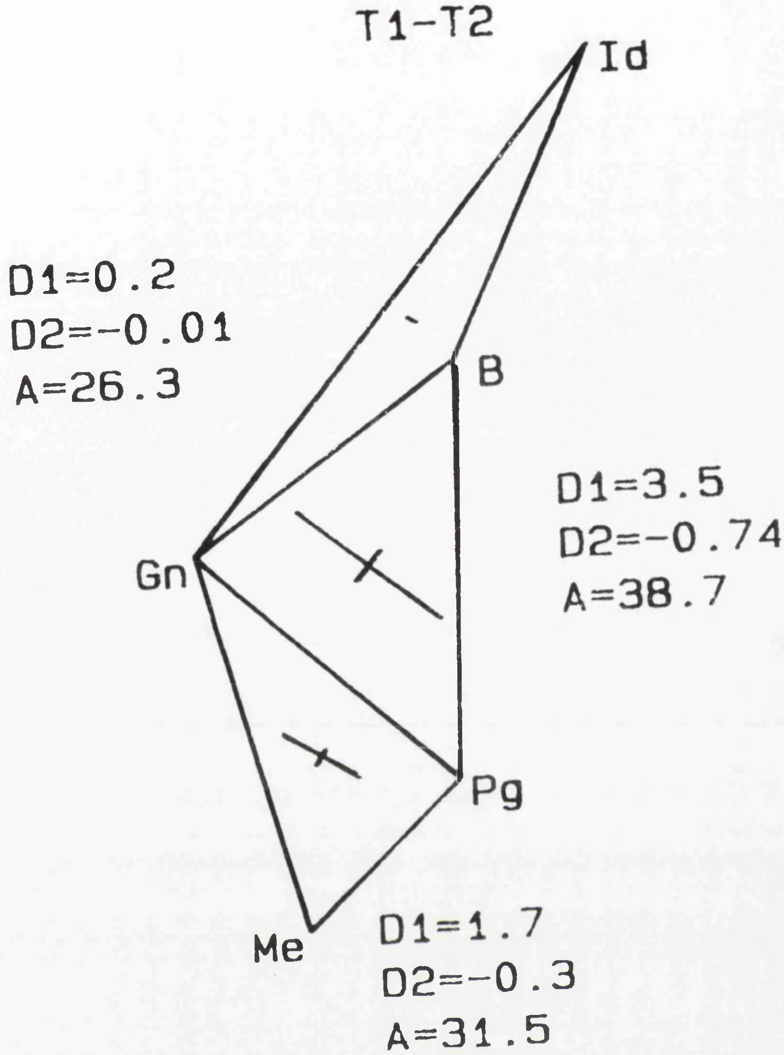
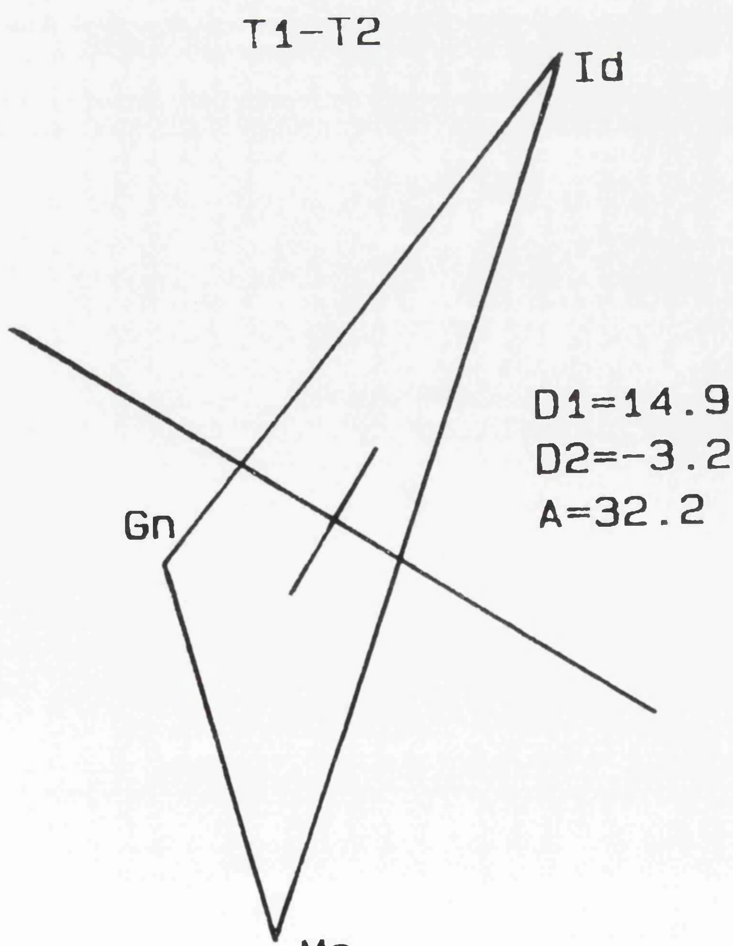


Figure 4.3b



Figures 4.3 a & b Finite elements used to assess surgical changes (T1-T2) following advancement genio-plasty.

D. Element Id-Me-Gn

The maximum principal strain is almost perpendicular to the line Infra-dentale-Menton which is coincide with the direction of advancement of the genial segment. The vertical minimal strain is due to anterior and upward rotation of the osteotomized segment reducing the total mandibular vertical height.

4.2.1.2 Euclidean Distance Matrix Analysis

The main surgical change was the forward sliding of the genial segment along a diagonal line parallel to the osteotomy plane, as shown by a 3.8 mm increase in the distance Menton-Genion (Table 4.5). The ratio of increase in the distance Genion-Pogonion was more than that of Genion-Menton distance. This is explained by the osteotomized segment having rotated slightly in an anti-clockwise direction with decrease of the vertical mandibular height (B-Menton distance) by 2 mm. The average 2 mm. reduction of the vertical mandibular height (B-Menton distance) was equal to the width of the surgical bur used for the bone cut. Surgery has resulted in a statistically significant change in morphology with an index of shape change 5.23 which was statistically significant when tested with Bootstrap technique ($p < 0.02$).

4.2.2 Changes at 6 months follow up (T2-T3)

4.2.2.1 Finite Element Analysis

Figures 4.4 a & 4.4 b show the elements used to assess postsurgical changes at the 6 months follow up check.

Table 4.5 Surgical changes following anterior advancement genioplasty (T1-T2) using EDMA

Point 1	Point 2	Dist T1	Dist T2	Ratio
Id	B	12.71	13.88	1.09
Id	Pg	27.19	25.15	0.92
Id	Me	34.49	33.07	0.96
Id	Gn	23.73	22.77	0.96
B	Pg	15.24	13.74	0.90
B	Me	22.01	19.97	0.91
B	Gn	11.37	10.16	0.89
Pg	Me	07.93	09.21	1.16
Pg	Gn	11.06	16.61	1.50
Me	Gn	14.01	17.84	1.27

T1 Preoperative assessment

T2 Immediate postoperative evaluation

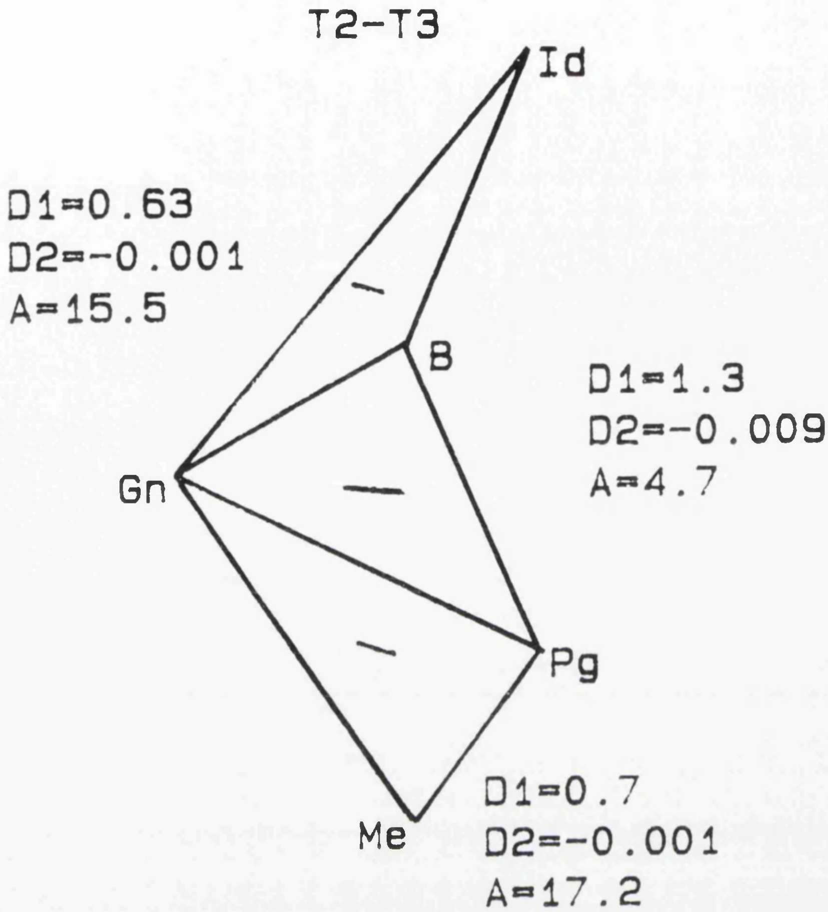


Figure 4.4a

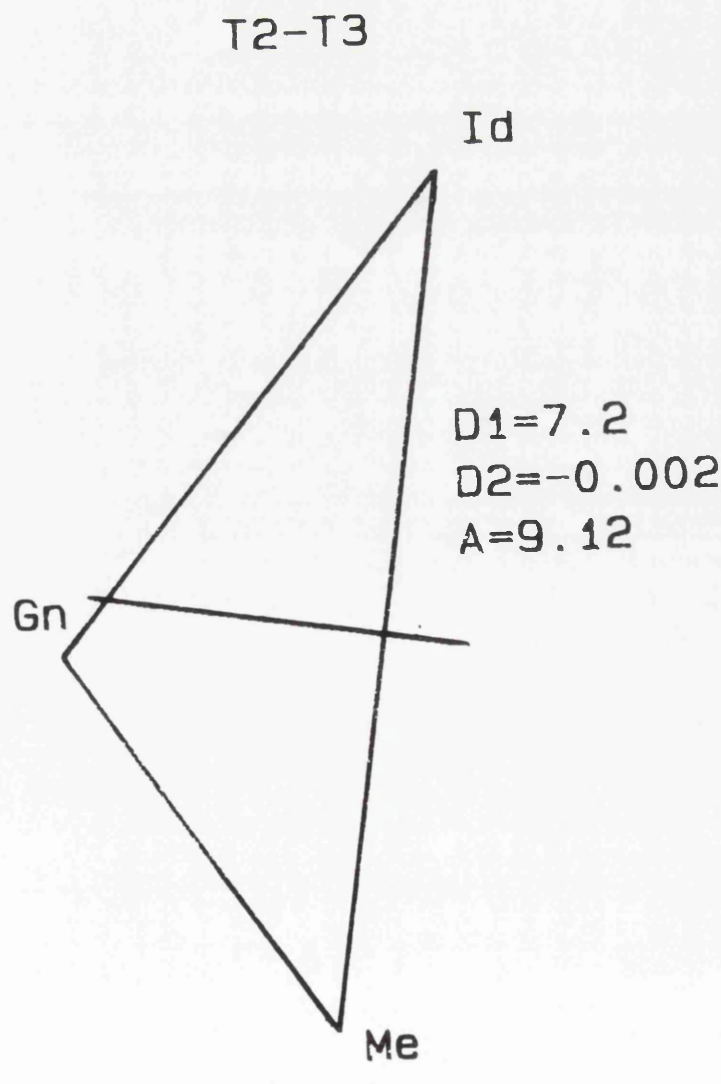


Figure 4.4b

Figures 4.4 a & b Show changes at 6 months (T2-T3) following advancement genioplasty.

A. Element Gn-Pg-Me:

The principal strain runs parallel to Pogonion-Genion line. This is most probably due to local remodelling of the mobilised segment in the form of bone apposition at Pogonion. No significant changes were detected in the vertical direction.

B. Element Gn-B-Pg:

The principal strain in this element is affected by bone apposition at Pogonion and on the outer surface of the mandible superior to the advanced segment. The orientation of the principal strain is more horizontal than the direction of the principal strain of the element Gn-Pg-Me. It will also be due to any movement of the genial segment affecting the position of Pogonion.

C. Element Gn-Id-B:

The principal strain is parallel to that of the element Gn-Pg-Me. It represents a similar bone remodelling in the form of bone apposition on the outer surface of the mandible superior to the advanced segment.

D. Element Id-Me-Gn

The principal strain is mostly horizontal in direction. This implies that postsurgical changes at Menton are in antero-posterior direction with minimal changes in the mandibular vertical height along Infra-dentale and Menton.

Bone remodelling was monitored by changes in the relationship of nodal points (landmarks) to each other in a given finite element whereas repositioning is identified by changes detected in the adjacent elements with shared nodes. Despite the bone apposition at Pogonion seen in the Element Pg-Me-Gn (T2-T3), Pogonion position was also affected by repositioning of the whole genial segment. Changes at Pogonion due to repositioning of the advanced segment were identified through the element Id-Me-Gn. Because Infra-dentale and Genion were relatively fixed points and were not affected by genioplasty, any change in the element Id-Me-Gn is due to positional change at Menton which has moved away from Genion. This can be only explained by a rotation of the genial segment around its contact with the anterior surface of the mandible. Examination of the radiographs showed bone resorption at the superior surface and the posterior inferior corner of the advanced segment (Figs. 4.5a & 4.5b).

The principal strains of the elements Gn-Pg-Me & Gn-Id-B were approximately parallel to each other due to bone apposition at B point and Pogonion. The direction of the major deformation in the Gn-B-Pg element was about 12 degrees different from these. This indicates that the angle of rotation of the genial segment was approximately 12 degrees. Thus Menton point also has rotated in an anti-clockwise direction during the first six months postsurgery. This was a rotation of the genial segment upward and forward occurring with a minimal vertical component. This affected the position of Pogonion and the principal strain seen in the element B-Pg-Gn was interpreted as a mixture of local remodelling (apposition) and repositioning of Pogonion (Figs. 4.5 a & b). This postsurgical forward and upward rotation of the genial segment may be the result of postero-superior action and shortening of the mentalis muscles. These muscles were stripped from the

Figure 4.5a

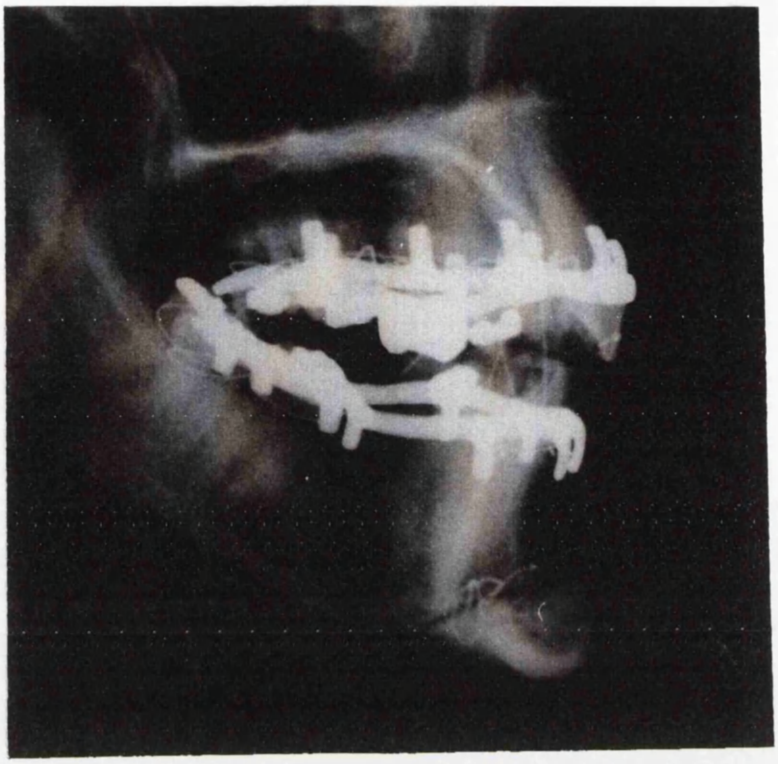
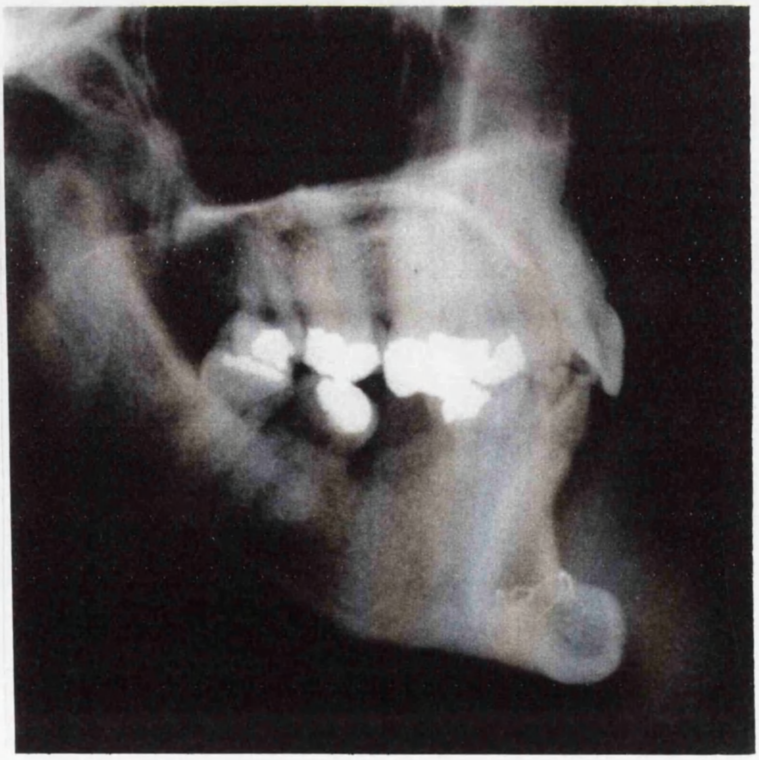


Figure 4.5b



Figures 4.5 a & b
Radiographs of a patient following advancement genioplasty.

underlying genial bone during surgery and became reattached to the advanced segment. Scarring and shortening of this muscle is a possible explanation of mechanism by which rotation of the genial bone segment occurred and could also explain the bone resorption seen radiographically at the superior surface of the advanced segment.

4.2.2.2 Euclidean Distance Matrix Analysis

Local remodelling of the genial segment occurred with bone apposition at Pogonion and B-point. The apposition showed as an increase in B-Genion and Pogonion-Menton distances (Table 4.6). Bone remodelling was monitored by measuring changes in the distances between landmarks in the same segment of bone. Whereas, repositioning was identified by changes detected in the distances connecting points on adjacent bone segments. Slight anti-clockwise rotation of the whole genial segment was also detected by an increase in the Genion-Menton distance and a decrease in the B-Pogonion distance. However, the average advancement and mandibular vertical height were stable within 0.5 mm. Although the changes detected were of some interest, they were neither clinically important nor did they reach statistical significance ($p=0.12$) for index of shape change 2.02.

4.2.3 Changes at 1 year follow up (T3-T4)

4.2.3.1 Finite Element Analysis

The minimal changes detected in all the elements were within the method error (Figs. 4.6a, 4.6b)

Table 4.6 Changes at six months following advancement genioplasty (T2-T3) using EDMA

Point 1	Point 2	Dist T2	Dist T3	Ratio
Id	B	13.88	13.02	0.94
Id	Pg	25.15	25.94	1.03
Id	Me	33.07	32.87	0.99
Id	Gn	22.77	21.91	0.96
B	Pg	13.74	14.93	1.09
B	Me	19.97	20.53	1.03
B	Gn	10.16	10.17	1.00
Pg	Me	09.21	08.27	0.90
Pg	Gn	16.61	16.92	1.02
Me	Gn	17.84	18.21	1.02

T2 Immediate postoperative evaluation

T3 Assessment at 6 months follow up

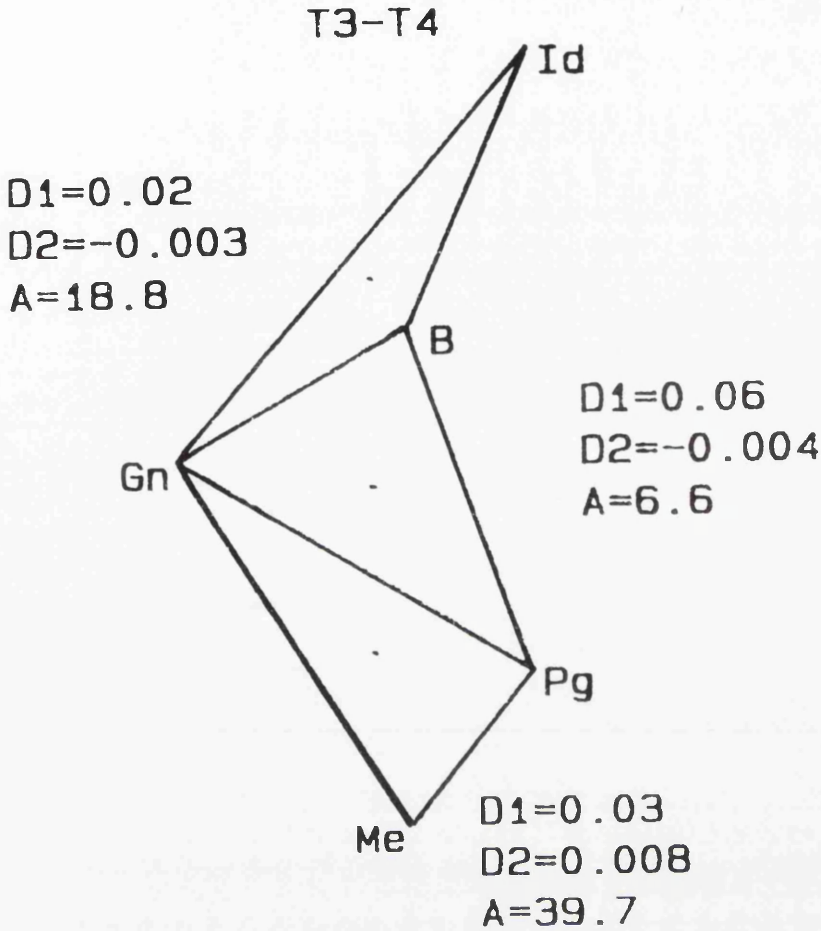


Figure 4.6a

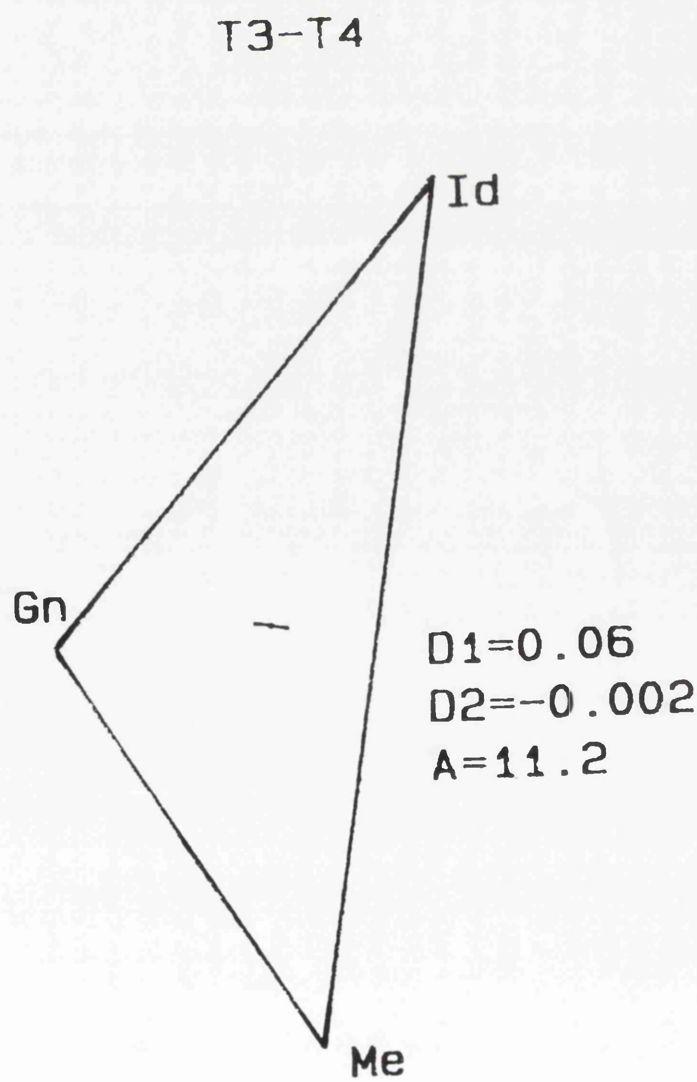


Figure 4.6b

Figures 4.6 a & b Show changes at one year (T3-T4) following advancement genioplasty.

4.2.3.2 Euclidean Distance Matrix Analysis

The average changes were all less than 0.2 mm. and within measurement error.

Figure 4.7 shows the profile before and after advancement genioplasty and at 1 year follow up of a case that was evaluated in this study.

4.3 Sagittal split osteotomy (Canniesburn)

Table 4.7 shows the group of linear and angular measurements used to assess surgical and postsurgical changes following sagittal split advancement osteotomy. Figures 4.8, 4.9 & 4.10 show the finite elements used to evaluate surgical changes and stability. Table 4.8 illustrates the entire matrix of EDMA used in the study. It consists of 9 distances at three occasions (T1, T2, T3) and three difference matrices (ratios between occasions). The index of shape difference for surgical changes was 3.6 with $p<0.001$ (Bootstrap). For the immediate to six months postoperative period, the index of shape change was 2.5 with $p<0.01$ (Bootstrap). However, the changes from 6 month to one year were not significant, the index of shape change was 3.5 and $p>0.05$.

4.3.1 Surgical changes (T1 - T2)

4.3.1.1 Conventional Cephalometric Analysis

The main surgical changes are clockwise rotation and advancement of the distal segment of 0.8 degrees and 4.5 degrees respectively. This increased the lower anterior face height by 2.3 mm. The proximal segment rotated in an anti-clockwise direction which

Table 4.7 Linear and angular measurements used to assess sagittal split advancement osteotomy.

Angular Measurements:

	T1	T2	T3	T4
SNA	82.7/5.1*	82.7/5.1	82.7/5.1	82.7/5.1
SN/Pg	74.9/4.5	79.8/3.2	78.8/3.5	78.6/3.3
SNB	73.6/4.4	78.1/3.2	77.1/4.4	76.9/3.5
SN/MP	33.5/7.2	34.3/7.3	35.7/7.8	35.8/7.3
GON	119.1/6.8	124.4/5.8	125.1/4.1	125.8/4.4
RAMUS	94.4/5.9	89.9/7.2	90.5/6.3	90.3/6.4

Distances

UAFH	53.0/3.8	53.1/3.8	53.6/3.0	53.9/2.3
LAFH	66.2/7.9	68.5/8.8	69.2/7.5	69.7/7.8
UPFH	48.6/5.1	48.7/5.1	48.9/5.0	50.0/5.0
LPFH	44.6/5.8	44.4/5.9	40.9/5.5	40.8/6.5

MP (Mandibular Plane),
GON (Gonial angle),
UAFH (Upper Anterior Facial Height),
LAFH (Lower Anterior Facial Height),
UPFH (Upper Posterior Facial Height),
LPFH (Lower Posterior Facial height).

*** Each measurement represents mean / standard deviation**

T1 Preoperative assessment

T2 Immediate postoperative evaluation

T3 Assessment at 6 months follow up

T4 Assessment at 1 year follow up

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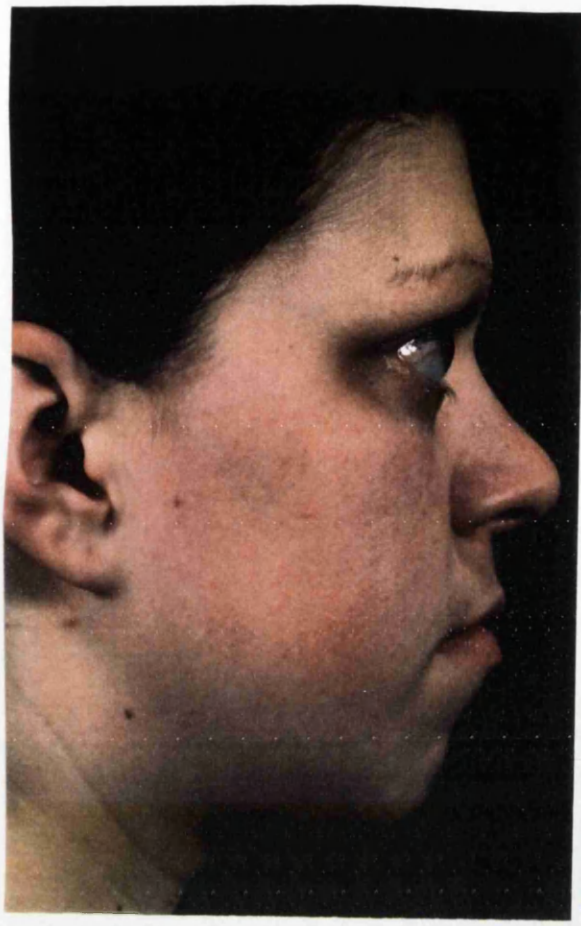


Figure 4.7 a

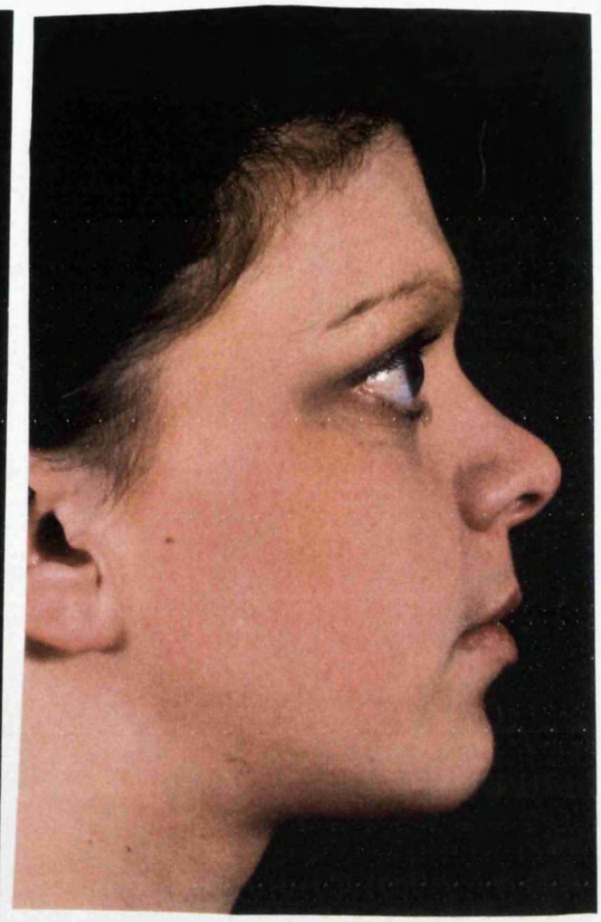


Figure 4.7 b

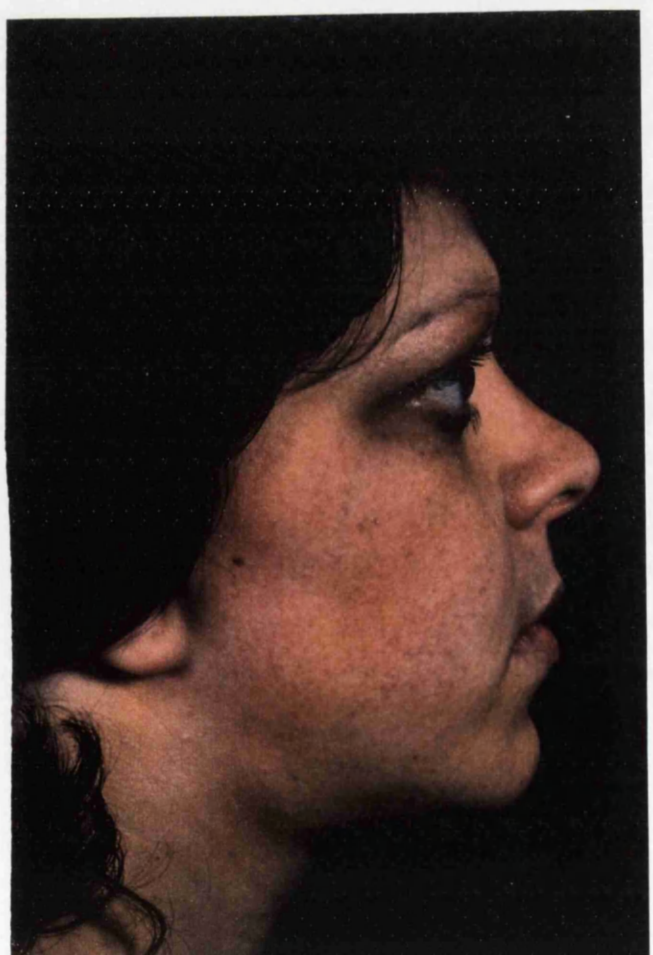


Figure 4.7 c

Figure 4.7 a, b & c
Pre and postoperative profile of one of the cases who had advancement genioplasty.

decreased the ramus angle by 4.5 degrees. The combined effect of the proximal and distal segments rotation in different directions increased the gonial angle by 5.3 degrees (Table 4.7).

4.3.1.2. Finite element analysis

A. Element S-N-Gn (Fig. 4.8)

This element illustrates the relationship of the distal segment to the base of the skull. The principal strain is almost parallel to Sella-Genion line. This represents the direction of surgical changes of the distal segment which is a combination of advancement and rotation. The minimum strain shows the change of Genion in relation to Nasion that resulted from clockwise rotation of the distal segment.

B. Element Cd-Go-Gn (Fig. 4.9)

This element demonstrates the surgical changes between the proximal and distal segments. The maximum strain bisects both Go-Cd-Gn angle and Gonion - Genion line. This represents a combination of posterior displacement of the proximal segment, measured at Condylion, and anterior advancement of the distal segment measured at Genion. The minimal strain is bisecting the angle Cd,Go,Gn which is explained as the anatomical transpositioning of Gonion due to surgery.

C. Element S-N-Cd (Fig. 4.10)

The element describes the change in the relationship between the condyle and the base of the skull. The principal strain shows the direction of condylar displacement during surgery. The direction of this strain is not quite vertical and is a result of a combination of posterior and inferior displacement of the condyle. The inferior

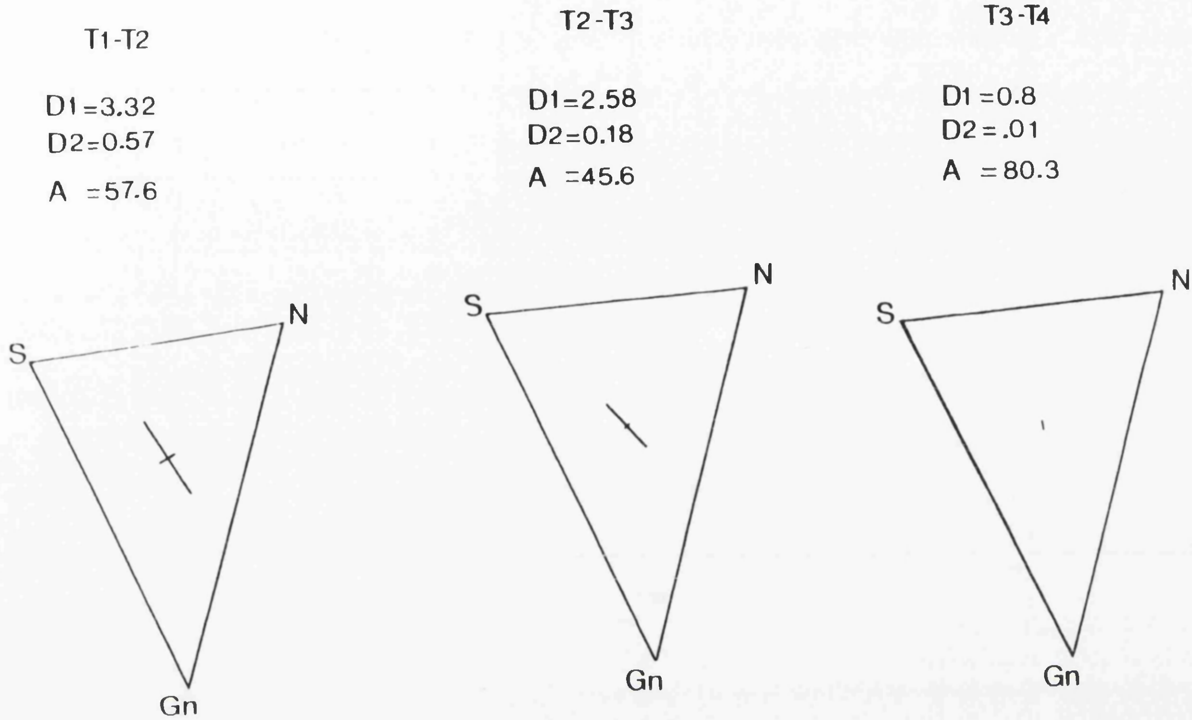


Figure 4.8
The finite element S-N-Gn used to assess surgical and postsurgical changes following sagittal split advancement osteotomy

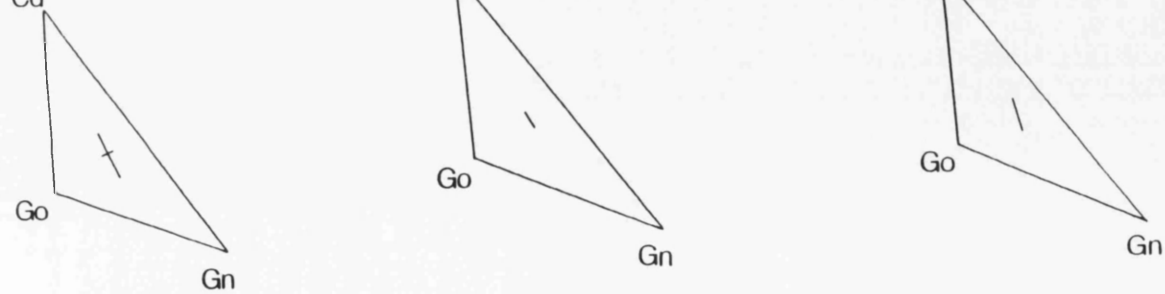


Figure 4.9
The finite element Cd-Go-Gn used to assess surgical and postsurgical changes following sagittal split advancement osteotomy

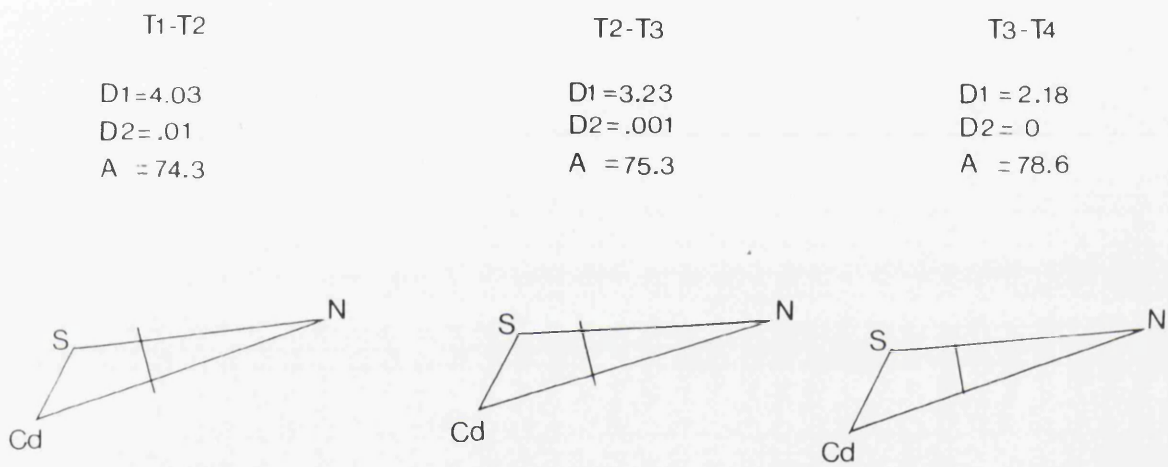


Figure 4.10
The finite element S-N-Cd used to assess surgical and postsurgical changes following sagittal split advancement osteotomy.

displacement of the condyle resulted from the use of occlusal splint for all the patients at the time of taking the immediate postoperative cephalograph.

4.3.1.3. Euclidean Distance Matrix Analysis

The mandible advanced about 6.5 mm as is measured by the distance Sella-Genion. The condyle was displaced posteriorly and inferiorly which was detected by increase in the Sella-Condylion and Nasion-Condylion distances by 0.9 mm and 1.2 mm respectively. This was partially due to the occlusal splint that held the condyles more inferiorly than their presurgical anatomical positions (Table 4.8).

4.3.2 Changes at 6 months follow up (T2 - T3)

4.3.2.1 Conventional Cephalometric Analysis

The mandible rotated in a clockwise direction with increase of both the mandibular plane angle and ramus angle by 1.4 degrees and 0.6 degree respectively. This was associated with increase of the gonial angle by 0.7 degree which resulted from local bone resorption at Gonion. The rotation of the mandible in a clockwise direction was associated with posterior shifting that decreased SNB angle by two degrees (Table 4.7).

4.3.2.2 Finite element analysis

A. Element S-N-Gn (Fig. 4.8)

The direction of the principal strain is due to the combined effect of posterior and superior transpositioning of Genion that resulted from clockwise rotation of the distal segment. The principal strain D1 is

Table 4.8: Components of the Euclidean Distance Matrices for assessment of sagittal split advancement osteotomy.

End Point Landmarks	Distances (mm.) on Occasion			Ratios of distances between occasions	
	T1	T2	T3	(T1/T2)	(T2/T3)
S Cd	24.8	25.7	27.0	1.03	1.04
S Gn	101.9	108.4	106.9	1.07	0.98
S B	101.0	109.9	107.2	1.09	0.97
N Cd	89.6	90.8	89.8	1.01	0.99
Gn Cd	89.3	96.2	93.0	1.08	0.97
Go Cd	55.4	55.8	53.6	1.01	0.96
Gn Go	55.2	59.0	59.0	1.07	1.00
N Gn	106.1	108.1	106.4	1.02	0.98
N Go	116.5	114.4	113.4	0.99	0.98
N Cd	89.1	90.2	89.2	1.03	1.03

T1 Preoperative assessment

T2 Immediate postoperative evaluation

T3 Assessment at 6 months follow up

more horizontally oriented (A=45.6) in comparison with its direction in the same element in the interval T1-T2. This shows that at 6 months follow up the vertical changes at Genion are less than vertical changes due to surgery.

(B) Element Cd-Go-Gn (Fig. 4.9)

The Element represents the remodelling changes between proximal and distal segments. The principal strain is parallel to Condylion-Genion line. This change is probably due to remodelling of the condylar surface.

(C) Element S-N-Cd (Fig. 4.10)

The principal strain is due to the combined repositioning and remodelling of the condyle. The direction of the principal strain is similar to its direction in the same element in the interval T1-T2. This indicates the condyle has almost returned to its former position before surgery.

4.3.2.3 Euclidean Distance Matrix Analysis

The distance Condylion-Genion decreased by 3.2 mm which is due to local resorption at the condylar superior surface. Removal of the occlusal splint would bring the condyles in a more superior position in their fossae. However, the distance Sella-Condylion is increased by 1.3 mm which means that the change is possibly caused by resorption of the condylar surface is more than the magnitude of superior shifting of the condyle due to occlusal splint removal. The condyle shifted anteriorly 1 mm shown by decrease of the distance Nasion-Condylion. The distance Nasion-Gonion decreased by 1 mm probably due to resorption at Gonion from ptrygo-masseteric pressure (Table 4.8).

4.3.3 Changes at 1 year follow up (T3-T4)

4.3.3.1 Conventional Cephalometric Analysis

The mandibular position was quite stable, the only change detected is the increase in gonial angle of 0.7 degrees. This is possibly due to further remodelling at Gonion that resulted in increase in the angle between the proximal and distal segments.

4.3.3.2 Finite element analysis

A. Element S-N-Gn (Fig. 4.8)

Changes detected were within measurement error

B. Element Cd-Go-Gn (Fig. 4.9)

The principal strain is due to combined remodelling at Condylion and Gonion. The amount of postsurgical changes seen in this element (D1=1.77) are more than that observed at 6 months follow up. More bone remodelling is detected at one year postsurgery. The principal deformation should not be misinterpreted as clockwise rotation of the distal segment since the vertical and horizontal positions of Genion were unchanged.

C. Element S-N-Cd (Fig. 4.10)

The orientation of the principal strain is almost parallel to the direction of the principal strain in the same element at 6 months follow up (T2-T3) (Fig. 4.10). This can be explained by further bone remodelling at the condylar surface.

4.3.3.3 Euclidean Distance Matrix Analysis

The only postsurgical change that was detected at one year follow up was the increase in Sella-Condylion and Sella-Gonion distances by 0.7 mm and 0.5 mm respectively. Again bone remodelling at the superior condylar surface and at Gonion is a possible cause.

Figure 4.11 is for one of the cases who had sagittal split advancement osteotomy with rigid internal fixation. The radiographs show the profile and face before surgery, immediately after surgery and at 1 year follow up.

No correlation existed between the magnitude of mandibular relapse as it measured by change in SNB angle (T2-T3) and preoperative mandibular plane angle. The magnitude of mandibular clockwise rotation during surgery did not correlate to mandibular relapse.

4.4 Bimaxillary osteotomy with non-rigid fixation

Table 4.9 shows the group of angular and linear measurements used to assess surgical and postsurgical changes. Figures 4.12, 4.13, 4.14 & 4.15 show the finite elements used to assess surgical and postsurgical changes. Table 4.10 Shows components of the matrices used to conduct the Euclidean distance matrix analysis. Each entire matrix has 19 by 19 components and there are four distance (one for each occasion) and three difference (ratios between occasions) matrices. Thus it is impractical to publish them in full and only components highlighted in the discussion are presented. The index of shape difference for the surgical changes was statistically significant with $p<0.004$ (Bootstrap). For the immediate to six months postoperative period, the changes were also

Table 4.9 Linear and angular measurements used to assess surgical and post-surgical changes of bimaxillary osteotomy cases with non-rigid fixation

Angular Measurements:

	T1	T2	T3	T4
SNA	80.2/5.7*	82.4/4.9	80.6/5.1	80.4/5.1
SN/Pg	75.5/4.9	80.8/3.6	79.9/3.9	79.8/4.1
SNB	74.4/4.9	78.5/3.9	77.7/4.5	77.5/4.5
SN/MP	39.0/9.1	35.8/7.1	37.7/7.8	38.6/8.2
GON	122.3/6.2	125.5/5.3	126.1/4.5	127.2/4.3
RAMUS	96.8/6.6	90.4/7.7	91.4/6.2	91.2/7.1
MAX	7.2/5.4	6.2/3.8	5.5/5.2	6.1/4.4

Distances

UAFH	56.0/4.4	55.1/3.6	54.6/3.0	53.9/2.3
LAFH	75.2/8.2	73.9/8.7	73.1/9.7	72.5/9.8
UPFH	51.5/5.4	51.9/4.9	51.8/5.0	51.9/5.0
LPFH	46.7/6.0	46.6/5.9	43.6/6.5	43.2/6.5

MP (Mandibular Plane),
GON (Gonial angle),
MAX (Maxillary plane angle),
UAFH (Upper Anterior Facial Height),
LAFH (Lower Anterior Facial Height),
UPFH (Upper Posterior Facial Height),
LPFH (Lower Posterior Facial height).

* Each measurement represents the mean/standard deviation.

T1 Preoperative assessment

T2 Immediate postoperative evaluation

T3 Assessment at 6 months follow up

T4 Assessment at 1 year follow up

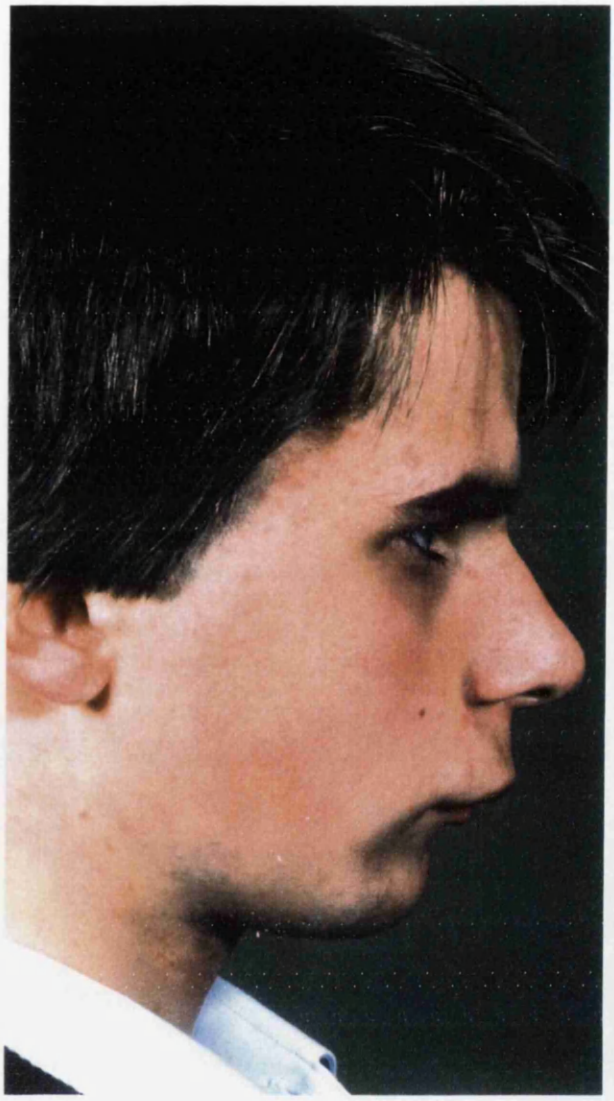


Figure 4.11 a

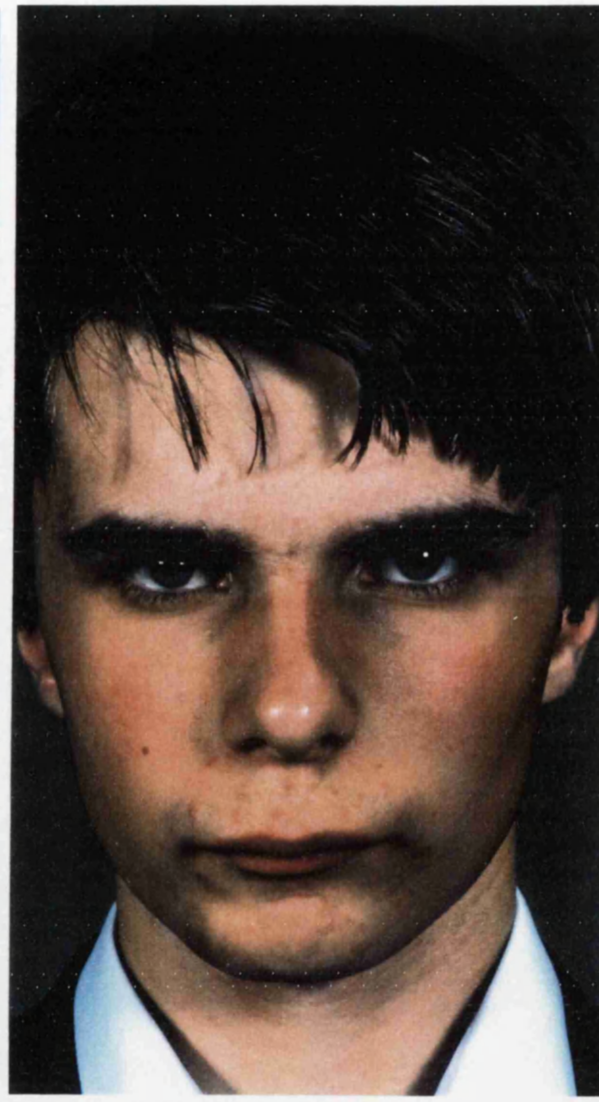


Figure 4.11 b

Figures 4.11 from a to i show facial views and lateral cephalographs of one of the cases who had sagittal split advanced osteotomy; a & b are the preoperative facial views; c shows the immediate postoperative profile, d profile at 1 year follow up; e shows the immediate postopertive frontal view; f frontal view at 1 year follow up; g preopertive cephalograph; h immediate postoperative cephalograph; i cephalograph at 1 year follow up.

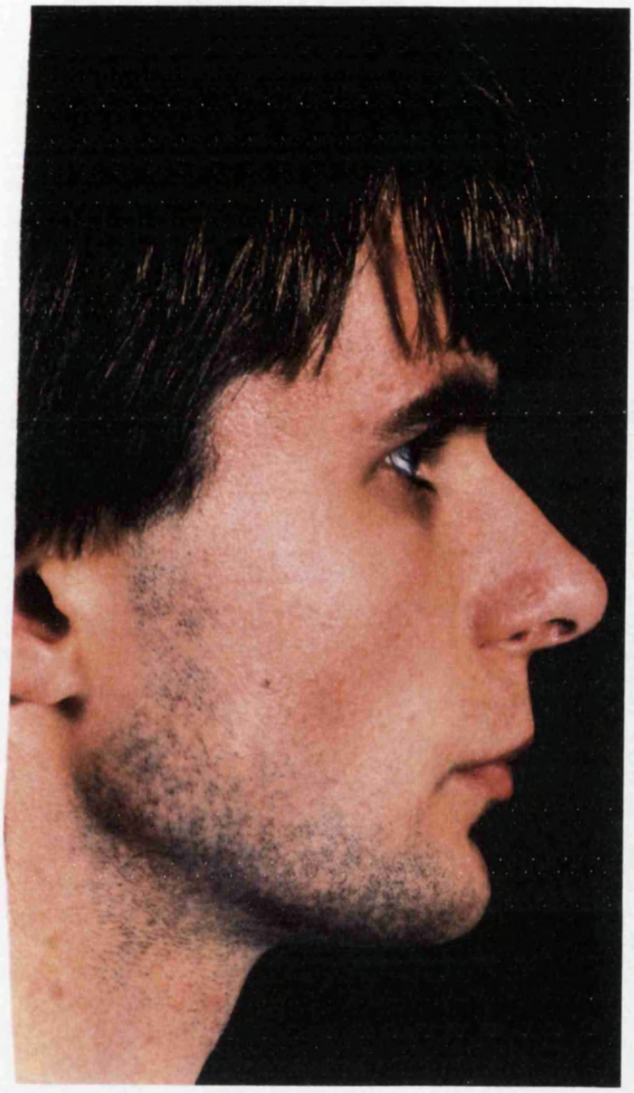


Figure 4.11 c

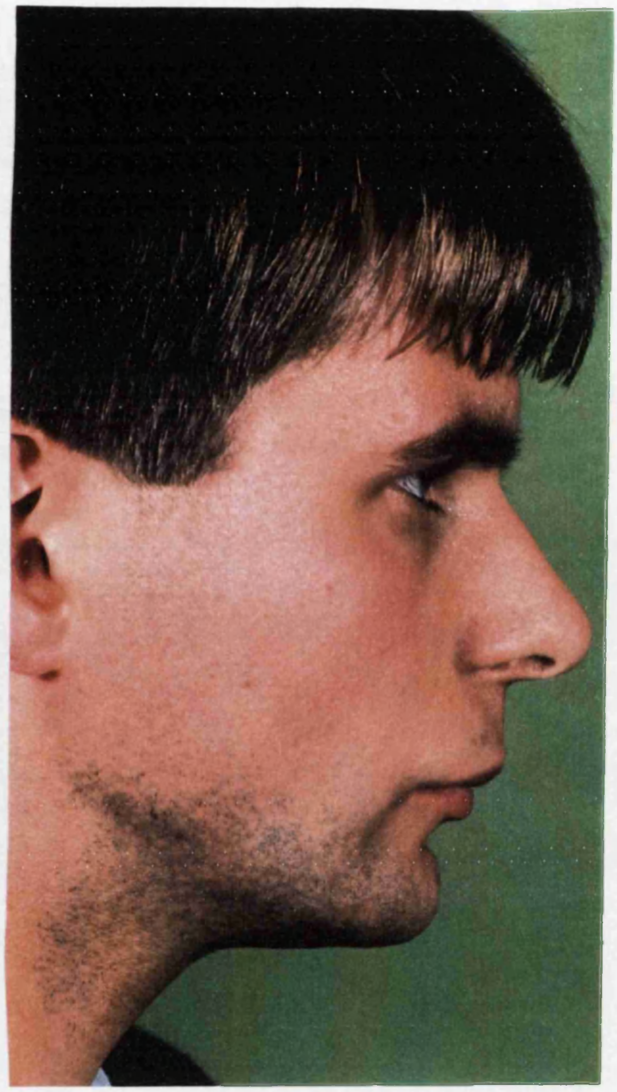


Figure 4.11 d

Continue Figure 4.11...

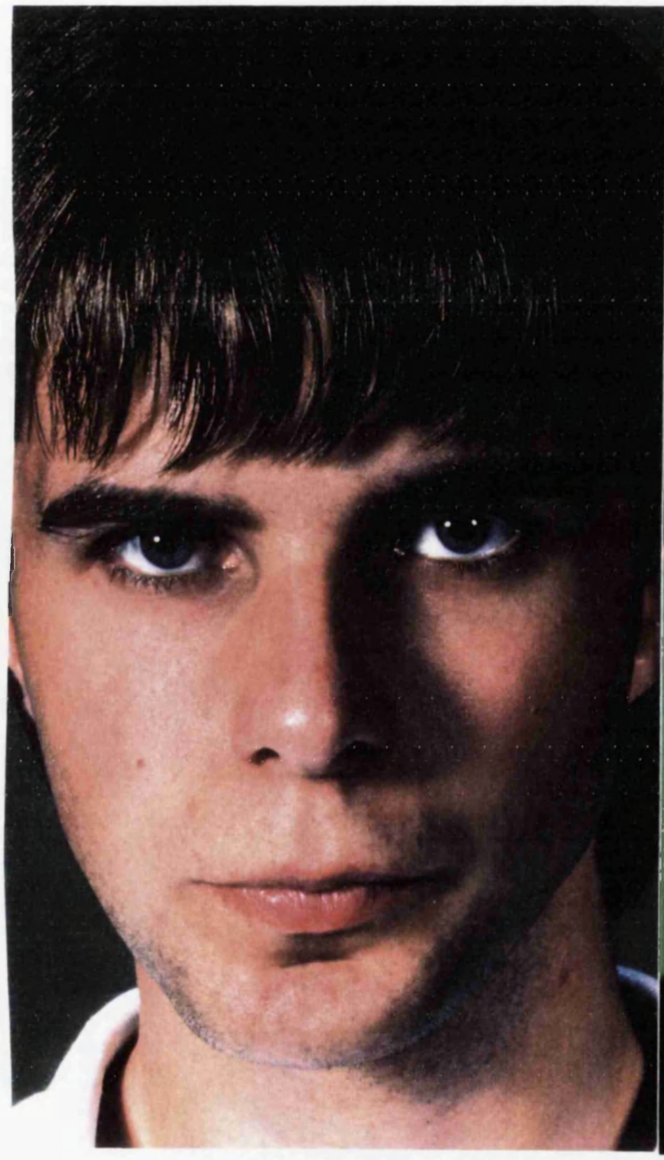


Figure 4.11 e

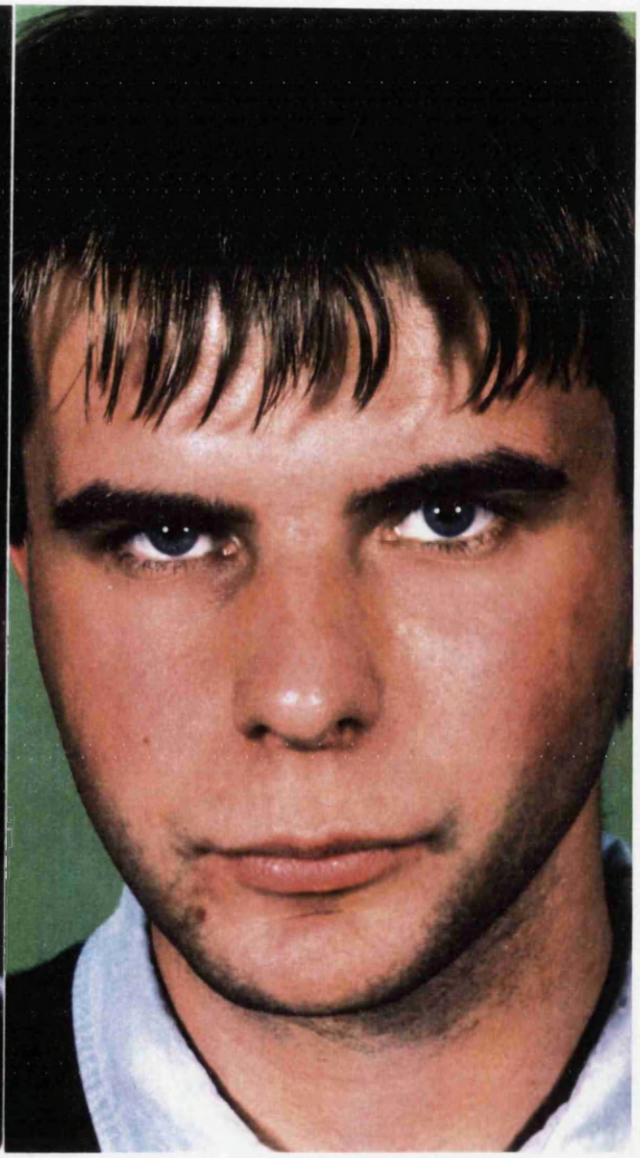


Figure 4.11 f

Continue Figure 4.11

Figure
4.11 g

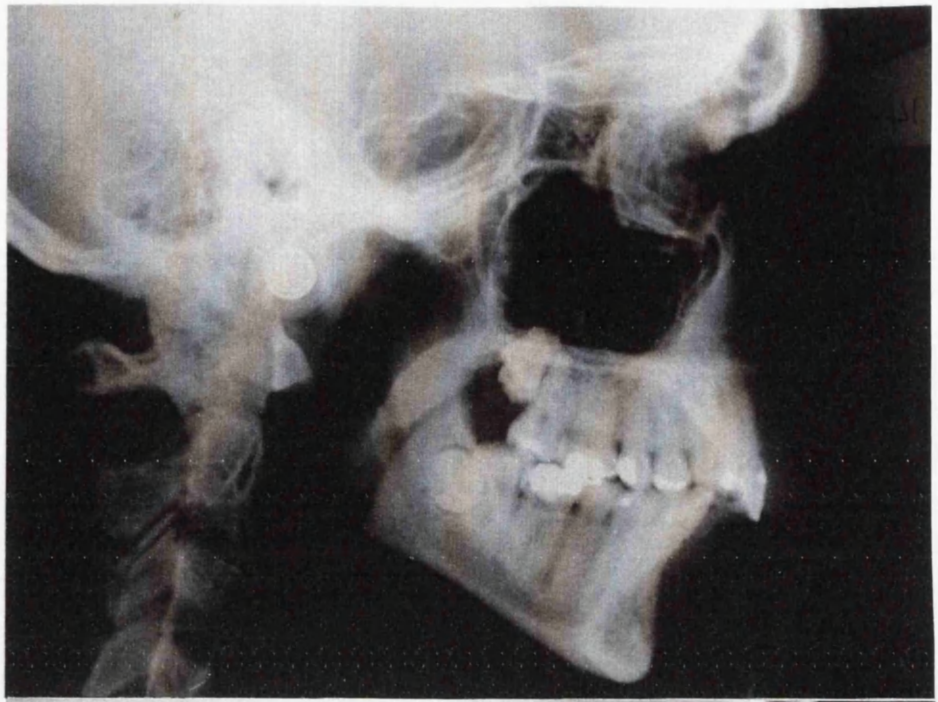


Figure
4.11 h

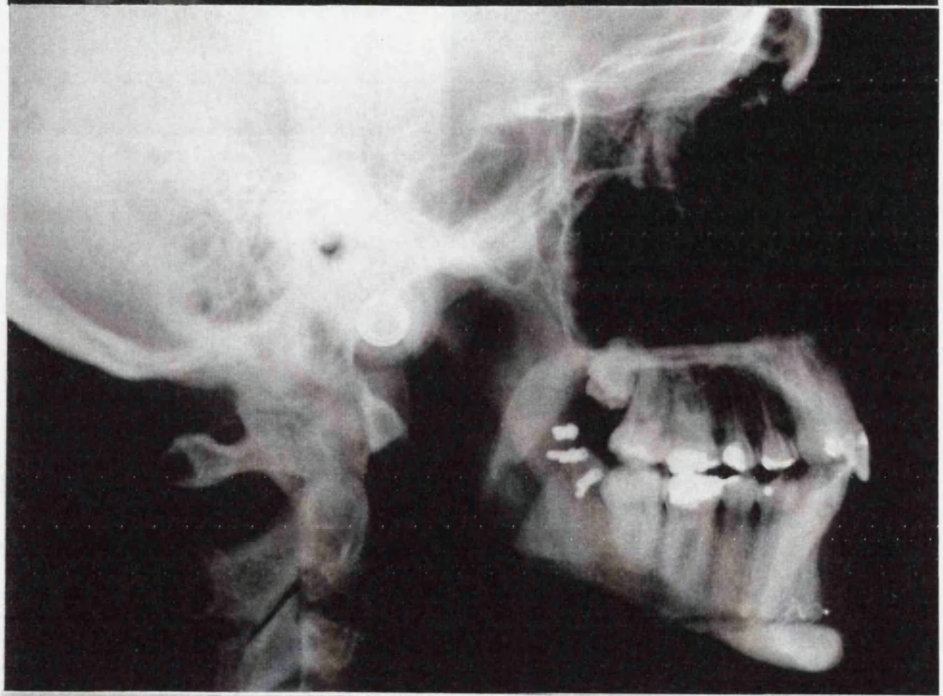
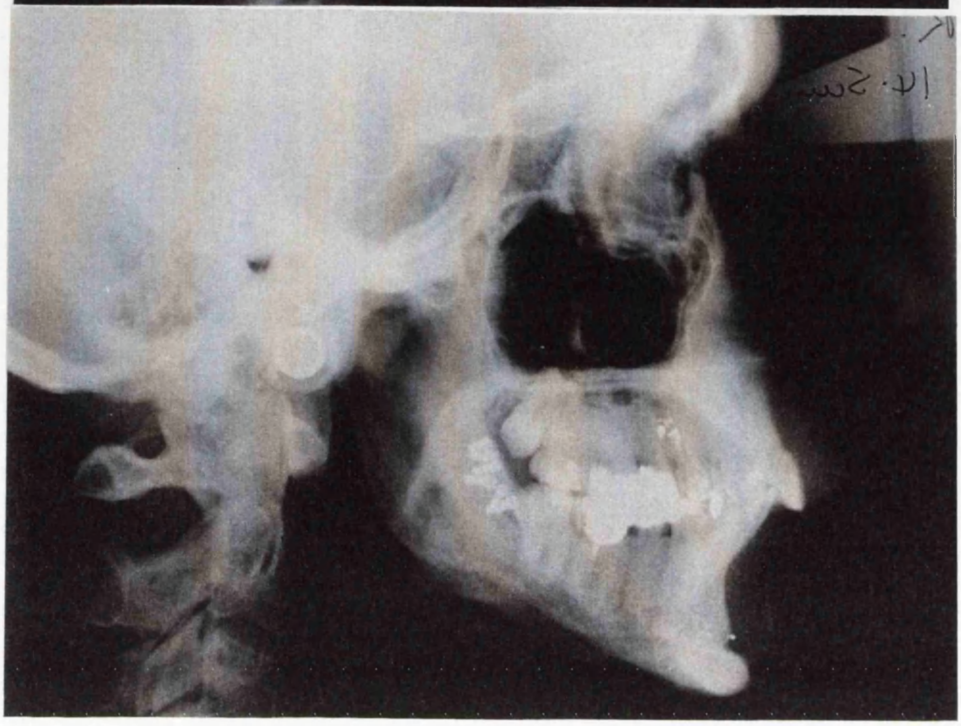


Figure
4.11 i



statistically significant with $p<0.01$ (Bootstrap). The changes from six month to one year postsurgery were just non-significant statistically with $p=0.054$ (Bootstrap). Given the small sample size it would be unwise to conclude that significant changes had not occurred.

4.4.1 Maxillary Surgical Changes (T1 - T2)

4.4.1.1 Conventional Cephalometric Analysis

The maxillary impaction decreased both the anterior and posterior upper facial heights by 1.9 and 0.5 mm. The maxilla rotated in an anti-clockwise direction about 1 degree from the presurgical maxillary plane. The maxillary advancement was one degree shown by increase in The SNA angle (Table 4.9). The Euclidean distances are considered with conventional cephalometric analysis.

4.4.1.2 Finite Element Analysis

Element S-PNS-ANS (Fig. 4.12) shows the maxillary movement, the principal deformation of the element is almost parallel to Sella-ANS and implies that the main deformation of the element is mainly due to surgical changes at ANS rather than PNS.

4.4.2 Mandibular Surgical Changes (T1-T2)

4.4.2.1 Conventional Cephalometric Analysis

The distal segment rotated in an anti-clockwise direction with a decrease of the mandibular plane angle by 3.2 degrees, in addition to 4.1 degrees advancement. The lower anterior facial height is decreased by 1.3 mm. The proximal segment rotated in an anti-clockwise direction by 6.4 degrees. The gonial angle increased by

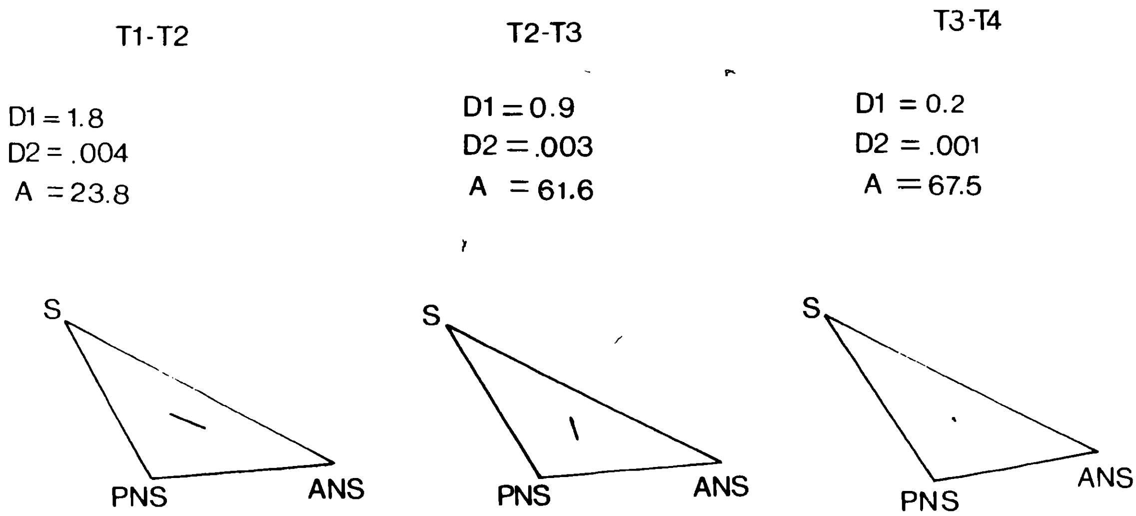


Figure 4.12
The finite element S-PNS-ANS used to assess surgical and postsurgical changes following bimaxillary osteotomy with non-rigid fixation.

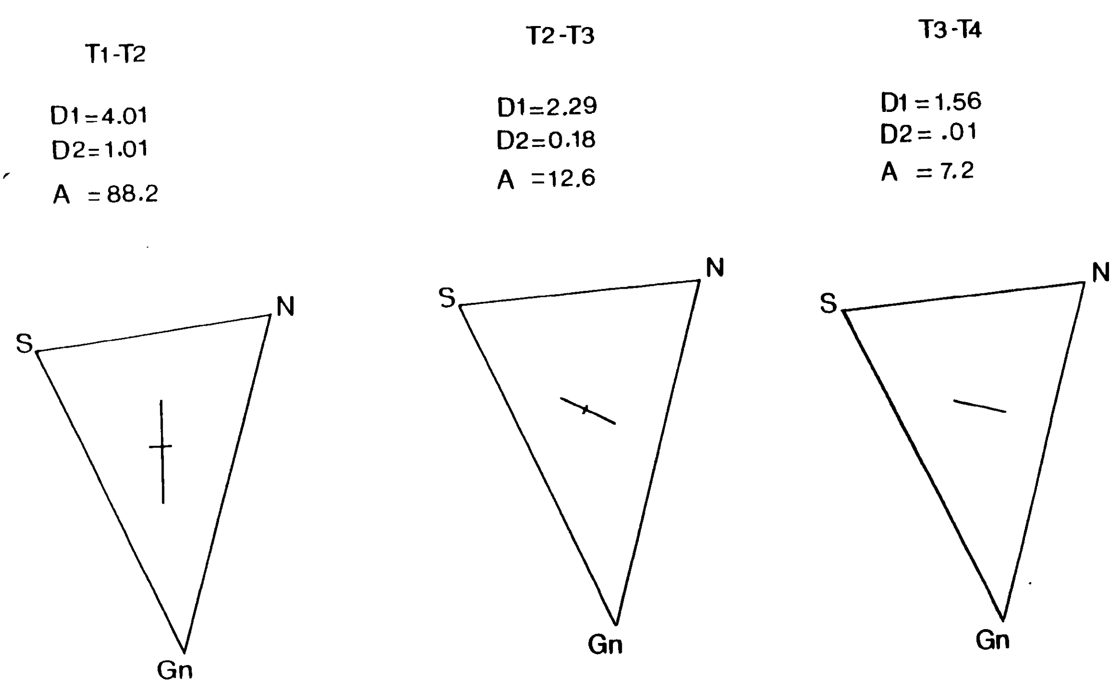


Figure 4.13
The finite element S-N-Gn used to assess surgical and postsurgical changes following bimaxillary osteotomy with non-rigid fixation.

3.2 degrees due to the combined rotation of both the proximal and distal segments. The lower posterior facial height was unchanged (Table 4.9).

4.4.2.2 Finite Element Analysis

A. Element S-N-Gn (Fig. 4.13)

The principal strains illustrate the relation between the distal segment and the base of the skull. The direction of the maximum principal strain shows the combined rotation and advancement of the distal segment. The net surgical changes at Genion are mainly vertical in direction with smaller changes antero-posteriorly. This is due to the anti-clockwise rotation of the distal segment.

B. Element Cd-Go-Gn

The principal strain in the element (Fig. 4.14) demonstrates the surgical changes between the proximal and distal segments. The principal strain was almost horizontal in relation to Gonion-Genion line which is explained by the increase in the angle between the proximal and distal segments.

C. Element S-N-Cd

The changes in condylar position are shown in this element (Fig. 4.15). The orientation of the principal strain shows that condylar displacement during surgery was both in horizontal and vertical directions. However, the vertical component of the strain is more than the horizontal one (A=78.5 degrees). The condyle was displaced inferiorly and posteriorly at the time of taking the immediate postoperative cephalograph. The inferior displacement is

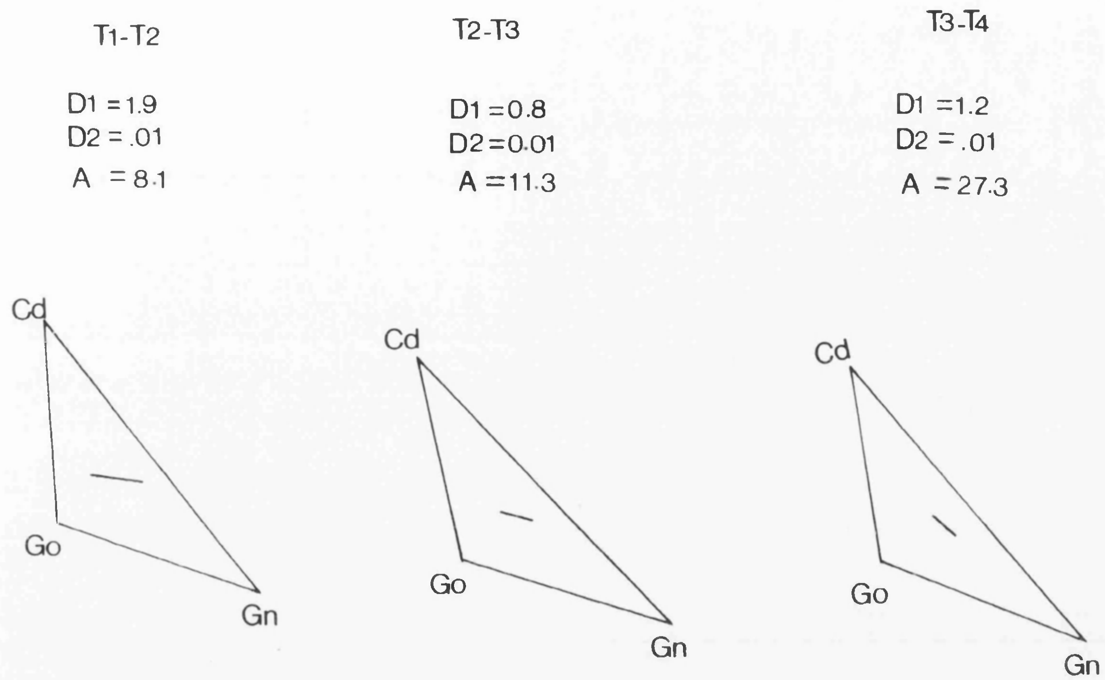


Figure 4.14
The finite element Cd-Go-Gn used to assess surgical and postsurgical changes following bimaxillary osteotomy with non-rigid fixation.

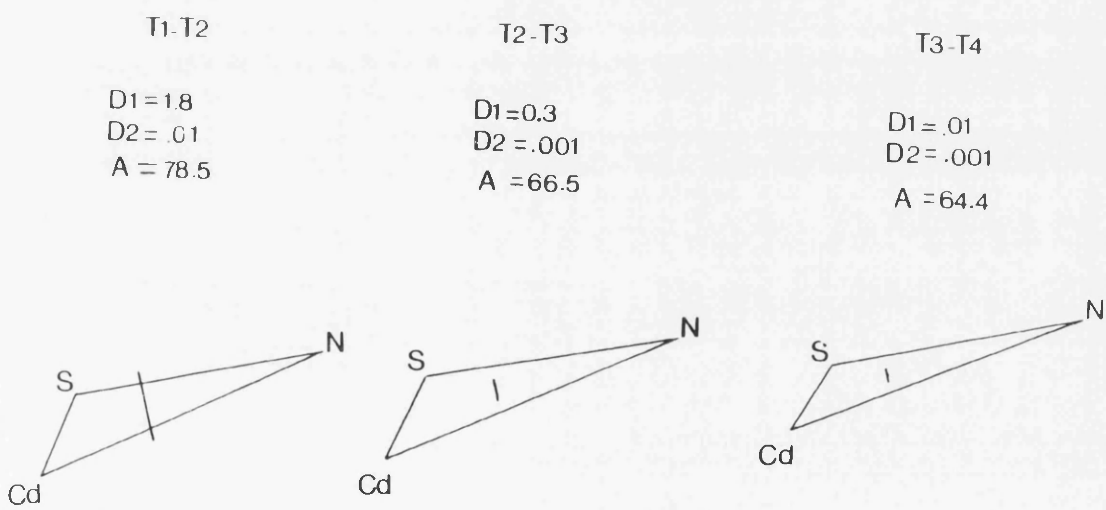


Figure 4.15
The finite element S-N-Cd used to assess surgical and postsurgical changes following bimaxillary osteotomy with non-rigid fixation.

due to the occlusal splint that is usually left fixed to maxillary teeth during the first six weeks after surgery.

4.4.2.3 Euclidean Distance Matrix Analysis

The length of the mandible increased about 4.1 mm measured by the increased in the distance Condylion-Genion. The condyle was displaced more inferiorly than posteriorly with increase of Sella-Condylion and Nasion-Condylion distances by 1.5 mm and 0.8 mm respectively. The length of the proximal segment (Condylion - Gonion) increased by 0.5 mm due to inferior transpositioning of Gonion. (Table 4.10).

4.4.3 Maxillary changes at 6 months follow up (T2-T3)

4.4.3.1 Conventional Cephalometric Analysis

The maxilla rotated slightly in an anti-clockwise direction but was stable within 1 mm of its immediate postsurgical position. This rotation is due to inferior settling of the posterior part of the maxilla. The upper posterior facial height increased by 0.4 mm. The maxilla was stable in antero-posterior direction.

4.4.3.2 Finite Element Analysis

The direction of the maximum principal strain of the element S-PNS-ANS (Fig. 4.12) indicates a vertical maxillary changes mainly in relation to PNS. The minimum strain in the horizontal direction is negligible which implies antero-posterior stability of the impacted maxilla.

Table 4.10: Components of the EDMA used to assess surgical and post-surgical changes following bimaxillary osteotomy with non-rigid fixation.

End Point Landmarks	Distances (mm.) on Occasion			Ratios of distances between occasions	
	T1	T2	T3	(T1/T2)	(T2/T3)
S Cd	26.1	27.6	26.1	1.05	0.94
S Gn	111.7	115.6	113.5	1.03	0.98
S B	109.9	113.9	112.5	1.04	0.99
N Cd	90.1	90.9	90.2	1.01	0.99
Gn Cd	96.7	100.8	99.9	1.04	0.99
Go Cd	55.4	55.9	54.6	1.01	0.96
Gn Go	59.8	61.2	62.1	1.02	1.02

T1 Preoperative assessment

T2 Immediate postoperative evaluation

T3 Assessment at 6 months follow up

4.4.4 Mandibular changes at 6 months follow up (T2-T3)

4.4.4.1 Conventional Cephalometric Analysis

The distal segment rotated about 2 degrees in a clockwise direction mean with opening of the gonial angle by 0.6 degrees. The proximal segment was also rotated 1 degree in the same direction as the distal segment. The mandible settled posteriorly with decrease in SNB angle by 1 degree. (Table 4.9).

4.4.4.2 Finite Element Analysis

A. Element S-N-Gn (Fig. 4.13)

The direction of the principal strain is that of the postsurgical changes (repositioning) occurring at Genion. Since Genion is not affected by the surgical bone cut, no remodelling changes are expected to be seen at this area. The element separates the repositioning from remodelling occurring at the distal segment. The principal strain is due to combined inferior and posterior shift of the distal segment.

B. Element Cd-Go-Gn (Fig. 4.14)

The principal strain is almost parallel to Genion-Gonion line which indicates more postsurgical changes in the horizontal direction than vertically. The strain is due to combined remodelling at Gonion and repositioning at Genion. Changes at the condylar surface have a minimal effect on the principal strains of this element.

C. Element S-M-Cd (Fig. 4.15)

The principal strain is almost parallel to the direction of the strain in the same element (T1-T2), which implies that the condyle returned to its former position. However, the principal strain D1 is less in magnitude than the principal strain of the same element due to surgical changes (T1-T2) which implies some remodelling changes at the condylar surface.

4.4.4.3 Euclidean Distance Matrix Analysis

The total mandibular length Condylion-Genion was decreased by 1 mm, however, the total facial depth measured by Sella-Genion was decreased by about 2 mm. The distances between Sella-Condylion and Nasion-Condylion were decreased by 1.5 and 0.7 mm, respectively this was due to superior shift of the condyle after removal of occlusal splint. The length of the proximal segment Condylion-Gonion decreased by 1.3 mm mainly due to local bone resorption at Gonion and Condylion (Table 4.10).

4.4.5 Maxillary changes at one year follow up (T3-T4)

The small changes detected were within the measurement error.

4.4.6 Mandibular changes at one year follow up (T3-T4)

The proximal segment was stable, however, the distal segment continued the clockwise rotation that increased the mandibular plane angle and gonial angles by about 1 degree each (Table 4.9). mean Increase in the Sella-Condylion due to bone resorption at Condylion. Element S-N-Cd (Fig. 4.15) shows these remodelling changes at the condyle which are smaller than those detected at 6 months follow up (T2-T3). This pattern of remodelling is more likely to be secondary to the clockwise rotation of the distal segment. The net backward repositioning measured at Genion was 1 mm posteriorly and 0.6 mm

Table 4.11 Linear and angular measurements used to assess surgical and post-surgical changes of bimaxillary osteotomy with rigid internal fixation (Canniesburn Cases).

Angular Measurements:

	T1	T2	T3	T4
SNA	77.5/3.4*	79.5/4.9	79.5/4.6	79.1/4.1
SNPg	69.9/4.4	77.0/3.9	75.5/3.9	75.1/3.6
SNB	69.5/3.9	74.8/4.1	73.6/3.9	73.4/3.8
MP	50.1/6.4	43.5/6.1	46.0/6.4	46.6/6.5
GON	130.3/6.5	130.7/5.9	130.6/5.2	132.3/5.3
RAM	99.9/4.6	92.1/5.0	94.4/4.9	94.6/4.7
MAX	8.4/5.0	7.1/4.5	7.8/4.7	7.7/4.4

Distances

UAFH	54.9/4.2	50.9/4.1	51.7/4.3	51.5/4.1
LAFH	77.1/6.4	75.6/4.1	74.2/3.4	74.5/3.8
UPFH	49.4/2.6	47.5/2.9	47.6/2.7	48.0/2.0
LPFH	40.3/3.6	42.1/4.0	39.2/4.7	39.2/4.9

MP (Mandibular Plane),
GON (Gonial angle),
MAX (Maxillary plane angle),
UAFH (Upper Anterior Facial Height),
LAFH (Lower Anterior Facial Height),
UPFH (Upper Posterior Facial Height),
LPFH (lower Posterior facial height).

*** Each measurement represents the mean / standard deviation**

T1 Preoperative assessment

T2 Immediate postoperative evaluation

T3 Assessment at 6 months follow up

T4 Assessment at 1 year follow up

inferiorly. These changes were very close to be statistically significant.

No correlation existed between relapse as measured by change in SNB angle (T2 - T4) and the magnitude of surgical changes as measured by maxillary autorotation (r=0.2). However, 34 % of relapse (SNB change from T2 to T4) was related to the magnitude of surgical advancement as measured by change in SNB angle from T1 to T2. On the other hand, 23% of mandibular relapse (SNB change from T2 to T4) was related to the preoperative mandibular plane angle. The most sensitive measure for relapse was the change in mandibular plane angle from T2 to T4 as 65% of this relapse was related to the magnitude of surgical change measured by SNB angle.

Figure 4.16 shows the clinical changes for one of the cases assessed in this study who had bimaxillary osteotomy with non-rigid internal fixation.

4.5 Bimaxillary osteotomy with rigid fixation (Canniesburn Cases)

Table 4.11 shows the immediate, six months and one year postoperative changes using linear and angular measurements. Figures 4.17, 4.18, 4.19 & 4.20) represent the finite elements used in the study. Figure 4.21 (a to i) show one of the cases with significant clinical relapse following mandibular advancement. Table 4.12 Shows components of the matrices used to conduct the Euclidean distance matrix analysis (EDMA). For the same reasons as given in section 4.4 only EDMA components highlighted in the discussion are presented. The index of shape difference value for

Figure 4.16 a

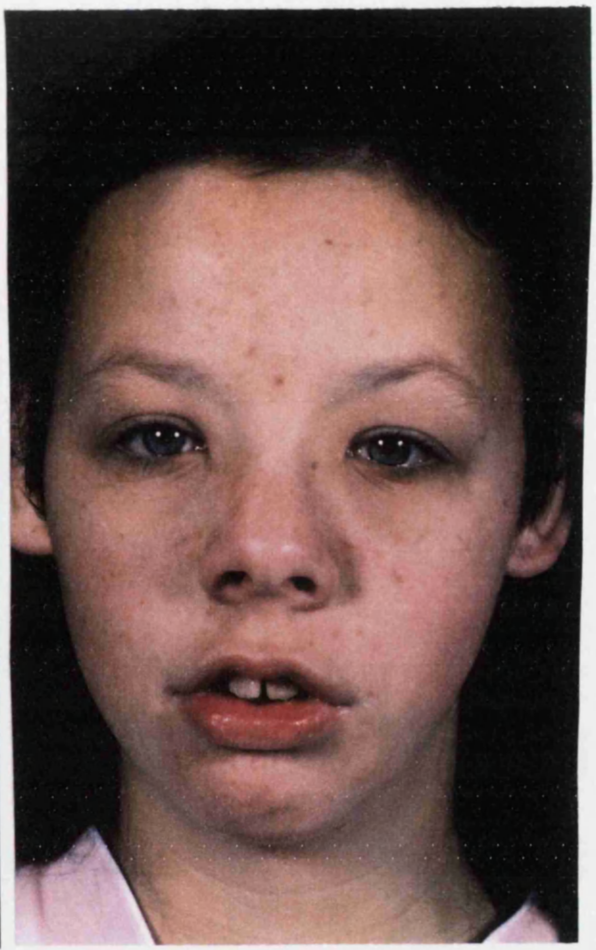


Figure 4.16 b

Figures 4.16 from a to i show facial views and lateral cephalographs of one of the cases who had bimaxillary osteotomy with non-rigid fixation; a & b are the preoperative facial views; c shows the immediate postoperative profile, d profile at 1 year follow up; e shows the immediate postopertive frontal view; f frontal view at 1 year follow up; g preopertive cephalograph; h immediate postoperative cephalograph; i cephalograph at 1 year follow up.

Figure 4.16 c

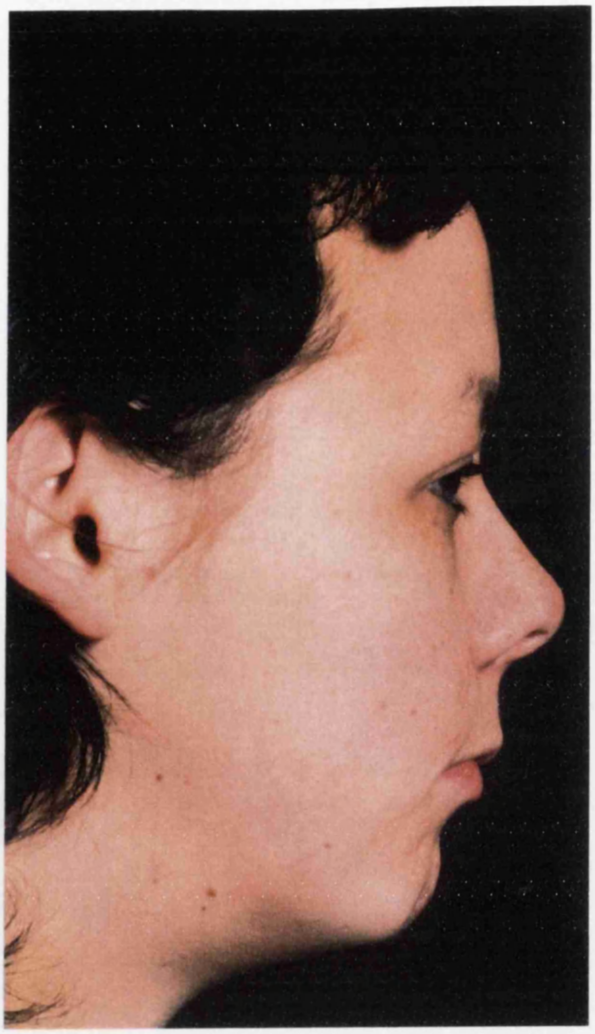


Figure 4.16 d

Continue Figure 4.16...

Figure 4.16 e

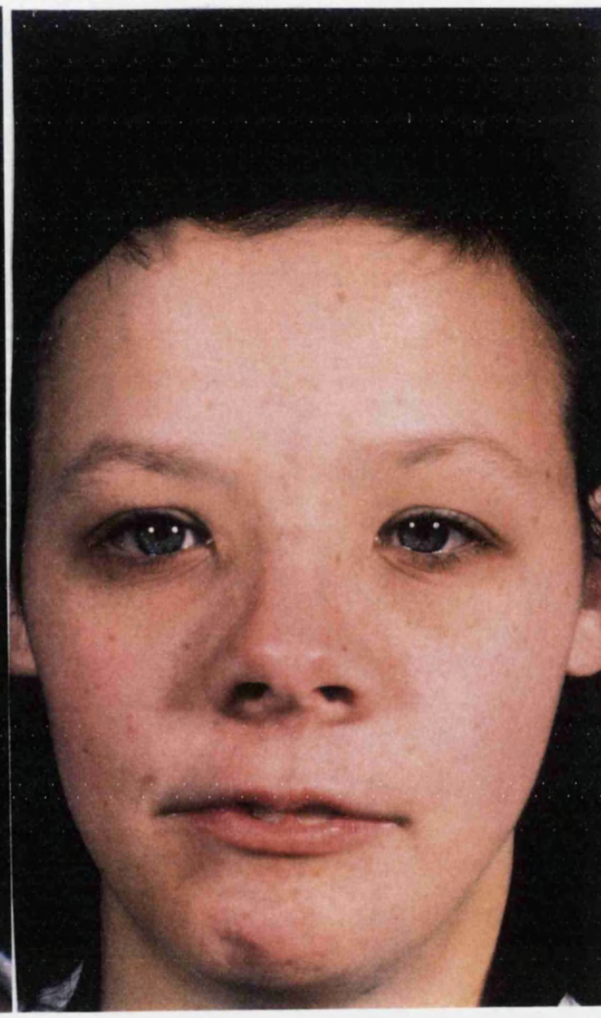


Figure 4.16 f

Continue Figure 4.16

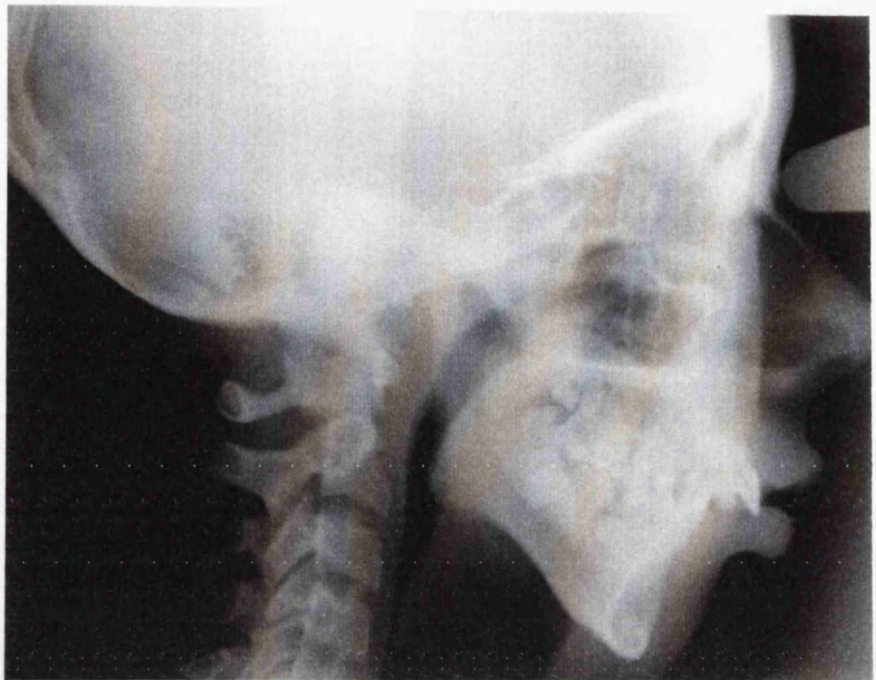


Figure 4.16 g

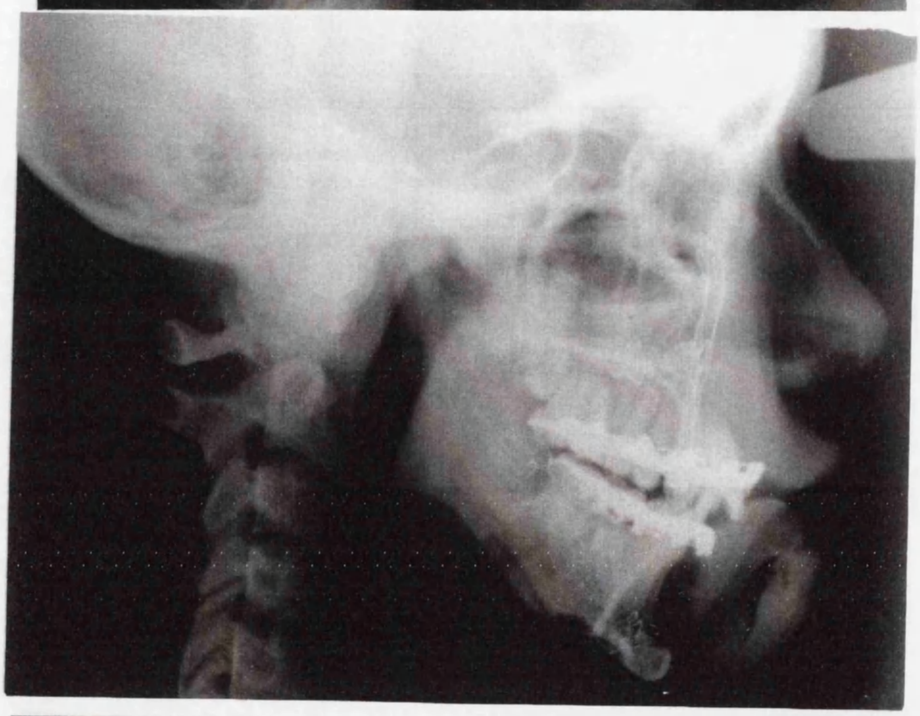


Figure 4.16 h

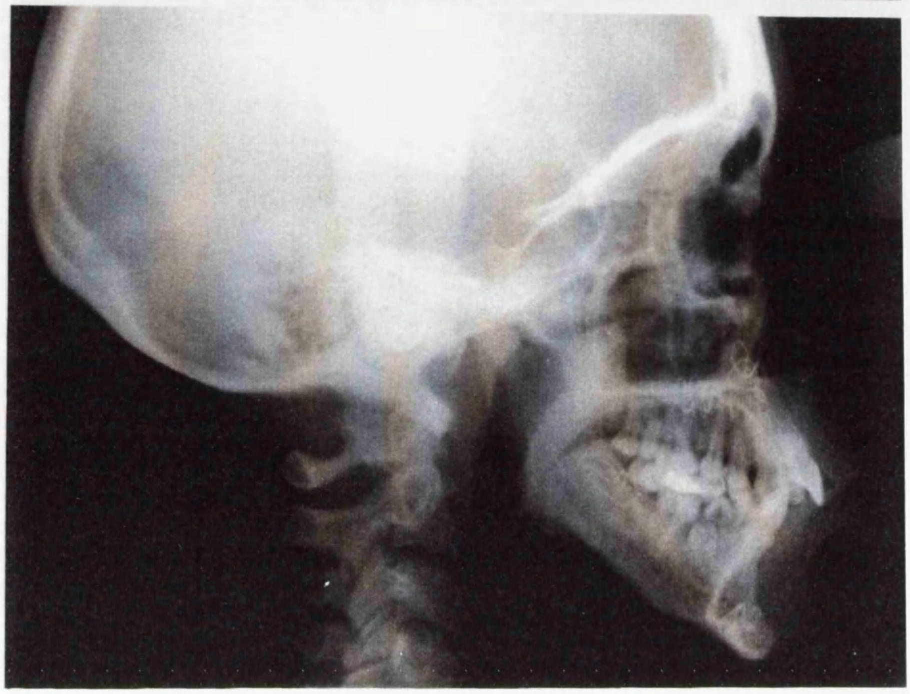


Figure 4.16 i

the surgical changes was statistically significant with index of shape change 2.83 and $p<0.004$ (Bootstrap). For the immediate to six months postoperative period, the changes were also statistically significant with $p<0.01$ (Bootstrap). The changes from six month to one year postsurgery were not statistically significant with $p=0.164$.

4.5.1 Maxillary Surgical Changes (T1 - T2)

4.5.1.1 Conventional Cephalometric Analysis

The maxillary impaction was 4 mm anteriorly (4 mm. decrease in the upper anterior facial height) and about 2 mm posteriorly (2 mm decrease in upper posterior facial height). The maxilla rotated in an anti-clockwise direction 1.3 degrees upward from the presurgical maxillary plane. Some of the Euclidean distances are considered with the linear measurements of the conventional cephalometric analysis (Table 4.11)

4.5.1.2 Finite Element Analysis

Element S-PNS-ANS (Fig. 4.17) shows the principal maxillary movement. The principal deformation of the element is parallel to Sella-ANS line which is due to more anterior maxillary impaction than posterior.

4.5.2 Mandibular surgical changes (T1-T2)

4.5.2.1 Conventional Cephalometric Analysis

The distal segment autorotated following maxillary impaction. This is shown by the decrease in both the ramus and mandibular plane

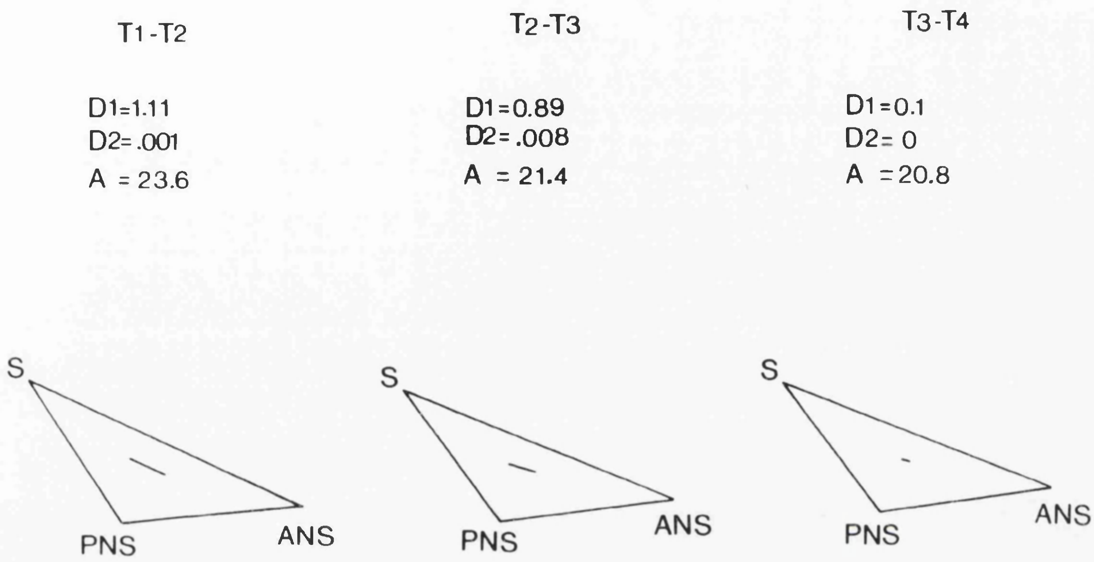


Figure 4.17
The finite element S-PNS-ANS used to assess surgical and postsurgical changes following bimaxillary osteotomy with rigid fixation (Canniesburn cases).

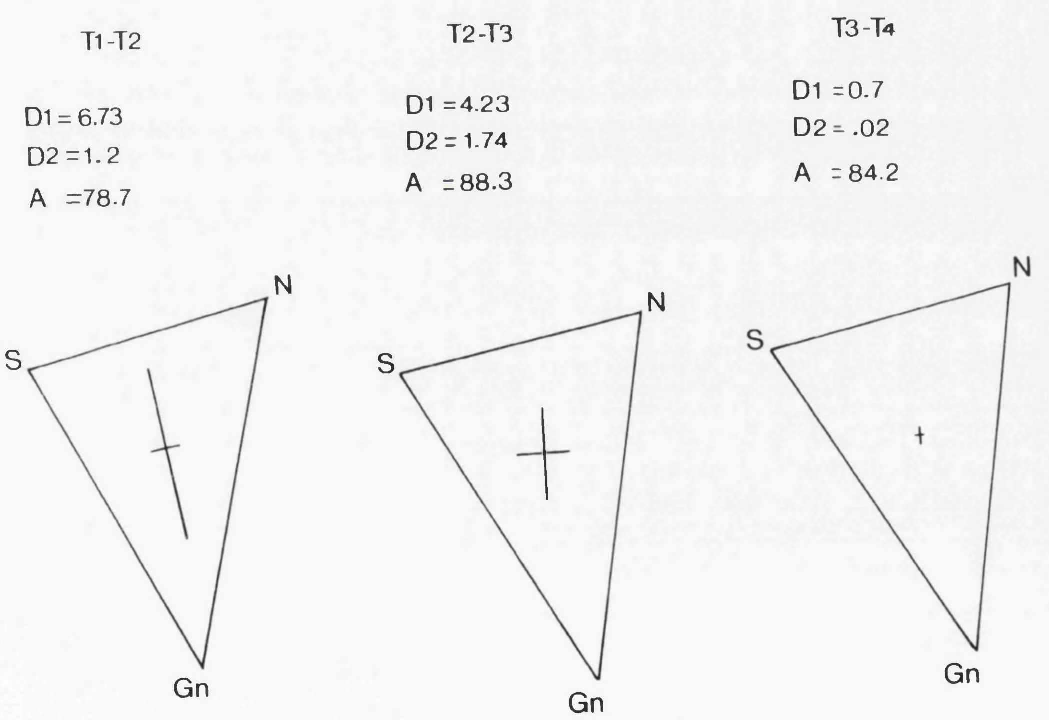


Figure 4.18
The finite element S-N-Gn used to assess surgical and postsurgical changes following bimaxillary osteotomy with rigid fixation (Canniesburn cases).

angles by 7.8 degrees and 6.6 degrees respectively. The anterior movement of the mandibular distal segment increased SNB angle by 5.3 degrees. The angle between the proximal and distal segments (gonial angle) was unchanged (Table 4.11).

4.5.2.2 Finite Element Analysis

A. Element S-N-Gn

The element (Fig. 4.18) shows the combined rotation and advancement of the distal segment. The direction of the principal strain bisects S-Gn-N angle which implies that surgical changes at Genion have equal relation to both Sella and Nasion. The minimum principal strain is quite small which shows that the net surgical changes at Genion were more vertical than horizontal.

B Element Cd-Go-Gn

The element (Fig. 4.19) shows the changes between the proximal and distal segment arising from surgery. The principal strain was almost parallel to the Gonion-Genion line showing there was very little angular change between the proximal and distal segments.

C Element S-N-Cd

The element (Fig. 4.20) shows the posterior and inferior displacement of the condyle. The direction of the principal strain is due to combined horizontal and vertical displacement of the condyle during surgery. The condyle is displaced posteriorly and inferiorly.

4.5.2.3 Euclidean Distance Matrix Analysis

The advanced distal segment increased the total mandibular length (Condylion - Genion) by 6.6 mm (Table 4.12). The net increase of

Table 4.12 Components of the EDMA used to assess surgical and post-surgical changes following bimaxillary osteotomy with rigid internal fixation (Canniesburn Cases)

End Point Landmarks	Distances (mm.) on Occasion			Ratios of distances between occasions	
	T1	T2	T3	(T1/T2)	(T2/T3)
S Cd	19.1	19.7	18.5	1.04	0.94
S Gn	102.7	107.3	105.1	1.04	0.98
S B	104.1	108.2	106.6	1.04	0.99
N Cd	85.7	87.4	85.9	1.02	0.99
Gn Cd	92.2	98.8	98.4	1.08	0.97
Go Cd	50.7	53.1	49.0	1.05	0.92
Gn Go	57.0	61.5	62.1	1.08	1.01

T1 Preoperative assessment

T2 Immediate postoperative evaluation

T3 Assessment at 6 months follow up

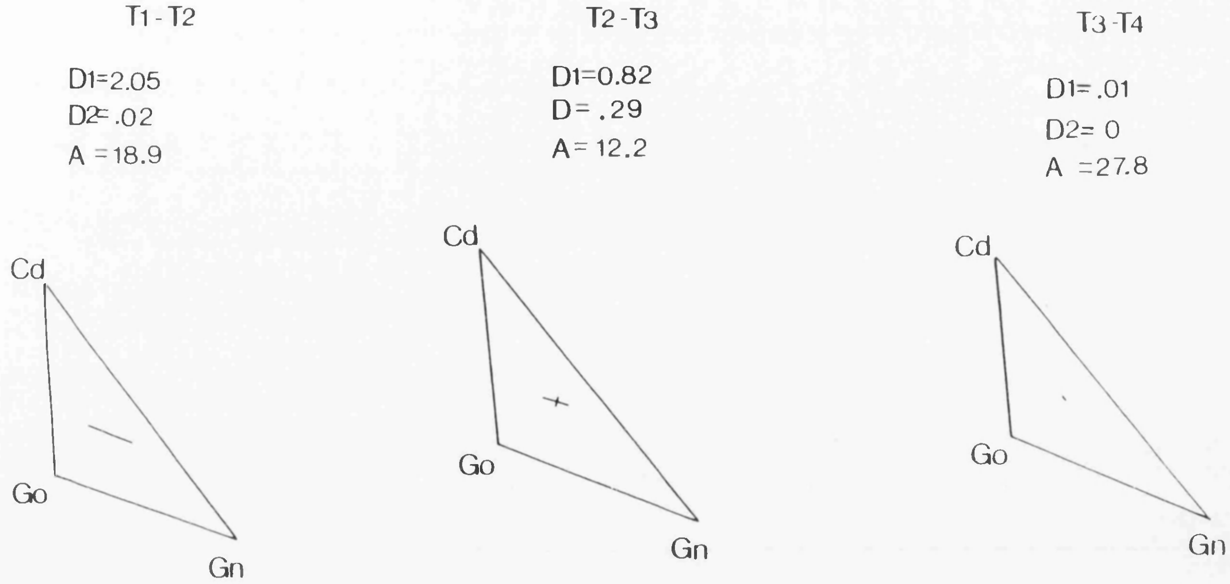


Figure 4.19
The finite element Cd-Go-Gn used to assess surgical and postsurgical changes following bimaxillary osteotomy with rigid fixation (Canniesburn cases).

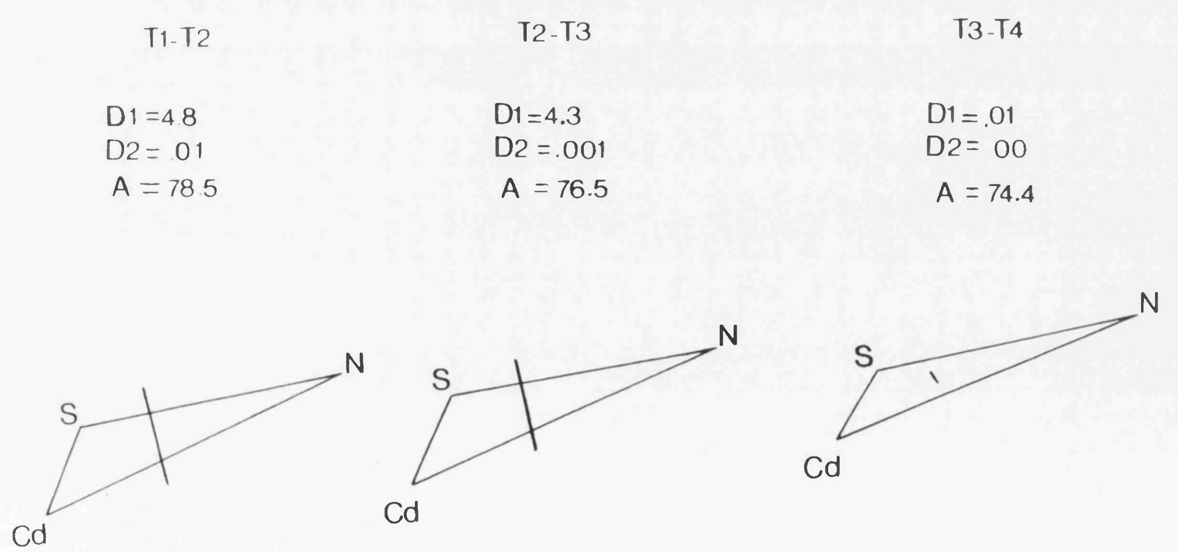


Figure 4.20
The finite element S-N-Cd used to assess surgical and postsurgical changes following bimaxillary osteotomy with rigid fixation (Canniesburn cases).

the facial depth (Sella - Genion) was 4.6 mm. The length of the proximal segment (Condylion - Gonion) increased by 2.4 mm. The distances Sella-Condylion and Nasion-Condylion were increased by 0.6 mm and 1.7 mm respectively. (Table 4.12). This shows that the condyle has been pushed more posteriorly than inferiorly during surgery.

4.5.3 Maxillary changes at 6 months follow up (T2-T3)

4.5.3.1 Conventional Cephalometric Analysis

The maxilla rotated in a clockwise direction about 0.7 degrees, with an increase in the anterior upper facial height of 0.8 mm. The centre of rotation was close to PNS with no changes detected at the posterior end of the maxilla. The maxilla generally stayed within 1 mm of its immediate postoperative position. The EDMA components are part of the conventional cephalometric analysis (Table 4.11).

4.5.3.2 Finite Element Analysis

The element S-PNS-ANS (Fig. 4.17) shows the principal strain parallel to Sella-ANS with small magnitude in comparison with the principal strain of the same element showing surgical changes (T1-T2). This illustrates maxillary stability.

4.5.4 Mandibular changes at 6 months follow up (T2-T3)

45.4.1 Conventional Cephalometric Analysis

The mandible rotated in a clockwise direction with increase in the mandibular plane angle by 2.5 degrees and the ramus angle by 2.3

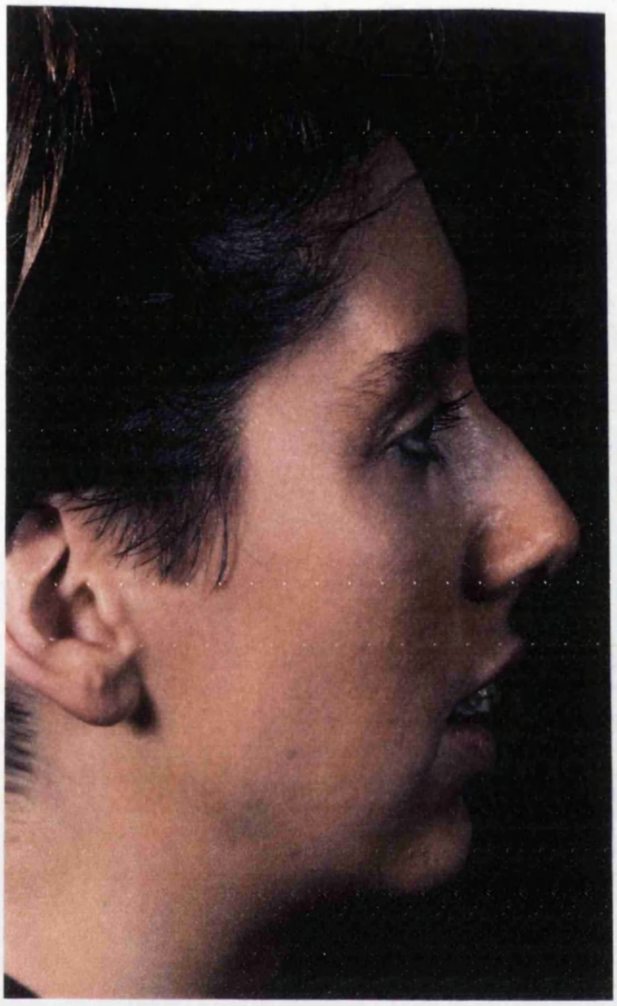


Figure 4.21 a

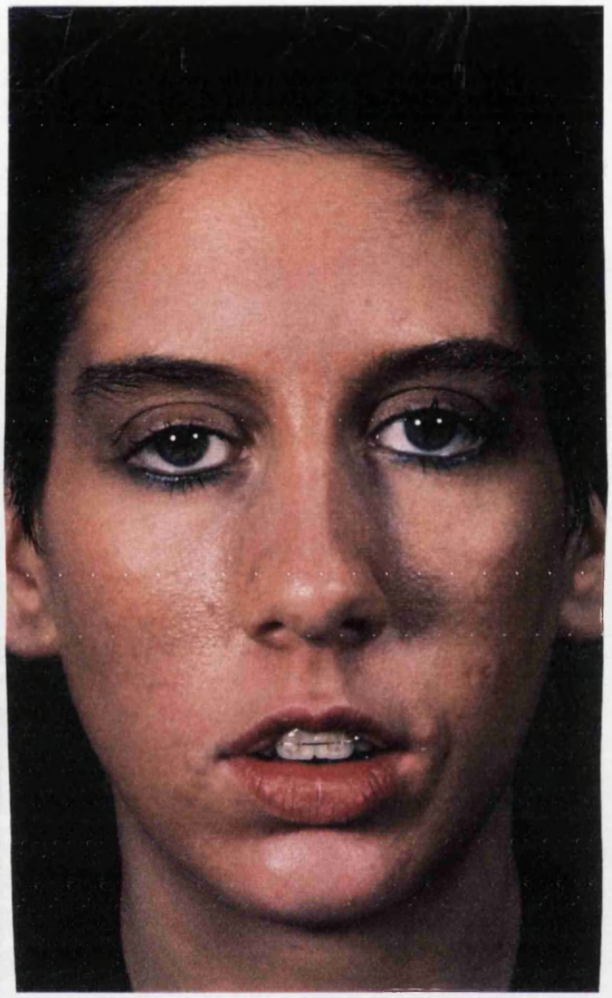


Figure 4.21 b

Figures 4.21 from a to i show facial views and lateral cephalographs of one of the cases who had bimaxillary osteotomy with rigid fixation at Canniesburn Hospital; a & b are the preoperative facial views; c shows the immediate postoperative profile, d profile at 1 year follow up; e shows the immediate postopertive frontal view; f frontal view at 1 year follow up; g preopertive cephalograph; h immediate postoperative cephalograph; i cephalograph at 1 year follow up.

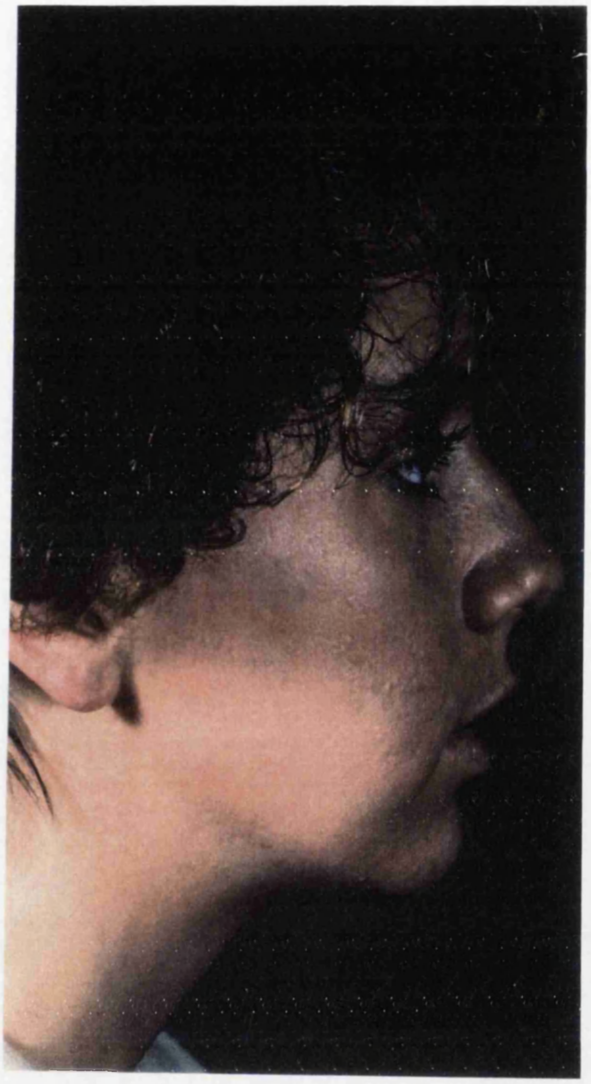


Figure 4.21 c

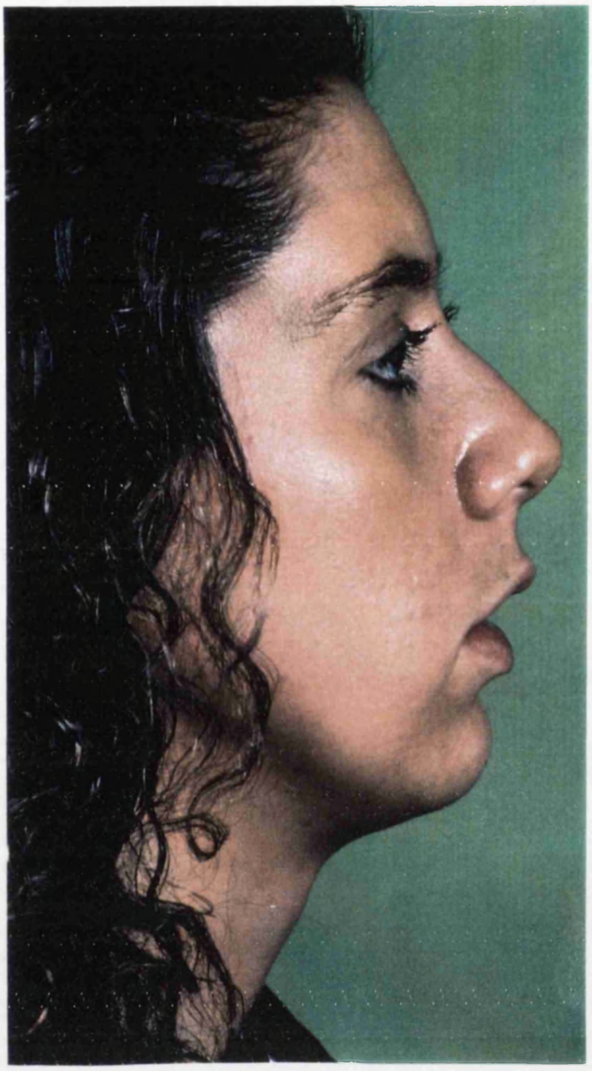
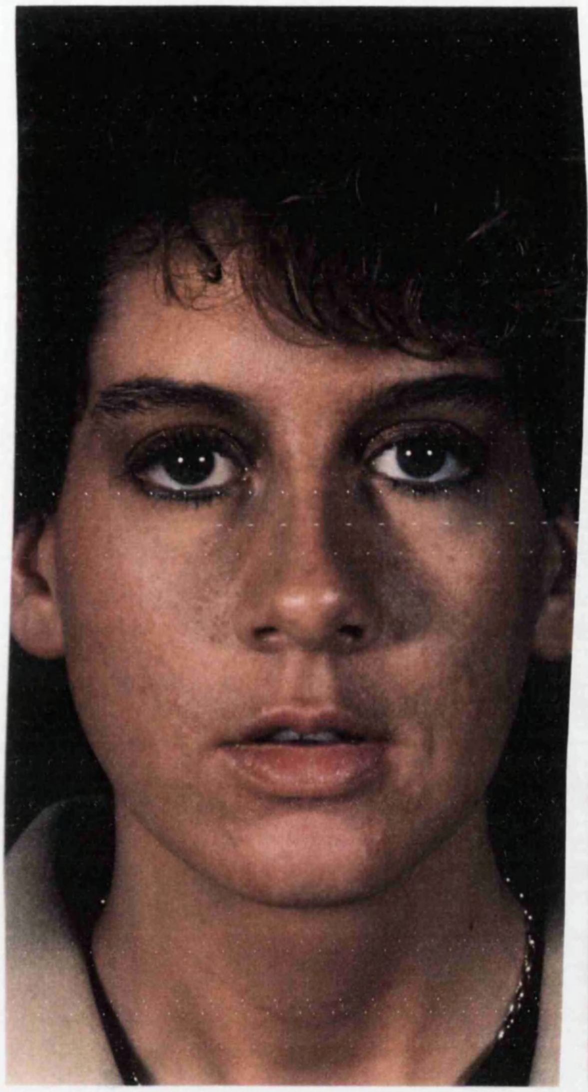


Figure 4.21 d

Continue Figure 4.21...



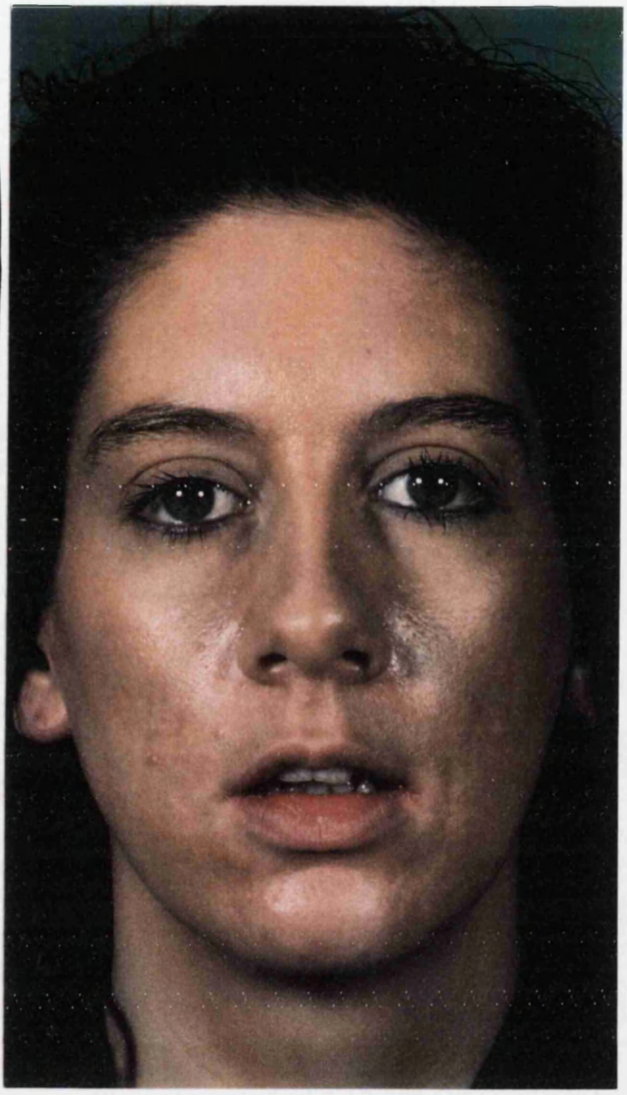


Figure 4.21 e

Figure 4.21 f

Continue Figure 4.21


Figure
4.21 g

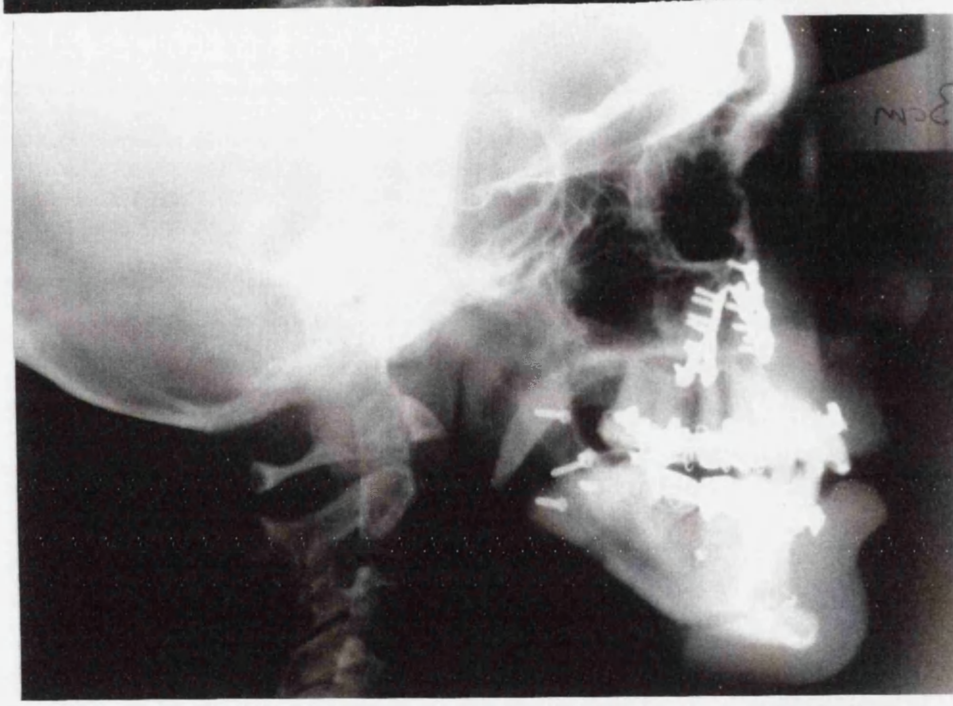


Figure
4.21 h

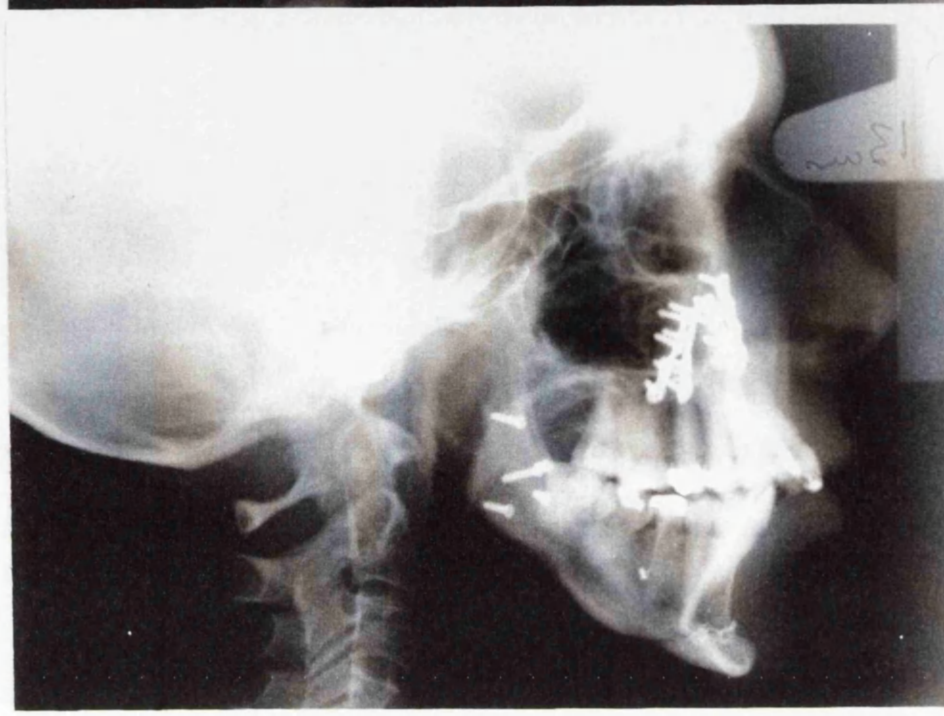


Figure
4.21 i

degrees. No change in the gonial angle was detected. The lower posterior facial height decreased by about 3 mm which is due to local remodelling at Gonion. The mandible settled posteriorly with decrease in SNB by 1.2 degrees.

4.5.4.2 Finite Element Analysis

A. Element S-N-Gn

The direction of the principal strain (Fig. 4.18) shows the combined vertical and horizontal repositioning at Genion. However, the vertical changes are predominant over changes in the horizontal direction. This implies that the distal segment is more stable horizontally than vertically.

B. Element Cd-Go-Gn

The principal strain of the element is due to the combined effect of local bone resorption at Gonion and repositioning of the distal segment at Genion. The maximum principal strain is in horizontal direction that coincides with the clockwise rotation of the distal segment as well as the horizontal changes at Gonion. The minimum principal strain is due to combined vertical settling at Genion and transpositioning of Gonion (Fig. 4.19).

C. Element S-N-Cd

The principal strain is almost equal in magnitude and parallel in direction to the principal strain of the same element immediately following surgery (T1-T2). This suggests that the condyle returned back to its former position. The condyle rotated and shifted anteriorly, this shift is shown in the element S-N-Cd (Fig. 4.20).

The condylar anterior shift follows the same angle as that of condyle's posterior distraction during surgery.

4.5.4.3 Euclidean Distance Matrix Analysis

The distance from the condylar surface to both Sella and Nasion were decreased by 1.2 mm and 1.5 mm respectively (Table 4.12). The total mandibular length (Condylion-Genion) was decreased by 0.4 mm with decrease in facial depth (Sella- Genion) by 2.2 mm. The distance from Condylion to Gonion was decreased by 4 mm due to combined resorption at both ends. The distance from Genion to Gonion was increased by 0.6 mm which implies that Gonion was transposed inferiorly and anteriorly.

4.5.5 Maxillary changes at one year follow up (T3-T4)

The small changes detected were within the measurement error and not statistically significant.

4.5.6 Mandibular changes at 1 year follow up (T3-T4)

The small changes detected were within the measurement error and not statistically significant.

No correlation existed between relapse as measured by change in SNB angle, from immediate postoperative to one year follow up, and the preoperative mandibular plane angle. Neither did the magnitude of surgical changes had any relation with relapse. Mild correlation of $r=0.4$ was detected between relapse (SNB change from T2 to T4) and the magnitude of Mandibular autorotation during surgery. Only 16% of relapse, measured by change in

Mandibular plane angle from the immediate postoperative to one year follow up, was related to surgical change of SNB angle (r=0.4). Seventeen percent of the changes in mandibular plane angle was also related to the extent of surgical mandibular autorotation.

4.6 Bimaxillary Rigid Fixation (Michigan)

Table 4.13 shows the conventional cephalometric values preoperatively, immediate postoperatively and at six months follow up. Figures (4.22, 4.23, 4.24, 4.25) are of the finite elements used to assess surgical and postsurgical changes. Table 4.14 Shows the matrices used to conduct Euclidean distance matrix analysis. The statistical significance of shape changes was tested by the Bootstrap method described by Lele & Richtsmeier (1991) using a custom written computer program. The index of shape change was 2.99 with $p<.001$. The index of shape change at 6 months follow up was 1.30 with $p=0.29$.

4.6.1 Maxillary Surgical changes (T1 - T2)

4.6.1.1 Conventional Cephalometric Analysis

The maxillary impaction decreased both the anterior and posterior upper facial heights by 0.6 mm and 0.5 mm respectively. The maxilla was advanced by 3.6 degrees with minimal changes in the maxillary plane angle.

4.6.1.2 Finite Element Analysis

Element S-PNS-ANS (Fig. 4.22) shows the principal maxillary movement. The principal deformation of the element is bisecting

Table 4.13 Linear and angular measurements used to assess surgical and post-surgical changes of bimaxillary osteotomy (Michigan cases).

Angular Measurements:

Angle	T1	T2	T3
SNA	77.2/6.8*	80.82/4.8	80.7/5.7
SN/Pg	73.53/5.7	78.4/4.7	78.1/4.4
SNB	73.27/5.6	76.4/4.8	75.9/4.8
SN/MP	44.4/8.6	40.8/6.9	41.2/6.8
GONIAL	127.1/10.6	128.2/9.1	127.9/8.1
RAMUS	97.4/7.9	92.5/6.2	93.2/5.7
MAX	8.5/4.0	8.7/5.3	8.6/3.7

Distances			
UAFH	54.7/4.2	54.1/4.1	54.6/4.3
LAFH	78.2/6.4	76.8/4.1	76.3/3.4
UPFH	51.3/2.6	50.8/2.9	50.9/2.7
LPFH	45.5/3.6	47.4/4.0	47.1/4.7

MP (Mandibular Plane),
GON (Gonial angle),
MAX (Maxillary plane angle),
UAFH (Upper Anterior Facial Height),
LAFH (Lower Anterior Facial Height),
UPFH (Upper Posterior Facial Height),
LPFH (lower Posterior facial height).

*** Each measurement represents the mean / standard deviation**

T1 Preoperative assessment

T2 Immediate postoperative evaluation

T3 Assessment at 6 months follow up

T4 Assessment at 1 year follow up

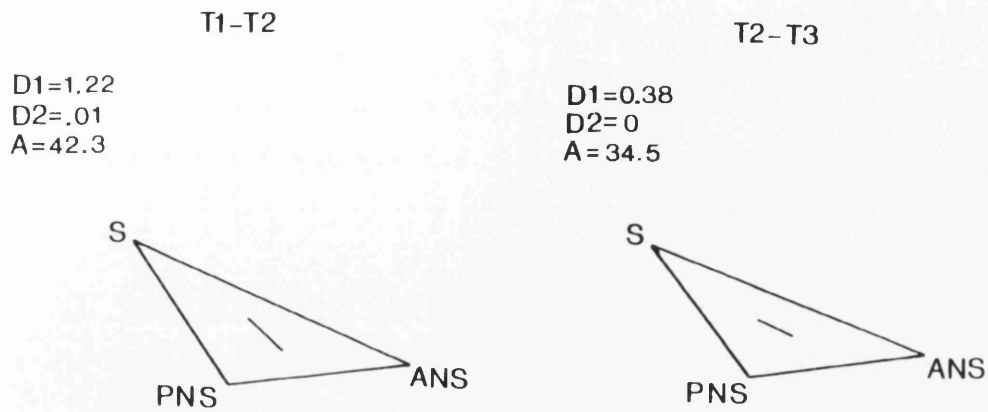


Figure 4.22
The finite element S-PNS-ANS used to assess surgical and postsurgical changes following bimaxillary osteotomy with rigid fixation (Michigan cases).

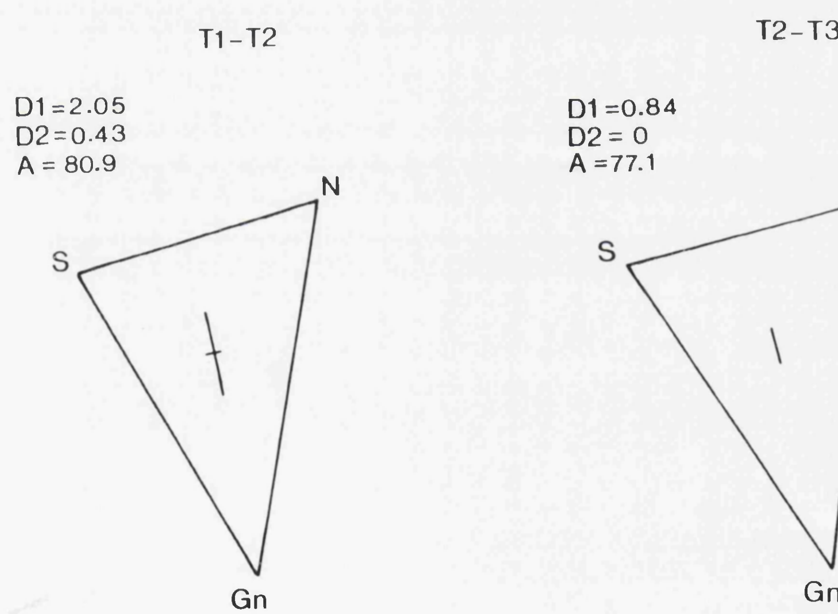


Figure 4.23
The finite element S-N-Gn used to assess surgical and postsurgical changes following bimaxillary osteotomy with rigid fixation (Michigan cases).

PNS-S-ANS angle which is due to equal anterior shift of ANS and PNS from Sella.

4.6.2 Mandibular Surgical Changes (T1-T2)

4.6.2.1 Conventional Cephalometric Analysis

The mandible autorotated about 3.6 degrees following the maxillary mean
impaction. This is shown by the decrease in both the ramus and mandibular plane angles by 4.9 degrees and 3.6 degrees respectively. The mandibular autorotation was combined with an advancement that increased the SNB angle by 3 degrees approximately. The angle between the proximal and distal segments mean
(gonial angle) increased by 1 degree approximately (Table 4.13).

4.6.2.2 Finite Element Analysis

A. Element S-N-Gn (Fig. 4.23)

The element shows the combined rotation and advancement of the distal segment. The principal strain bisects the angle S-Gn-N which implies that Genion shifted equally in relation to both Sella and Nasion.

B. Element Cd-Go-Gn (Fig. 4.24)

The principal maximum strain is parallel to Gonion - Genion line which implies that the main surgical change was in a horizontal direction parallel to the inferior border of the mandible with minimal vertical rotation. There is a small alteration in the angle between the proximal and distal segments.

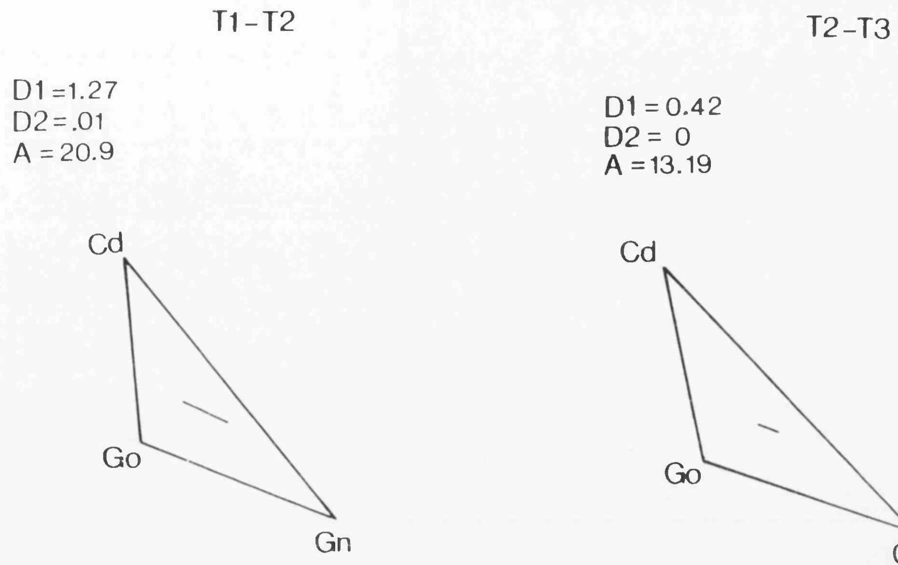


Figure 4.24
The finite element Cd-Go-Gn used to assess surgical and postsurgical changes following bimaxillary osteotomy with rigid fixation (Michigan cases).

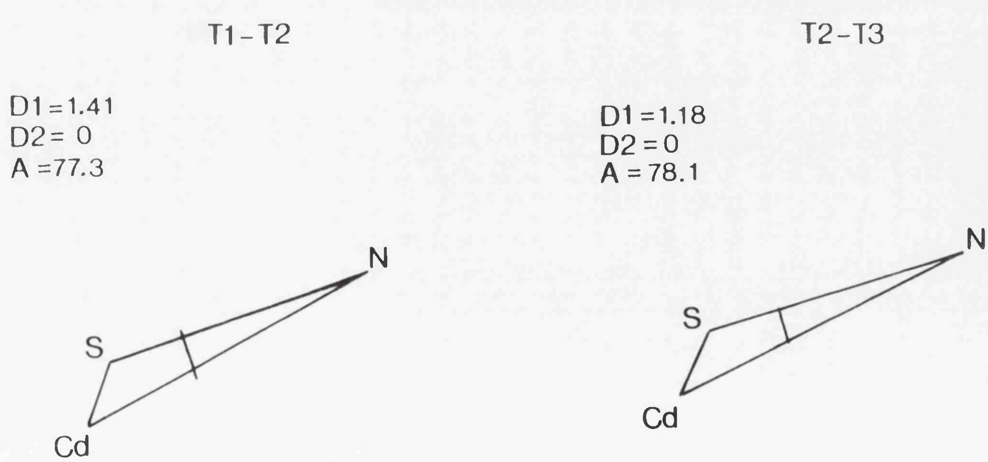


Figure 4.25
The finite element S-N-Cd used to assess surgical and postsurgical changes following bimaxillary osteotomy with rigid fixation (Michigan cases).

C. Element S-N-Cd (Fig. 4.25)

This element elucidates the change in position of the condyle in relationship to the base of the skull. The magnitude of the principal strain show that condylar displacement is minimal.

4.6.2.3 Euclidean Distance Matrix Analysis

The distal segment was advanced about 3 mm, increasing the total mandibular length (Condylion - Genion) by about 3 mm. The net increase of the facial depth (Sella - Genion) was 2.6 mm. The length of the proximal segment (Condylion - Gonion) was almost unchanged (Table 4.14). The distances Sella-Condylion and Nasion-Condylion increased by 1.7 mm and 0.6 mm respectively.

4.6.3 Maxillary changes at 6 months follow up (T2-T3)

The maxilla was stable within 1 mm of its immediate postsurgical position with minimal changes of all cephalometric measurements and Euclidean distances (Tables, 4.13 & 4.14). Changes detected by the finite element S-PNS-ANS (Fig. 4.22) were within measurement error.

4.6.4 Mandibular changes at 6 months follow up (T2-T3)

4.6.4.1 Conventional cephalometric analysis

mean values

The mandible was quite stable with slight rotation in a clockwise direction. Both the mandibular plane angle and ramus angle are increased by 0.4 degree and 0.7 degree respectively. The mandible settled posteriorly by 0.5 degree (Table 4. 13).

Table 4.14 Components of the EDMA used to assess surgical and post-surgical changes of bimaxillary osteotomy (Michigan cases).

End Point Landmarks	Distances (mm) on Occasion			Ratios of distances between occasions	
	T1	T2	T3	(T1/T2)	(T2/T3)
S Cd	22.8	24.5	23.7	1.08	0.97
S Gn	111.0	113.6	113.1	1.04	0.99
S B	112.3	114.5	114.2	1.04	1.00
N Cd	89.5	90.1	90.3	1.02	0.99
GnCd	99.6	102.7	101.8	1.03	1.01
GoCd	55.9	55.2	55.6	0.99	1.01
GnGo	57.0	61.5	61.1	1.08	1.01

T1 Preoperative assessment

T2 Immediate postoperative evaluation

T3 Assessment at 6 months follow up

4.6.4.2 Finite Element Analysis

A. Element S-N-Gn (Fig. 4.23)

This element expresses the postsurgical changes of the distal segment in relation to the base of the skull. The orientation and magnitude of the principal strain demonstrate that the mandible was quite stable and the changes detected are due to inferior rather than posterior settling of the distal segment.

B. Element Cd-Go-Gn (Fig. 4.24)

The changes observed in this element concern the relation between the proximal and distal segments. They are very small and within measurement error.

C. Element S-Cd-N (Fig. 4.25)

The principal strain is almost equal in magnitude and opposite in direction to the principal strain of the same element at the interval (T1-T2). This suggests that the condyle moved in a superior direction to its former position. The direction of condylar adjustment follows the same angle as the direction of inferior displacement during surgery. Removal of occlusal splint is the reason for the superior condylar movement.

4.6.4.3 Euclidean Distance Matrix Analysis

The condyles moved upward after removal of the occlusal splint, this was demonstrated by a decrease of the Sella-Condylion and Nasion-Condylion distances. Some bone remodelling in the form of bone resorption was detected at the condylar surface and at Gonion. This was demonstrated by a decrease in Condylion-Genion distance as well as Genion-Gonion distance by 0.9 mm and 0.5 mm respectively. The facial depth (Sella-Genion) decreased by 0.5 mm (Table 4.14).

A weak correlation existed between the magnitude of mandibular relapse, as measured by changes in SNB angle from immediate postsurgery and at six month follow up, and the presurgical mandibular plane angle ($r=0.3$). However, 45% of the postoperative changes in SNB could be related to mandibular autorotation during surgery. Whereas, 25% of the relapse was due to mandibular advancement (Change in SNB angle from T1 to T2), the correlation coefficient being ($r=0.5$)

Chapter 5

Discussion

5.1 Methods of analysing surgical changes

The past two decades have witnessed extensive development of morphometric theories and methods as well as novel application of these techniques to biological data sets. Finite Element (FE) and Euclidean Distance Matrix (EDM) analyses are examples of these methods. FE and EDM analyses were used in this thesis to assess changes following orthognathic surgical procedures to correct mandibular retrognathia.

Two general classes of morphometric methods can be used to analyse landmark coordinate data: coordinate-based methods and coordinate-free methods. In coordinate-based methods, the choice of the coordinate system is arbitrary: results can be altered by changes of the reference coordinate system. Coordinate-based methods measure shape changes as a deformation from the reference to a target form, or as the fit resulting from superimposition of two forms. Consequently, any change or imprecision in superimposition alters the interpretation of shape change. Coordinate-free methods analyse differences in shapes without reference to a coordinate system. Neither the orientation of shapes nor superimposition method affect the assessment of shape changes.

Finite Element and Euclidean Distance Matrix analyses are coordinate-free methods. An arbitrary coordinate system was only used to check the accuracy of recording cephalometric points at the two occasions of digitization. It was also used to provide a consistent orientation of the finite elements for presentation but does not affect the calculation of the components of FEA. Cephalometric superimposition was not required to assess surgical and follow up changes. These techniques when used to evaluate orthognathic surgery are independent of patient orientation at the time of taking cephalographs. External frame of references e.g Sella-Nasion or Frankfort planes, which are usually required to conduct conventional cephalometric analysis, were not needed when FE and EDM analyses were applied. Therefore, changes at the cranial base due to growth or imprecision of identifying end points of reference planes have minimal effect on the accuracy of these techniques in assessing changes and stability following orthognathic surgery.

Finite element analysis provides three basic types of information about surgical changes.

1. The size difference , as it measures the increase or decrease of the second shape in relation to its initial form.
2. The shape difference, if the values of the principal strains (D1 & D2) are equal it means the second form did not change in shape in relation to its initial form, but it may be increased or decreased in size depending on the values of the principal strains.
3. The pattern of shape difference is evaluated from the direction of the principal strain.

Finite element analysis method does not lend itself to simple statistical analysis, and this is the main problem associated with the method. Statistical studies within-group variation or differences among multiple groups using FEA are also problematic. In this case, an arbitrary single standard element must be chosen, typically the mean of a group of cases. However, the dimensions that distinguish this reference element from each other element are different for each individual and at each nodal point. Thus, a compromise is necessary: choosing a standard element that is "optimal" for a group of cases as a whole, though sub-optimal for each individual. Moreover, the standard element that is the best for contrasting postsurgical changes in relation to presurgical shape may not be useful in describing the follow up changes in relation to the immediate postsurgical shape. Thus, one of the major intuitive advantages of FEA, the sensitive description of shape changes, is partially lost in statistical analysis of multiple individual and group comparisons. Nevertheless, FEA remains extremely useful, especially for the characterisation of surgical changes and stability. Its ability to localise changes between forms to the areas surrounding cephalometric landmarks is particularly valuable, especially when graphically presented. The ability to interpret this method needs a biological understanding of bone physiology as well as surgical techniques.

3 authors

Richtsmeier *et al.* (1992) explained that "if the measure of form difference changes when forms are translated, rotated or reflected, then form difference has not been described optimally". Since the form of an object is invariant under translation, rotation, and reflection, it follows that an approach for comparing forms should start with a representation of the forms that is invariant under those operations. For landmark data, and to assess surgical changes, one such optimal method is based on the analysis of Euclidean distance matrices that are coordinate-free representations of shapes. The strength of EDMA lies in its ability to maintain geometric integrity of shapes while retaining information on individual dimensions. This is done by analysing all linear distances between the cephalometric points simultaneously. This does not mean that all linear distances are equally relevant to the difference between shapes. As in any cephalometric analysis, the surgeon determines the set of landmarks that adequately represents the maxilla or the mandible to evaluate surgical changes and assess long term stability. From the complete set of data, EDMA identifies those inter-landmark distances that are most influential in describing differences between shapes under consideration. EDMA is easier to interpret than FEA, it also lends itself more readily to statistical investigation. The method identifies surgical changes in clinically interpretable linear measures (mm or cm) which may be more useful to clinicians rather than the strains obtained by FEA. Unlike FEA, EDMA does not infer any information about how the interior of the shape may have changed. The only real information obtained is the relative positions of landmarks, or equivalently the distances between them. The surgical changes and long term stability cannot be represented graphically and rotational changes that are demonstrable with FEA cannot be assessed.

These new methods of morphometric analysis, FE and EDM analyses provide a new horizon of evaluating surgical changes. Nevertheless, they appear to complement rather than replace conventional techniques of cephalometric analysis. FE and EDM analyses are sensitive tools that can aid understanding of surgical changes.

5.2 Clinical variations of Mandibular Retrognathia

Patients in this study included three types of mandibular retrognathia. Type I mandibular retrognathic patients present with a round or square face. The upper third of the face appears normal, as does the middle third. The lower third of the face is short and somewhat over-closed, with lip competence and absence of normal inter-labial space. The labio-mental fold is pronounced, the soft tissue chin shows strong projection relative to the lower lip. The mandibular angles are broad. Patients with mandibular retrognathia type I tend to have a greater SNA angle than normal, and SNB angle that is close to normal, an ANB difference that showing the basic antero-posterior discrepancy. The mandibular plane angle is low with prominent bony and soft tissue chin. Occlusal examination demonstrates an Angle Class II cuspid and molar relation, an excessive curve of Spee as well as deep overbite. To correct the deep bite and the mandibular retrognathia, all these cases had orthodontic treatment to adjust the exaggerated curve of Spee and sagittal split mandibular advancement to correct the skeletal deformity. During surgery the mandible was rotated in a clockwise direction to decrease the deep bite.

Severe cases of type I mandibular retrognathia were not included in the study. Such cases have a significantly decreased vertical dimension, with the maxillary teeth being completely hidden beneath the upper lip. In these cases maxillary Le Fort I downfracture with autogenous bone grafting to increase the lower face height and place the upper teeth into a normal position with the upper lip was the surgery of choice. Thus, these cases were beyond the scope of this study.

Patients have good facial proportion in type II mandibular retrognathia. The deformity is not obvious in the frontal view, except in more severe cases when the lower lip rests behind the upper anterior teeth. The nasolabial angle is within normal limits. The chin, however, is retrusive. The labio-mental fold is often pronounced as a result of maxillary dental interferences with the lower lip. The SNA angle is normal with a decreased SNB which is reflected in the increased ANB angle. Both the mandibular ramus and body lengths are a little less than normal. The maxillary arch form is more V-shaped, a Class II cuspid and molar relationship exist. For these patients bilateral sagittal split advancement osteotomy was the treatment of choice, with or without advancement genioplasty. In milder cases only advancement genioplasty was applied to correct the retruded mandibular profile

In type III mandibular retrognathia the face appears long and tapering. The upper third of the face is normal. There is excess length in both the middle and lower thirds of the face. The angles of the mandible are narrow. An excessive amount of upper gingivae is seen even at rest, and variable degrees of lip incompetence are present when the lips are relaxed. The long lower third of the face and retruded chin are evident. The labio-mental fold is less pronounced and some cases show a soft tissue double chin. SNB angle is decreased with a high mandibular plane angle. Mandibular ramus length and body length are less than normal with an increased gonial angle. A Class II molar and canine relationship, with decreased overbite tendency toward open bite exists. For these patients bimaxillary osteotomy was the selected treatment modality. The maxilla was impacted at Le Fort I level and the mandible advanced by sagittal split ramus osteotomy with or without advancement genioplasty. Superior repositioning of the maxilla allows the mandible to autorotate in an antero-superior direction.

The patients were motivated to have orthognathic surgical correction either for disturbance in function or appearance. The most common patient complaints were reduced ability to masticate, temporomandibular joint dysfunction, facial disproportion and an inability to maintain labial seal. The inadequately projected chin and excessive gingival exposure were very noticeable in a large number of the cases.

5.3 Methodological Error

Several studies have been conducted using the finite element method to assess changes in craniofacial morphology. Moss *et al.* (1985) studied craniofacial growth in a group of rats. For each element the computer program determined the direction and amount of the maximum and minimum growth changes in relation to the average age of the rats. The authors concluded that finite element analysis provided absolute quantitative descriptions of cranial skeletal shape and shape changes independent of any external local frame of references. Our study supports this finding. However, Moss *et al.* (1985) study did not consider the possible errors in cephalometric measurements that may affect the sensitivity of finite element analysis

Lavelle, (1989) applied finite element analysis to lateral cephalographs of class I patients before and after orthodontic treatment (extraction and non-extraction) to assess craniofacial shape changes. Lavelle distinguished between the measurement of size or shape changes by summing or subtracting the principal strain values and dividing by two. The author did not comment on the method used to record the coordinates of the nodal points nor did he assess the possible sources of error and their influence on the finite element analysis. The components of finite element analysis that describe the direction of the principal strain in relation to the element's sides were not considered in his study.

Random errors are important in that they add to the natural variability of the measurements and reduce the correlation between variables. The greatest source of random error is the difficulty in identifying a particular landmark. The results of this thesis show that the average absolute distances between repeated digitization of points Infra-dentale, Genion are higher than for the other points. The superimposition of overlying structures e.g arch bar fixation for Infra-dentale point and the bone structure for Genion point may have affected the accuracy of their identification.

Finite element analysis is a method sensitive to small changes in landmark location. The precision of measuring the components of FEA was poor despite the reproducibility of the cephalometric landmarks being excellent with indices of reliability of at least 0.98 (Table 4.1). The small changes in the landmark coordinates between the replicates had a great effect on the calculation of the finite element variables (maximum strain D1, minimum strain D2, Theta A) because of the computational sensitivity of the method. In order to achieve acceptable levels of precision for the finite element components, the level of precision for locating landmarks has to be increased. This can only be achieved by averaging data from replicate digitization. However, the small error in recording the fiducal points that are used for superimposition, would limit the extent to which replication is useful. It is unlikely that FEA will be useful in assessing single cases because of the number of the replicates needed to obtain stable results. Provided there is no systematic bias the effects of random error are reduced for pooled data as the number of cases used increases. Thus, FEA could be a useful tool for studying groups of like cases.

5.4 Genioplasty

Stability of the advanced genial segment is usually reported as very good, irrespective of the method of fixation. However, determination of changes in osseous position are difficult because both translation of the advanced genial segment and osseous remodelling may occur simultaneously. There are warnings in the literature (Precious & Delaire, 1985; Davis *et al.*, 1988) against the use of Pogonion as a reference point when studying the stability of genioplasty. They argue that bone remodelling at this site can invalidate conclusions about skeletal stability since differentiating between changes due to remodelling and repositioning is impossible. In spite of the controversy over the use of Pogonion, it is still the most important landmark to be assessed in any genioplasty study, as it defines the chin prominence and there is no other landmark that can be substituted.

Finite element analysis is a unique method capable of separating changes due to repositioning from those due to remodelling. Repositioning is failure of the bone segment to maintain its position in relationship to adjacent bones. This repositioning may be unrelated to the direction of the movement occurring during surgery. Remodelling is a combination of bone resorption and apposition causing shape change rather than positional change. Bone remodelling can be monitored by changes in the relationship of nodal points (landmarks) to each other in a given finite element. When using EDMA, remodelling was assessed by measuring the distances between landmarks in the same segment of bone. Repositioning was identified by changes detected in the adjacent elements with shared nodes, it was also identified by changes detected in the distances connecting points on adjacent bone segments. Bone apposition occurring at Pogonion is demonstrated by the changes seen in this element (Fig. 4.4a) and the increase in B-Pogonion distance (Table 4.6), Pogonion position is also affected by repositioning of the whole genial segment. Changes at Pogonion due to repositioning of the advanced segment can be identified through the element Id-Me-Gn. Because Infra-dentale and Genion are relatively fixed points and are not affected by genioplasty, any change in the element Id-Me-Gn (Fig. 4.4b) is due to positional change at Menton which has moved away from Genion. This can be only explained by a rotation of the genial segment about its contact with the anterior surface of the mandible (Fig. 5.1). The anti-clockwise rotation of the whole genial segment is also demonstrated by an increase in the Genion-Menton distance and a decrease in the Genion-Pogonion distance (Table 4.6). The major deformations of the elements Gn-Pg-Me & Gn-Id-B (Fig. 4.4a) are approximately parallel to each other due to bone apposition at B point and Pogonion. The direction of the major deformation in the Gn-B-Pg element (Fig. 4.4a) is about 12 degrees different from these. This indicates that the angle of rotation of the genial segment is approximately 12 degrees. Thus Menton point also has rotated in

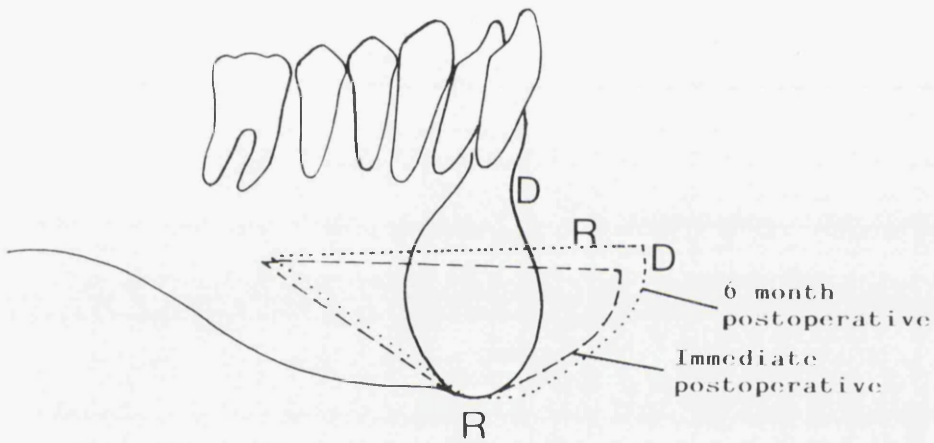


Figure 5.1 Changes of the advanced genial segment during the first six month post surgery. The interrupted line shows the immediate postoperative changes, the dotted line shows the change in the segment position at six month period. "D" represents areas of bone deposition; "R" represents areas of bone resorption.

an anti-clockwise direction during the first six months postsurgery. This rotation of the genial segment upward and forward occurs with a minimal vertical component. It affects the position of Pogonion and the dilatation seen in the element B-Pg-Gn is interpreted as a mixture of local remodelling (apposition) and repositioning of Pogonion (Fig. 4.4a). This postsurgical forward and upward rotation of the genial segment may be the result of postero-superior action and shortening of the mentalis muscles. These muscles were stripped from the underlying genial bone during surgery and became reattached to the advanced segment. Scarring and shortening of this muscle is a possible explanation of the mechanism by which rotation of the genial bone segment occurred and it could also explain the bone resorption seen radiographically at the superior surface of the advanced segment. Variable remodelling patterns of the advanced segment with bone resorption at Pogonion and bony apposition at B point were reported (McDonnel *et al.*, 1977). My findings are in agreement with this study regarding bone apposition at B point, however bone apposition was also detected at Pogonion. The findings of this thesis are in harmony with the results of Bell, (1981). A similar pattern of bone remodelling has been reported when a special bone plate was used for fixing the advanced segment (DeFretias *et al.*, 1992). However, these bone plates may modify the pattern of local bone remodelling at Pogonion so that the changes could be different from other genioplasty fixation techniques. Bone resorption was detected radiographically at the superior surface and the postero-inferior corner of the advanced genial segment. This finding is in agreement with previous investigations of bony changes following advancement genioplasty (Tulasne, 1987; Park *et al.*, 1989; Polido *et al.*, 1991). This bone resorption may be due to periosteal and soft tissue pressure (Fitzpatrick, 1974; Davis *et al.*, 1988).

Many investigators have attempted to establish criteria for predicting changes following genioplasty by means of cephalometric tracings. To obtain and determine a reliable result, it is imperative to use reference planes or landmarks that are not altered by surgery. In the literature several methods have been described that depend on reference planes of doubtful reliability to determine hard and soft tissue changes related to chin surgery. In all of them the postoperative cephalograph was superimposed in some way on the preoperative one to assess the surgical changes at the chin area. However, the influence on the position of the chin of other concomitant surgical procedures (mandibular or maxillary) and changes of orientation of the whole mandible to any reference plane were not considered (Bell & Dann 1973; McDonnel *et al.*, 1977; Bell, 1981; Scheideman *et al.*, 1981).

The osteotomy line was used by Davis *et al.* (1988) as a reference plane to evaluate the changes following advancement genioplasty. The use of an osteotomy cut as a reference plane is debatable. Alterations in this plane may occur from local remodelling, leading to misinterpretation of the changes.

The occlusal plane has been used as a reference plane to assess genioplasty. However, the occlusal plane may be altered when there are changes in the position of the teeth that define its end points. Thus it is potentially unstable as a reference plane for evaluating genioplasty although it has been used for this (Park *et al.*, 1989).

Cranial base superimposition is a method used to determine and predict overall surgical changes of the jaws. However, this method creates problems in the study of dimensional changes of the hard and soft tissues of the chin, because concomitant jaw surgery can affect the mandibular position. Therefore superimpositions based on cranial reference planes such as the Frankfort or Sella-Nasion planes, are not suitable for determining dimensional differences in the chin area unless the rest of the mandible maintains its position in spite of the surgery.

Both FE and EDMA are able to separate changes at the chin occurring through genioplasty from the effects of other simultaneous surgery. The methods do not depend on a remote frame of reference. The superimposition of the finite elements was on their centroids, thus eliminating the effect of other surgery on the chin shape and position.

My study has shown that the standard advancement genioplasty produced excellent results. Bone stability was generally very good no matter what other concomitant orthognathic surgery was also carried out.

5.5 Sagittal split osteotomy

The group of patients treated by sagittal split osteotomy are type I mandibular retrognathia. The nature of this deformity determines the manner in which the surgery is performed. As a result of the decreased lower anterior facial height and deep overbite, the mandible is advanced and rotated in a clockwise direction to decrease the deep bite. Surgical changes should be carefully interpreted bearing in mind the occlusal splint that is used by all the patients in this group at the time of taking the immediate postoperative cephalograph. The occlusal splint also adds to the clockwise rotation of the mandible following surgery. The main surgical changes are the increase of the mandibular length and lower anterior facial height by 6.9 mm and 2.3 mm respectively (Table 4.7). The condyles are displaced inferiorly and posteriorly. This is demonstrated by a decrease of the ramus angle, the principal strain of the finite element S-N-Cd (Fig. 4.10) and the increase of Sella-Condylion and Nasion-Condylion distances (Table 4.8). There are two aspects to this problem, the cause and the effect. The cause of the inferior displacement of the condyle is the occlusal splint which should not affect the stability of the surgical procedure. However, postsurgical changes secondary to posterior condylar displacement are expected and have been of concern to several authors (Gallo *et al.*, 1976; Epker *et al.*, 1978; Souyirs, 1978). Posterior condylar displacement is either due to imprecise manipulation of the proximal segment after mandibular splitting or screw fixation as it has been reported by several investigators as the main disadvantage of rigid fixation (Kundert & Hadjianghelou, 1980; Thomas *et al.*, 1986).

These findings are similar to that group of patients which had simultaneous maxillary impaction and sagittal split mandibular advancement. Therefore, surgical changes and stability following mandibular advancement are compared with another group concurrently investigated who had simultaneous maxillary imapation. This comparative assessment may clarify and highlight the role of different factors in the stability following surgical correction of mandibular retrognathia.

5.6 Bimaxillary Osteotomy

Three groups of patients who had had simultaneous maxillary impaction, at the Le Fort I level, and sagittal split advancement osteotomy are studied in this thesis. Two group of cases had rigid internal fixation, treated at two different centres (Canniesburn Hospital and Michigan University Hospital). In the third group of cases, the maxillary impaction and mandibular advancement were stabilised by non-rigid internal fixation. In all the cases superior repositioning of the maxilla allowed mandibular autorotation; as the mandible autorotated it came forward helping to correct the mandibular retrognathia.

Instead of evaluating the results of each group of patients separately, inter-group comparisons will be considered in the following manner:

1. Comparison between two groups of patients, treated at Canniesburn Hospital, with different fixation technique.
2. Comparison between two groups of patients who had rigid internal fixation and treated at different centres.

5.6.1 Rigid versus Non-rigid Fixation

This assessment was carried out between the two group of cases treated at Canniesburn Hospital with different fixation technique. The study showed that the maxilla is relatively more stable than the mandible following bimaxillary osteotomy. In both groups the maxilla relapsed in an inferior-posterior direction with an increase in the upper facial height by 1 mm and decrease in SNA angle by 0.6

degree (Tables 4.9, 4.11). While these figures are relatively small, they were greater than those reported by Satrom *et al.* (1991). However, the average magnitude of the maxillary impaction in their sample was about 50% less than the impaction in our cases. The posterior maxilla showed only slight vertical settling. Proffit, Phillips & Turvey, (1987) studying single jaw maxillary impaction also found good stability after maxillary superior repositioning with inter-osseous wires. They reported 0.33 mm of maxillary inferior settling, compared with the 0.8 mm reported by Satrom *et al.* (1991) who used additional infra-orbital suspension wires for the maxilla. This data seems to indicate that Le Fort I impaction is generally a stable procedure and postsurgical changes are small regardless of fixation method.

In contrast, the stability of the sagittal split ramus osteotomy differed between the two groups. Mandibular postsurgical changes in non-rigid fixation cases are in general more than with rigid fixation. However, at 6 months postoperatively there was more inferior settling and clockwise rotation of the distal segment in the rigid fixation group than in the non-rigid fixation group. Nevertheless, at the 1 year follow up non-rigid fixation cases showed further increase of the mandibular plane angle by an average of one degree. Posterior and inferior relapse of the distal segment was also detected in addition to local bone resorption at the condylar surface and Gonion. No changes were detected in the rigid fixation cases between six month and one year following surgery.

In the rigid fixation cases the condyles were pushed posteriorly in the glenoid fossae. The principal dilatation of S-N-Cd element (Fig.

4.20) and the increase in the distances Sella-Condylion, Nasion-Condylion illustrate this change (Table 4.12). The condyles were seen to have readjusted their position becoming more central in the glenoid fossa at the six month follow up assessment. The posterior condylar displacement during surgery and the anterior shift during the first six month postsurgery may be in part responsible for the mandibular clockwise rotation, seen in the rigid fixation cases. In non-rigid fixation, the condyles were more central in their fossae, they were slightly displaced inferiorly due to the occlusal splint. This inferior displacement is shown by increase in S-Cd distance, which returned to normal after removal of the splint (Table 4.10).

Schendel & Epker, (1980) reported that distraction of the mandibular condyles from their functional position in the glenoid fossae results in dramatic skeletal relapse immediately upon release of intermaxillary fixation. This skeletal relapse occurs because of a large discrepancy between the functional occlusal position (centric occlusion) and terminal hinge position (centric relation). Lake *et al.* (1981), also found the position of the proximal segment to be the predominant influence on postoperative stability.

The main disadvantage of mandibular rigid fixation, as reported by Thomas *et al.* (1986) is the alteration of the relationship of the mandibular condyle to the fossa. They explained that wire osteosynthesis may allow some orthopaedic repositioning of segments in the postoperative period which is impossible following rigid fixation. This finding has been also confirmed by Kundert & Hadjianghelou, (1980) their results showed larger displacements of the condyles with screw fixation than when using inter-osseous wiring.

In both groups, the distal segments rotated in an anti-clockwise direction to maintain occlusal contact during surgery. This type of rotation may also play an etiologic role in the relapse seen in both groups. The elevator muscles of the mandible may cause an upward shift of the posterior part of the mandible while the supra-hyoid muscles rotate the anterior part of the distal segment downward and backward resulting in a posterior translation and rotation of the mandible.

During surgery, the gonial angle in the rigid fixation group was unchanged. However, both the distal and proximal segments rotated in an anti- clockwise direction (Table 4.11). The distal segment rotated during its advancement, following the maxillary occlusal plane. This rotation brought the lower posterior corner of the distal segment (lingual plate) more inferiorly in relation to the proximal segment. Thus, the increase in the Condylion-Gonion distance seen as a surgical change (T1-T2) (Table 4.12) may be explained as an inferior anatomical transposition of Gonion point secondary to anti-clockwise rotation of the distal segment (Fig. 5.2). This type of distal segment rotation would only occur in cases with a deep curve of Spee and a long horizontal lingual bone cut during sagittal osteotomy. The anti-clockwise rotation brought the lower posterior corner of the distal segment (Lingual plate) more inferiorly in relation to the proximal segment and increased Condylion-Gonion distance. The proximal segment was also rotated in anti-clockwise direction secondary to the postero-inferior displacement of the condyle. In the non-rigid fixation group the gonial angle increased

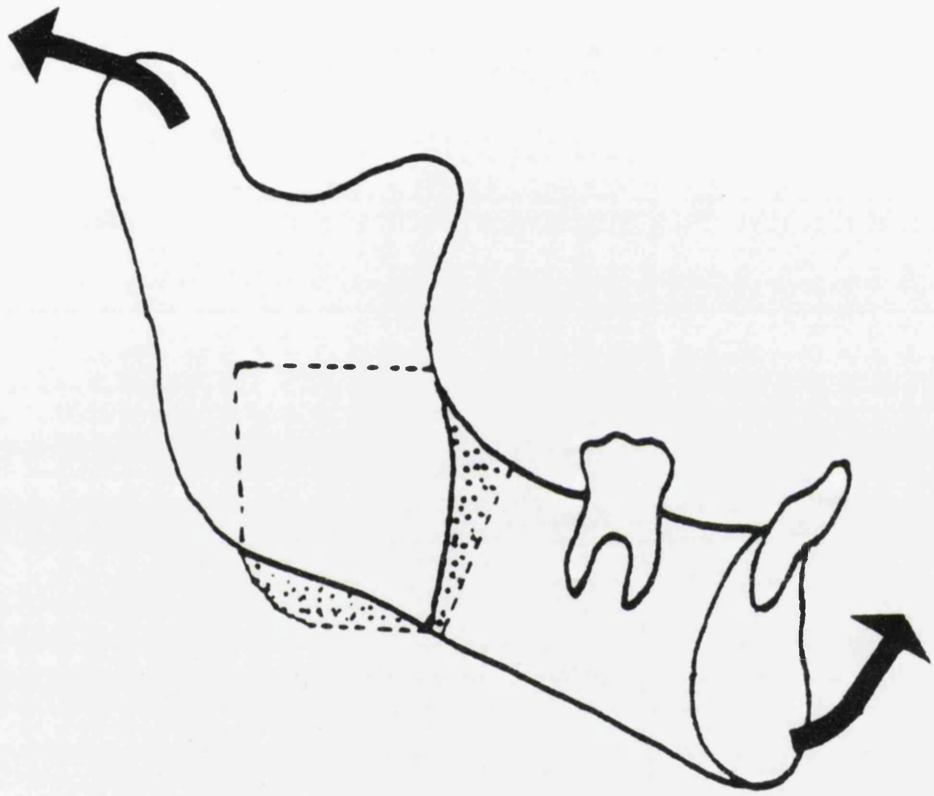


Figure 5.2 Rotation of the proximal and distal segments during sagittal split osteotomy. The distal segments rotated in an anti-clockwise direction with inferior transpositioning of Gonion inferiorly. The proximal segment displaced in inferior and posterior direction.

during surgery secondary to clockwise rotation of the distal segment (Table 4.9).

The gonial angle was stable in our rigid fixation cases but increased by an average 1.8 degree in the non-rigid cases during the first year postsurgery. The mandible rotated in a clockwise direction as one unit in the rigid fixation cases, whereas, the distal segment rotated independent to the proximal segment in the non-rigid fixation cases. Zauthor
Similar finding was reported by Satrom *et al.* (1991), they showed opening of the gonial angle of about 1.5 degrees for the rigid fixation group and 4.2 degrees for the wire fixation group. Reitzik & Schoorl, (1983) investigated histologically and biochemically the bone repair in the mandible at the osteotomy site. They concluded that rigid fixation produced primary bone healing that was denser and stronger than non-rigid fixation.

Therefore, the difference in stability of the gonial angle between rigid and non-rigid fixation groups may be due to the quality of bone formed at the osteotomy site. Rigid fixation appears to produce a denser and stronger bone scar at the osteotomy site which prevents the distracting muscles forces causing opening at the gonial angle.

Ellis & Carlson, (1983) showed that the supra-hyoid muscle pull at the distal segment may be stretched by the advancement procedure. The effect of this tension is to cause posterior and inferior displacement of the distal segment. These forces have minimal effect in rigidly fixed osteotomies, however they have significant influence in the non-rigid fixation cases. In non-rigid fixation cases, these forces may cause opening of the gonial angle. The results of our study support this hypothesis.

Assessment of relapse as a percentage of the achieved surgical changes is not ~~an~~ a very useful approach to explain this phenomenon. It is dependent on the measurements chosen as well as the magnitude of surgical changes. Percentage changes neither explain the mechanism of relapse nor the components of relapse in term of remodelling and repositioning. In our rigid fixation cases, the mandibular relapse was 26% of the achieved reduction of the mandibular plane angle during surgery, 38% of the increased SNB angle due to distal segment advancement, and 40% of the increased mandibular length as measured from Sella to Genion. No one of these values is more informative than the other, each parameter explains one aspect of mandibular change. Attempts at analysis of individual measurements of the maxillo-mandibular complex when multiple interrelated variables are involved should be undertaken carefully, as these changes rarely occur as isolated events. Relapse occurs in three dimensions and requires great care in evaluation. Moreover, in most of the studies, the reported percentage for mandibular relapse was related to a single parameter which does not add to the understanding of the complex changes occurring post-surgically.

Lake *et al.* (1981) reported 26% mandibular relapse following advancement osteotomy, 25% relapse was reported by Schendel & Epker, (1980) while was less than the relapse of 40% reported by Kohn, (1978). However, this relapse is much greater than the 9% reported by Ellis & Gallo, (1986) but their investigation was during fixation period only. In all these reports the mandibular advancement was with wire fixation only. In studies of double jaw ? while surgery, mandibular relapse with wire fixation has been reported to be 14% by Brammer *et al.* (1980) 27% by Wade, (1988) and 20% by Turvey *et al.* (1988) On the other hand with rigid internal fixation, Van Sickels *et al.* (1986) reported 8% mandibular relapse and 6% was reported by Satrom *et al.* (1991). These authors used SNB and ANB angles to evaluate mandibular changes. These are insensitive measures of mandibular change. The mandible may rotate superiorly or inferiorly with little change in ANB angle. On the other hand, ANB angle cannot separate primary mandibular changes from secondary effects on mandibular position arising from maxillary repositioning.

The correlation between mandibular relapse, as measured by the change in SNB angle from the immediate postoperative to one year follow up, and the magnitude of surgical mandibular advancement was different in the two groups. A stronger correlation existed in the non-rigid fixation group where 34% of relapse could be explained by the magnitude of mandibular advancement. In the rigid fixation group 16% of relapse could be explained by the degree of surgical advancement. The influence of the presurgical mandibular plane angle on mandibular relapse was more pronounced in the non-rigid fixation group. In these cases the correlation between the preoperative mandibular plane angle and postoperative changes in SNB angle was 0.5. Thus 25% of relapse in this group is related to the preoperative mandibular plane angle. In the rigid fixation group no correlation existed between relapse and presurgical mandibular plane angle. It seems that when using rigid fixation the effect of variables such as the preoperative form and magnitude of surgical changes have less influence on mandibular relapse than the same factors have when non-rigid fixation is used. Condylar position following mandibular advancement surgery has been evaluated by a limited number of investigators. Freihofer & Petresevic, (1975) studied 38 patients who had had bilateral sagittal osteotomy for mandibular advancement. Although ten of 26 condyles appeared to be positioned anteriorly in the glenoid fossae, differences in projection angle made direct comparison with preoperative films impossible.

To assess the condylar position following surgery, the condylar position of 14 patients who had mandibular advancement were analysed by Kundert & Hadjianghelou, (1980). Circumferential wiring was used for fixation of the proximal and distal segments of 50% of the patients, in the rest of them screw fixation was applied. Temporomandibular joint tomograms, lateral oblique ramus films, and postero-anterior skull films were taken prior to surgery and at the fifth week of follow up. The lateral oblique radiographs were used to measure the dimension of the joint space anteriorly, cranially and posteriorly. In 75% of the condyles studied there was a narrowing of the joint space that was explained as posterior condylar displacement. Fifty percent of the condyles also exhibited changes in axial inclination. The displacements of the condyle was greater when using screws than when using circumferential wiring.

Satrom *et al.* (1991) reported an increase in the Articulare-Gonion distance at surgery. They explained this as surgical oedema in the bilaminar tissue of the temporomandibular joint. Nevertheless, Articulare is liable to change with any rotation in the proximal segment so it cannot be used to measure changes at the condylar surface.

Several authors have proposed techniques and devices by which the correct position of the proximal segment can be maintained during surgery (Booth, 1981; Will *et al.*, 1984; Epker & Wylie, 1986). None of these techniques, however, could be easily used in procedures involving both the mandible and maxilla. These techniques also failed to maintain the position of the proximal segment in the three dimensions during fixation of the bone segments. Condylar positioning appliances have not been tested for their reliability as a tool in maintaining the proximal segment in the same position postsurgery as it was.

Several causes of mandibular relapse following sagittal split advancement osteotomy have been suggested. These include; the influence of the supra-hyoid musculature, inadequate periods of maxillo-mandibular fixation, inadequate fixation between the proximal and distal segments, insufficient bony union, and condylar distraction. In our sample the rigid internal fixation between the proximal and distal segments ensured bony union. Nevertheless, some mandibular relapse was detected. During surgery the proximal segment was pushed posteriorly in the glenoid fossa (Fig. 4.20) (Table 4.12). Similar findings were reported by Kundert & Hadijianghelou, (1980), they measured the temporomandibular joint spaces anteriorly, posteriorly and cranially to document the condylar changes during surgery in 14 cases of mandibular advancement. They noted that in 75% of the condyles studied, there was a narrowing of the joint space concomitant with posterior condylar displacement.

Skeletal relapse following surgical advancement of the mandible is multi-factorial. In our sample, the distraction of the mandibular condyle during surgery was thought to be the primary mechanism causing mandibular relapse in the rigid fixation cases. During surgery the proximal segment was manipulated in an attempt to maintain its presurgical anatomical position. The achievement of this requires clinical judgement which is liable to error. In wire fixation cases, the non-rigid fixation and the quality of bone formed at the osteotomy site allowed self-adjustment of the proximal segment into its anatomical position. The small movements between the proximal and distal segment as a result on non-rigid fixation allow self correction of any clinical error to placement of the condyle in its fossa. In this situation the condyle has only secondary effect on mandibular position following surgery in non-rigid fixation cases.

Wessberg *et al.* (1982) showed that skeletal relapse following surgical advancement of the mandible was not significantly influenced by supra-hyoid myotomy. In our rigid fixation cases the supra-hyoid muscles although not primarily responsible for mandibular relapse, may be a contributory factor. However, the role of supra-hyoid muscle pull is more important in non-rigid fixation cases. The relapse noted in that group of cases was thought to be due to tension exerted by the stretched supra-hyoid muscles on the advance distal segment. Opening of the gonial angle and the clockwise rotation of the distal segment tends to support this role of the supra-hyoid muscles in mandibular relapse.

Finite element analysis allows evaluation of remodelling changes at the proximal segment. In the rigid fixation group the element Cd-Go-Gn (T2-T3) (Fig. 4.19) shows the major axes of deformation to be parallel to Gonion-Genion line with a 4 mm decrease in the Genion-Gonion distance (Table 4.12). These findings are due to local bone resorption at Gonion, since Genion was not affected by surgery. The other minor axes of deformation of the same element were interpreted as arising from local bone remodelling (resorption) at the condylar surface. This finding is supported by the 3 mm decrease in the Condylion-Genion distance (T2-T3) and the deformation occurring in the element S-N-Cd.

Most of the measuring methods that have been used to assess changes following orthognathic surgery have been based on cranial base superimposition of patients' cephalographs. As has been explained by Moyers & Bookstein, (1979) changing the plane of orientation and superimposition alters the perception of the surgical changes. The traditional cephalometric measurements cannot separate the primary changes of the mandible from secondary change due to alteration in maxillary position in bimaxillary osteotomy cases. It also does not differentiate remodelling from repositioning which is of clinical importance.

The interpretation of surgical changes shown by EDMA or finite element analysis requires both surgical and biological understanding. EDMA is an easier method to understand and apply. It lends itself to statistical manipulation more readily than finite element analysis. However, it cannot be used to assess the rotational changes that are illustrated with finite element analysis. Like other morphometric techniques, they can be used to test hypotheses or as an exploratory method to gain insight into shape changes. These new methods of morphometric analysis appear to complement rather than replace more conventional techniques and are sensitive tools that aid the understanding of surgical changes.

The variability of individual patient response, the limitations of cephalometric assessments, and the difficulties in obtaining adequate samples of sufficiently similar procedures are factors that help account for the variety of changes reported in the literature.

The following conclusions are drawn from the study:

1. The Le Fort I maxillary osteotomy was a stable surgical procedure with little differences between rigid and non-rigid fixation. In both fixation techniques the maxilla stayed within 1 mm of its postsurgical position.

2. There was a difference in the magnitude and pattern of mandibular relapse following sagittal split advancement osteotomy between rigid and non rigid fixation subjects. The mandible was more stable in the rigid fixation group.

3. Rigid fixation produced better control of the angle between the proximal and distal segment. This rotation control appeared to be an important factor in the increased overall stability of the rigid fixation sample.

4. Rigid internal fixation was associated with posterior displacement of the condyles.

5. Finite Element and Euclidean Distance Matrix analyses do not require cephalometric superimposition, and do not depend on a remote frame of reference e.g Sella-Nasion plane. These new methods of morphometric analysis are sensitive tools that aid in the understanding of surgical changes. They are able to separate only changes in the maxilla from these in the mandible as well as bone remodelling from repositioning which are the components of clinical relapse.

5.6.2 Canniesburn versus Michigan Cases

The result of this investigation demonstrate that the maxillary Le Fort I osteotomy is more stable than mandibular advancement in both samples. The average maxillary surgical changes in Michigan cases were advancement and only slight impaction. Whereas, for Canniesburn cases maxillary impaction was the predominant maxillary surgical change with only slight advancement. In both groups the maxilla was stable and stayed within 1 mm of its immediate postsurgical position (Tables, 4.11, 4.12, 4.13, 4.14).

The mandibular position for Michigan cases was relatively more stable than the cases treated at Canniesburn. Three general factors could be implicated in the difference of mandibular stability between the two groups.

1. Severity of the mandibular retrusion and the mandibular plane angle (MPA).
2. Problems with surgical technique.
3. Physiological adaptation of the oro-facial musculature to alteration in form and function.

1. Severity of mandibular retrusion and MPA: ?what were they

Despite using quite restrictive criteria for case selection in order to obtain closely matched samples from the two centres, some general differences in the presurgical morphology were found. The cases treated at Canniesburn showed more severe mandibular retrusion, shorter mandibular body length and a more obtuse mandibular plane angle than the cases treated at Michigan (Tables 4.11, 4.13). The average lower posterior facial height was much less in Canniesburn group than the Michigan group. There is a considerable debate in the literature concerning a correlation between postoperative stability and the magnitude of presurgical deformity. Lake *et al.* (1981) found a positive correlation between increasing mandibular plane angle (MPA) and a tendency to relapse. However in their sample the patients with high MPA underwent greater advancement which may have been a further contributory factor for relapse. Hiranaka & Kelly, (1987) showed no relationship between MPA and surgical advancement of the mandible in their study of the sagittal split ramus osteotomy. This is in agreement with previous investigations (Ive *et al.*, 1977; Smith *et al.*, 1985) but their studies were restricted to the immediate postoperative period during inter-maxillary fixation. Kohn, (1978) similarly found no association between preoperative MPA and relapse in a long term study. The literature is thus inconclusive on the role of facial form in relation to relapse. ?authors ×2

2. Surgical technique problems:

Bell *et al.* (1980) showed that poor treatment planning, compromise of the blood supply to the osteotomy site, inadequate inter-osseous fixation and condylar distraction were among the factors causing relapse following mandibular advancement. The surgical technique used in the two centres was the same. However, EDMA showed that for the Canniesburn group the condyles were displaced 1.7 mm posteriorly during the surgery (Table 4.12) but inferiorly by about 1.7 mm for the Michigan group (Table 4.14). These differences account for the variation between the two groups shown in geometry of element S-N-Cd in the two groups (Figs. 4.20, 4.25). The principal strain on the S-N-Cd element and the increase in the distances Sella-Condylion, Nasion-Condylion illustrate this change. During surgery placement of the proximal segment into its anatomical presurgical position relies on clinical judgement and technique. There seems to be a difference in the way which the proximal segment is manipulated between the two groups.

In the Michigan cases the inferior displacement of the condyle seen was due to the occlusal splint left in place during surgery. Removal of the splint caused slight mandibular autorotation and adjustment of the condyle in its fossa. In the Canniesburn cases, however, the posterior displacement of the condyle may be the primary factor responsible for the clockwise rotation of the mandible during the first six month post surgery. Finite element analysis shows that the condyle readjusted its position to the presurgical anatomical relation. The forward movement of the condyle during the first 6 months after surgery is likely to be a contributory factor to mandibular relapse.

3. Adaptation of the oro-facial musculature:

A third factor that could have affected the amount of tension generated by the supra-hyoid muscles, and therefore the amount of relapse, is the magnitude of mandibular advancement. The mandibular length was increased by 6.6 mm in Canniesburn cases in comparison with 3.1 mm in the Michigan cases. The hypothesis that the amount of skeletal relapse is related to the amount of the surgical change was mentioned by Ive *et al.*, (1977) and evaluated by Lake *et al.*, (1981) whose figures showed that a third of the relapse could be explained by the extent of the surgical change. It has been suggested that large advancements, of more than 7 mm, stretch the surrounding muscles and connective tissue (Van Sickels *et al.*, 1986). Until adaptation to the new position occurs, this could cause forces to act at the osteotomy site that might lead to relapse. However, rigid fixation techniques have proved to be superior to wire osteosynthesis in preventing this complication (Souyirs, 1978). Rigid internal fixation allowing primary bone healing and is a prerequisite for minimising relapse permitting physiological adaptation at the muscle-tendon and tendon-bone interfaces (Spiessl & Tschopp, 1980; Spiessl, 1982).

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In our study two groups had internal rigid fixation for both the maxilla and mandibular osteotomies. The supra-hyoid muscles, although not primarily responsible for mandibular relapse, may be a further contributory factor.

Epker *et al.* (1978) described three types of mandibular movements in advancement cases. Type I clockwise and forward movement; type II straight forward movement; type III anti-clockwise and anterior movement. Type III mandibular movement cases have been found to have high incidence in relapse. The muscles of mastication are lengthened in the ramus area. As these muscles attempt to

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return to their original positions, they rotate the mandible in a clockwise direction. In Michigan cases the distal segments were advanced in a straight forward movement (type I) whereas in Canniesburn cases the distal segments were advanced and rotated in an anti-clockwise direction which may contribute to the relapse observed. Despite the fact that rigid fixation generally prevents this movement, it may still occur to a lesser degree.

In conclusion, the difference in extent of relapse between the two groups would seem to be explicable in two ways either the difference in preoperative form and extent of surgery, or the position of the proximal segment at surgery, or possible a combination of the two. The preoperative form and the desired magnitude of mandibular advancement are not within the control of the surgeon. However, the posiiion of the proximal segment during surgery is under his control. The number of cases in both groups was too small to obtain sub samples matched on morphology and the extent of surgery which would have allowed us further examination of the relative influence of these relapse factors. Larger scale studies will be needed for this.

5.7 Sagittal split versus Bimaxillary osteotomy

Simultaneous mobilisation of both jaws to achieve a harmonious facial aesthetics produce the most effective correction of the occlusion (Epker *et al.*, 1982; Bell, Jacobs & Quezeda, 1986; Turvey *et al.*, 1988). In addition, several studies have shown that there are clinical, biological, and biomechanical advantages for performing simultaneous two-jaw repositioning (Gross & James, 1978; Finn, *et al.*, 1980; Throckmorton, Finn & Bell, 1980; Bell

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& Jacobs, 1981; Bell, Sinn & Finn, 1982; LaBanc *et al.*, 1982; Turvey, 1982; Bell, Jacobs & Legan, 1984). Using a biomechanical model of jaw function, Finn *et al.* (1980) have suggested that mandibular advancement by itself dramatically decreases the mechanical efficiency of the masseter and temporalis muscles. The practical consequence of decreasing the mechanical advantage is elevated muscle activity for similar functional manoeuvres. Increased force is thus required to do equivalent work. The increased force associated with the adductor-depressor fore coupling during the closing phase of the mastication tends to generate rotatory movement in the area of least resistance, the site of sagittal split osteotomy. Using a similar model, Throckmorton *et* 3 authors *al,* (1980) showed that superior repositioning of the maxilla accompanied by mandibular autorotation increases the efficiency of the jaw adductors. According to their model, when mandibular advancement is necessary, the deleterious alteration in mechanical advantage and muscle activity tends to be offset by the favourable effect of maxillary intrusion.

However, there is considerable debate in the literature concerning the biomechanical role of maxillary impaction in improving the stability of mandibular sagittal split osteotomies. LaBanc *et al.* 3 authors (1982) reported increased relapse with two jaw procedure as compared to a single jaw surgery when they evaluated 100 patients with bimaxillary surgery and wire fixation. On the other hand, Hiranaka & Kelly, (1987) reported that the overall stability of the mandibular surgery is increased by concomitant maxillary impaction. Hennes *et al.* (1988) reported that maxillary impaction does not contribute to mandibular stability when they compared their results with those of isolated mandibular advancement surgery.

In an attempt to resolve conflicts in the literature concerning the effect of maxillary impaction on mandibular stability, the results of our two groups (sagittal split osteotomy versus bimaxillary osteotomy) were compared. In the cases which had only a sagittal split osteotomy at Canniesburn Hospital, the main surgical change was 6.9 mm increase in the mandibular length as measured by the distance Condylion-Genion (Table 4.18)). The distal segment rotated slightly in a clockwise direction this was partially due to the thickness of the occlusal splint in site at the time of taking the immediate postoperative cephalograph. These cases were of type I mandibular retrognathia with a decreased lower anterior facial height and a deep bite so that the clockwise rotation of the distal segment was desirable during surgery. The cases treated by simultaneous maxillary impaction, were type II and III mandibular retrognathia with an increased anterior facial height and mandibular plane angle. In these cases the mandible rotated in an anti-clockwise direction by about 6.6 degrees. The mandibular lengths were increased by an average of 6.6 mm. The angle SNB increased in both groups by an average of 5.4 degrees. The ramus angle was decreased by 7.8 degrees in bimaxillary cases and decreased by 4.5 degrees in sagittal split advancement cases. This difference in ramus angle was not surprising because in cases of bimaxillary osteotomy the whole mandible rotated in an anti-clockwise direction following maxillary impaction. However, in both groups the proximal segment rotated in anti-clockwise direction with the condyles being displaced posteriorly and inferiorly (Tables 4.8, 4.12) (Figs. 4.10, 4.20).

The magnitude of mandibular postsurgical changes (relapse) seen at 6 months follow up was similar in both groups (Bimaxillary and sagittal split groups) with slight tendency to be less in single jaw surgery cases. Relapse was mainly in the form of mandibular clockwise rotation where the condyles returned to their former position following surgery. In single jaw surgery cases the mandible rotated about 1.4 degrees (Table 4.7), element S-N-Gn shows this rotation (Fig. 4.10). In bimaxillary osteotomy cases the mandible rotated 2.5 degrees in anti-clockwise direction. This was measured using mandibular plane angles. The increase of ramus angle was more in bimaxillary cases than in sagittal split cases (Tables 4.7, 4.11) due to the rotation of the mandible as a one unit in a clockwise direction.

At the one year follow up no changes were detected in bimaxillary cases, whereas, a different remodelling pattern was detected in the sagittal split osteotomy cases. Finite element analysis was sufficiently sensitive to detect these changes. Gonion moved anteriorly and superiorly in a more vertical direction than occurred at 6 months following surgery. The element Cd-Go-Gn (Fig. 4.9) showed this changes. Conventional cephalometric measurements were not sensitive enough to detect these remodelling changes, however, the graphical presentation of finite elements illustrated these changes more clearly. The remodelling observed at the surface of the condyle and at Gonion is a form of self alteration to achieve equilibrium when the surrounding musculature is stretched beyond its biological limitations.

The general concept that mandibular advancement decreases the mechanical advantage of the masseter and temporalis muscles should be undertaken carefully. This would have occurred only when the mandible was advanced and rotated in an anti-clockwise direction which would have increased the length and tension of the mandibular adductors. On the other hand, mandibular advancement with a clockwise rotation was a stable procedure due to the increased mechanical advantage of the masseter and temporalis. As a result of decreasing posterior facial height by simultaneous maxillary impaction, autorotational advancement of the mandible was increased while absolute ~~mandibular~~ advancement of the mandible was decreased. Furthermore, any posterior maxillary impaction minimises the necessity for an anti-clockwise rotation of the distal segment. Thus, the bony interface is optimised, the enveloping soft tissue tension is minimised, and the biomechanical efficiency of the masticatory apparatus is increased.

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Cases of bimaxillary osteotomy treated at Canniesburn hospital did not seem to gain the ultimate benefit of a simultaneous maxillary impaction. The favourable effect of maxillary impaction was offset by the unfavourable anti-clockwise rotation of the advanced distal segments. Cases with sagittal split osteotomy only were mostly of a type I mandibular retrognathic nature, where the distal segment was advanced with minimal rotation. The mandibular postoperative changes observed in both groups were similar in pattern and direction.

It would seem that displacement of the condyle during surgery plays an initial role in this relapse. Nevertheless, the possible influence of the stretched supra-hyoid muscles on mandibular relapse can not be ignored. The condyles were displaced posteriorly during surgery in both groups. The ramus angle was decreased by 4.5 degrees in the sagittal split group, but this was mainly due to posterior rotation of the proximal segment. At the six month follow up the ramus angle increased by 0.6 degrees instead of decreasing by 1 degree as a result of removing the occlusal splint. The whole mandible rotated in a clockwise direction with an increase of both ramus and mandibular plane angles. This postsurgical rotation resulted from a condylar adjustment following surgery.

It is reasonable to conclude that in these cases, mandibular stability was not influenced by impaction of the maxilla as was shown in a model by Throckmorton *et al.* (1980). This result is similar to the findings of Hennes *et al.* (1988) as they showed that there was no influence of simultaneous maxillary impaction on mandibular stability. In their study, bimaxillary osteotomies were stabilised with internal rigid fixation. This is contrary to the findings of studies done by LaBanc *et al.* (1982) and Hiranaka & Kelly, (1987). The first study consisted of 100 patients with bimaxillary surgery and wire fixation, there appeared to be increased relapse in bimaxillary procedures as compared to single jaw surgeries (LaBanc *et al.*, 1982). In the second study in a sample of 18 cases who had had simultaneous bimaxillary osteotomy with wire fixation, it was observed that mandibular relapse decreased when mandibular surgery was performed in combination with maxillary impaction (Hiranaka & Kelly, 1987). Perhaps, the biomechanical advantage of

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temporalis and masseter muscles as a result of maxillary impaction may play a secondary role in mandibular stability when rigid internal fixation is used. In general, the groups of patients studied in this thesis were not sufficiently large to permit a statistical validation of the adjunctive procedures for stabilisation.

It would seem that these adjunctive modalities should be considered with larger advancement of the mandible or when cephalometric prediction studies indicate that the biomechanical environment is unfavourable with regard to stability.

It is clear that there are many factors contributing to the postoperative skeletal changes observed following simultaneous repositioning of the maxilla and mandible. Further studies are recommended with more homogeneous and larger samples to identify precisely the role of each factor in mandibular stability.

5.8 Recommendations for further studies

Perhaps we have stretched the usefulness of measurements from landmarks on lateral cephalographs to their extreme limit as a tool for assessing surgical changes and long term stability. Relapse occurs in three dimensions and unless implants, as internal bone markers, are placed within each bone segment during surgery, further improvement in the understanding of the location and mechanisms of relapse will be difficult to obtain. Implants have been used previously to assess craniofacial growth and they can provide an additional dimension in the understanding of growth to that possible with conventional cephalometric methods.

This study had highlighted the importance of the condylar position in the overall stability of sagittal split osteotomy. A variety of condylar position guiding appliances are available and their usefulness for improving control and stability in orthognathic surgery should be assessed..

This study had focused on skeletal changes following different orthognathic surgical procedures only in two dimensions. More comprehensive investigations are recommended to allow three dimensional assessment of surgical and postsurgical changes. Evaluation of the condylar position, in a medio-lateral direction, following sagittal split osteotomy may explain some of occlusal and skeletal alterations seen after surgery.

Multi-centre studies are highly desirable to compare and contrast surgical changes and the stability of similar group of cases. These studies would need to standardise surgical techniques, methods of assessment and this should increase the predictability of orthognathic surgery.

Further investigations that might clarify more precisely the mechanism of relapse would be beneficial when determining methods of prevention. In addition, further studies analysing the soft tissue changes associated with combined maxillary and mandibular procedures would lead to a closer approximation of the clinical and aesthetic results achieved. The patient's ultimate aesthetic outcome resides not so much within the skeletal changes brought about by surgery, but more with the resulting soft tissue changes.

CONCLUSIONS:

1. The new methods of morphometric analysis, FE and EDM analyses provide a new horizon of evaluating surgical changes. They are able to separate changes in the maxilla from those in the mandible, as well as bone remodelling from repositioning, which are the components of clinical relapse. Nevertheless, they appear to complement rather than replace conventional techniques of cephalometric analysis.

2. Averaging the data from replicate digitisation of cephalographs increases the level of precision for locating landmarks used for cephalometric analysis.

3. The stability of standard advancement genioplasty is very good no matter what other concomitant orthognathic surgery is carried out.

4. The Le Fort I maxillary osteotomy is a stable surgical procedure with little difference between rigid and non-rigid fixation. In both fixation techniques the maxilla stayed within 1 mm of its immediate postsurgical position.

5. There is a difference in the magnitude and pattern of mandibular relapse following sagittal split advancement osteotomy between rigid and non- rigid fixation subjects. The mandible is more stable in the rigid fixation group.

6. Rigid fixation produces better control of the angle between the proximal and distal segment. This rotation control appears to be an important factor in the increased overall stability of the rigid fixation sample.

7. Rigid internal fixation is associated with posterior displacement of the condyles.

8. In cases which had bimaxillary osteotomy, there was no influence of simultaneous maxillary impaction on mandibular stability.

9. Cases of bimaxillary osteotomy treated at Michigan University Hospital showed more stable results than those treated at Canniesburn Hospital. The number of patients studied in these groups, however was not sufficiently large to elicit statistical significance.

10. It was not possible to identify statistically the factors which contributed to the factors contributing to the postoperative skeletal changes observed following simultaneous repositioning of the maxilla and mandible. Further studies are recommended with more homogeneous and larger samples to identify precisely the role of each factor in mandibular stability.

Finite element and Euclidean distance matrix analyses should be more widely used as tools for evaluating shape changes. This would allow for a deeper understanding of the changes occurring following orthognathic surgery.

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THE FOLLOWING PUBLICATIONS AND PRESENTATIONS INCLUDE MATERIAL PRESENTED AS PART OF THIS THESIS

A. PUBLICATIONS:

1. Papers Accepted for Publication:

I. Evaluation of changes following advancement genioplasty using Finite Element Analysis.
Brit J Oral Maxillofac Surg (In Press)
Ayoub, A.F., Stirrups, D.R. & Moos, K.F.

II. The practicability of Finite Element Analysis for assessing changes in the craniofacial morphology from cephalographs.
Arch Oral Biol (In Press)
Ayoub, A.F., Stirrups, D.R.

III The stability of Bimaxillary osteotomy after correction of skeletal class II malocclusion
Int J Adult Orthod & Orthog Surg (In Press)
Ayoub, A.F., Stirrups, D.R., Moos, K.F.

2. Papers Submitted for Publication:

I. The assessment of chin surgery using a coordinate free method.
Int J Cranio Maxillofac Surg
Ayoub, A.F., Stirrups, D.R., Moos, K.F.

II. The stability of bimaxillary osteotomy after correction of class II skeletal deformities

Int J Adult Orthod Orthog Surg

Ayoub, A.F., Stirrups, D.R. & Moos, K.F.

III. Relapse following simultaneous maxillary impaction and mandibular advancement: A two centre study (Michigan University Hospital and Canniesburn Hospital)

Am J Oral Maxillofac Surg

Ayoub, A.F., Tratmon, C., Stirrups, D.R. & Walmot, J.

4. Published abstracts:

I. The application of finite element analysis to evaluate genioplasty.

J Dent Res, 1992, 72:7

Ayoub, A.F., Stirrups, D.R., Moos, K.F.

II. Comparison between finite element and conventional cephalometric analyses measurements to evaluate genioplasties.

Brit J Oral Maxillofac Surg, 1992, 30:338-346

B. PRESENTATIONS TO SCIENTIFIC SOCIETIES:

1. How do condylar abnormalities affect mandibular growth.

Presented to the British Association of Dental Research

Newcastle Upon Tyne

18-21 April 1991

2. Comparison of cephalometric and Finite Element measurements to evaluate genioplasties.

Presented to the British Association of Oral & Maxillofacial Surgeons.

Glasgow

24-27 April 1992

3. The application of Finite Element Analysis to evaluate genioplasty.

Presented to the International Association of Dental Research

Glasgow

1-4 July 1992

4. Relapse following bimaxillary osteotomy for class II skeletal deformity: Rigid versus non-rigid fixation

Presented to the British Association of Oral & Maxillofacial Surgeons

Cardiff, Wales

1-3 April 1993

PAPERS SUBMITTED FOR PRESENTATION AT THE FOLLOWING MEETINGS:

A. TO THE AMERICAN ASSOCIATION OF ORAL AND MAXILLOFACIAL SURGEONS,

September 29 - October 3, 1993

Orlando - Florida - U.S.A.

1. Relapse following bimaxillary osteotomies for correction of class II skeletal deformity: A two centre study

2. A new condylar positioning appliance in sagittal split ramus osteotomy.

B. TO THE BRITISH ASSOCIATION OF ORAL AND MAXILLOFACIAL SURGEONS

September 1993

London - U.K

1. Stability following sagittal split advancement osteotomy: Single versus Double jaws surgery

British Journal of Oral and Maxillofacial Surgery (1993) ●. 000–000

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BRITISH JOURNAL OF ORAL & MAXILLOFACIAL SURGERY

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To follow

MANU ARTW

Evaluation of changes following advancement genioplasty using finite element analysis

A. F. Ayoub, D. R. Stirrups, K. F. Moos

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SUMMARY. **This study examined skeletal stability and the remodelling process following advanced pedicled genioplasty. Twenty patients who had advancement genioplasty concomitant with other adjunctive orthognathic surgery were evaluated. A finite element analysis method was used to assess these changes. The stability of the advanced segment was excellent after 6 months. At 6 months bone remodelling was observed in the form of bone apposition at B point and Pogonion with bone resorption at the superior aspect of the advanced segment. The genial segment rotated about 12 degrees antero-superiorly which was thought to be due to the action of the mentalis muscle. Finite element analysis is a sensitive tool for assessing changes after genioplasty and was able to separate them from the effects of other adjunctive orthognathic surgery.**

INTRODUCTION

Among primates, only humans exhibit a prominent chin, and it is a distinguishing feature of the normal face. It is not surprising, therefore, that many corrective procedures have been developed to treat the abnormal chin, particularly one that is deficient. The surgical advancement of the anterior inferior border of the mandible has become a routine orthognathic procedure since its introduction by Trauner and Obwegeser in 1957.[1] Behrman[2] advocated that a horizontal advancement genioplasty should be carried out as a total free graft. However, Ellis *et al.*[3] showed that pedicled genial segments underwent significantly less resorption than the free genial segments. The advanced genial segment has traditionally been stabilized with wire osteosynthesis. Studies have shown that this method affords good stability.[4–7] Kirschner wires and Steinman pins have also been used and are also thought to produce good stability.[8,9] Bone plate osteosynthesis and screw fixation are other stabilization methods now widely used.[10,11]

Many studies have been conducted to evaluate changes following advancement genioplasty. However, the influence on the position of the chin of other concomitant surgical procedures (mandibular or maxillary) and changes of orientation of the whole mandible to any reference plane were not considered.[4] Davis *et al.*[6] used the osteotomy line as a reference plane to evaluate the changes following advancement genioplasty. The use of an osteotomy cut as a reference plane is debatable. Alterations in this plane may occur from local remodelling of the osteotomized segment, leading to misinterpretation of the changes. The occlusal plane may be altered when there are changes in the position of the teeth which define its end points. Thus it is potentially unstable as a reference plane for evaluating genioplasty although it has been used for this purpose.[12]

In reviewing the literature we could find no report of a measurement method that was able to evaluate changes related to genioplasty independently of any other adjunctive orthognathic surgery.

Moyers and Bookstein[13] showed that conventional cephalometric analysis using linear and angular measurements is deficient as a tool for morphanalysis. It misinforms by fabrication, camouflage and confusion. Changing the plane of orientation, for example, from S-N to Frankfort plane will also alter the perception of any shape changes occurring. This effect is described as fabrication. Traditional cephalometric analysis amalgamates changes of landmark positions as a statistically intractable composite of translation and remodelling, which is another source of fabrication. Since fabrication occurs through using orientation planes so the perception of shape change determined by superimposition of a series of cephalographs on registration planes provides a camouflaged view of the changes. There is no best registration and it is not possible to decide whether any registration is concealing or camouflaging crucial co-variation.

Bookstein[14] introduced tensor analysis as a new method of evaluating shape changes. This is a simplification of the more widely recognised method of finite element analysis, a system of mathematical modelling best known from its applications in engineering. In finite element analysis the structure under investigation is subdivided by a series of imaginary lines into triangular elements, a process called discretization. In discretization the assumption is made that all the points within a given finite element share a common behaviour. This assumption becomes more accurate as the number of elements is increased and their size is decreased. The three points that define a finite element are called nodes, these may be common

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to adjacent elements. When applied to cephalographs anatomical landmarks can be used as nodes. An analysis of changes using finite element method necessitates accurate location of each node on each occasion by the precise determination of their coordinates within a cartesian framework (X and Y axis). Elements are observed in matched pairs, for example pre- and postoperative. Inside the first triangular finite element a circle can be drawn so that it touches the three sides (Fig. 1A). Changes in the locations of the nodal points of the element will distort the circle into ellipse (Fig. 1B). The ellipse has two axes that are 90° to one another and these are called the principal axes of deformation. These principal deformation axes are drawn at the centroid of each element (Fig. 1C). If the deformation is greater than 1.00 it represents a stretching or dilatation; if less than 1.00 it represents a shrinkage or compression (Fig. 1D).

The aim of this study was two fold:

1. To assess the changes at the chin following advancement genioplasty.
2. To evaluate the applicability of a finite element analysis technique for assessing changes following genioplasty, independent of any other concomitant surgery.

MATERIAL AND METHODS

Sample selection:

This study was carried out on 20 patients who had pedicled advancement genioplasty. The changes following surgery were evaluated by comparing the immediate preoperative (T1), immediate postoperative (T2), 6 months (T3) and 1 year postoperative (T4) cephalographs.

Surgical technique:

The patients underwent traditional advancement genioplasty using a broad pedicled flap from an intraoral incision. The bone segment was cut using a Stryker saw or Ash surgical bur, the segments were mobilized and fixed in the new position using a triple wire osteosynthesis. The wires were attached to the lateral surface of the anterior mandible and the lingual cortical plate of the advanced segment.

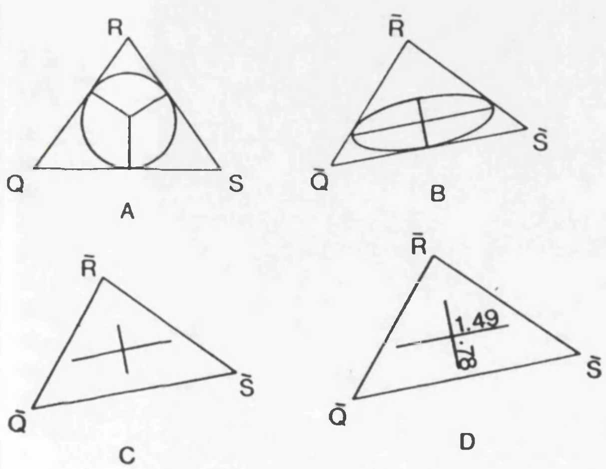

Fig. 1 – Finite element analysis. A, Undeformed element with a circle touching the three sides. B, The strain ellipse. C, The principal axes of deformation at the centroid of the element. D, The deformation values.

Cephalometric analysis:

Cephalographs were taken in the natural head position and this was only used to provide a reference horizontal plane to orient the plots. One author carried out all the digitization. Each landmark was digitized twice and if the difference in the coordinates between the first and second time of digitization was more than 0.5 mm the point was redigitized twice until a satisfactory accuracy was obtained. The whole procedure was repeated not less than 2 weeks after the first occasion and the average of the two occasions used in the study. The following points were used to evaluate changes at the chin region

Infra dentale (Id): The most superior and anterior point of the bony lamella covering the lower central incisors.
Point B (Supramentale): The most posterior position of the concavity on the labial surface of the mandible in the mid line superior to pogonion.
Pogonion (Pg): The most anterior point of the bony chin.
Menton (Me): The most inferior point on the lower border of the mandible.
Genion (Gn): The most superior point of the genial tubercles.

The application of finite element analysis:

In this study the mandible was subdivided into 4 triangular finite elements, with 5 anatomical points used as nodes for those finite elements (Fig. 2). The finite elements were defined as follows:

Element 1. Gn-Pg-Me
Element 2. Gn-B-Pg
Element 3. Gn-Id-B
Element 4. Id-Me-Gn

A custom written finite element analysis computer programme was developed for the study. The magnitude of the principal deformations in each element were calculated, the angle (Theta) between the direction of maximum deformation and the natural head position defined horizontal plane was measured. The average deformations and average theta of each element were calculated. Detailed analysis of the error of the method have been published elsewhere.

RESULTS

1. Preoperative—postoperative (T1-T2) (Fig. 3A & B)

A. Element Gn-Pg-Me: There is a dilatation almost parallel to the Gn-Pg line with shrinkage along Me-

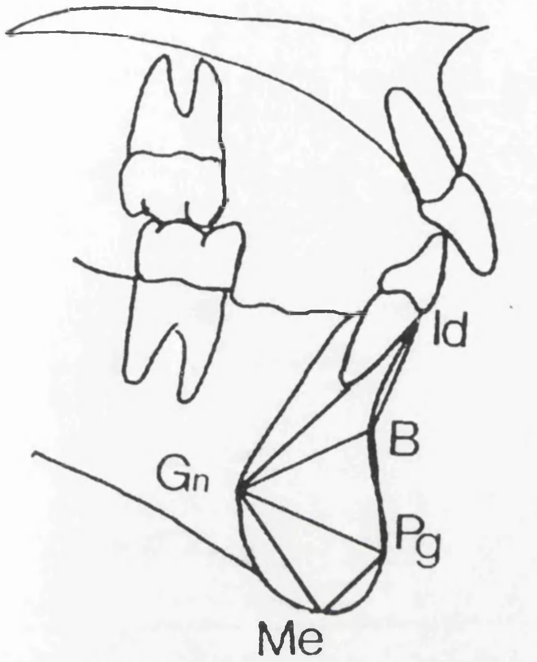

Fig. 2 – The subdivision of the anterior part of the mandible into elements for finite element analysis method.

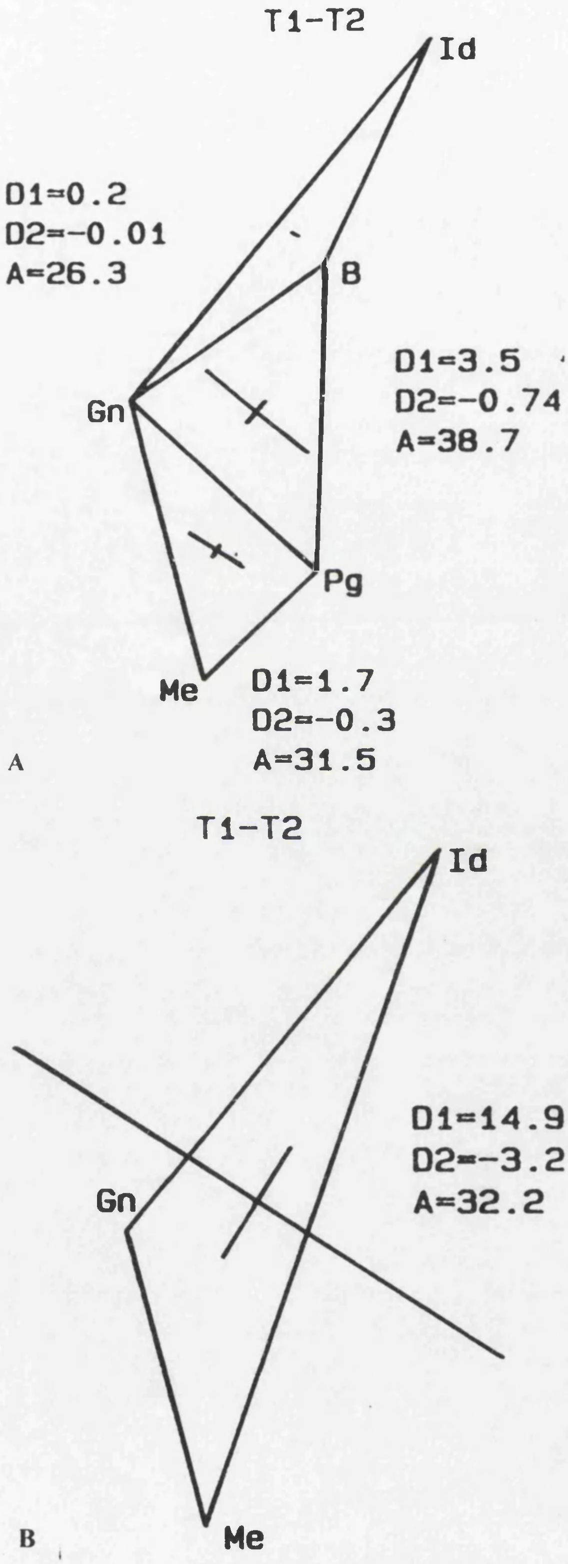

Fig. 3A & B – Immediate postoperative changes, D1 is the principal deformation along the direction of greatest change; D2 the principal deformation along the direction of least change; Theta is the angle between the greatest deformation and the horizontal plane.

Pg. These changes show the actual surgical advancement of the genial segment and shifting of Menton anteriorly and superiorly.

B. Element Gn-B-Pg: This shows a dilatation almost parallel to Pg-Gn line due surgical advancement of the genial segment. There is also shrinkage approximately along B-Pg due to the superior rotation (anticlockwise) of the osteotomized segment.

C. Element Gn-Id-B: The changes in this element are within digitization error.

D. Element Id-Me-Gn: Dilatation is almost perpendicular to the line Id-Me, that is parallel to the average direction of advancement of the genial segment. The vertical shrinkage seen is due to anterior and upward rotation of the osteotomized segment reducing the total mandibular vertical height.

2. Immediate to 6 months postoperative. (T2-T3) (Fig. 4A & B)

A. Element Gn-Pg-Me: Dilatation occurred parallel to Pg-Gn which is due to local remodelling of the genial segment in the form of bone apposition at Pogonion. No significant changes were detected in relation to Menton.

B. Element Gn-B-Pg: The dilatation in this element is affected by bone apposition at Pogonion and on the outer surface of the mandible superior to the advanced segment. It will also be due to any movement of the genial segment affecting the position of Pogonion.

C. Element Gn-Id-B: The dilatation of this element is affected by bone apposition on the outer surface of the mandible superior to the advanced segment. It will also be due to any movement of the genial segment affecting the position of Pogonion.

D. Element Id-Me-Gn: This shows vertical stability with anterior superior rotation without any change in the total mandibular vertical height. Examination of the radiographs showed bone resorption at the

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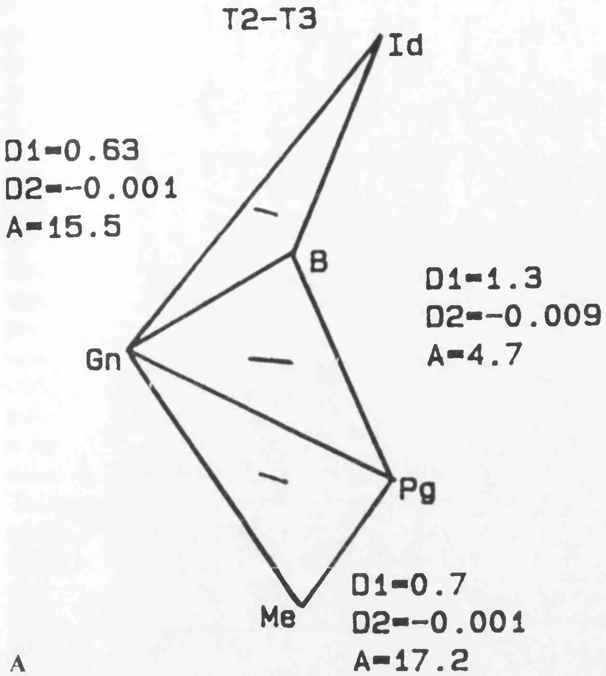
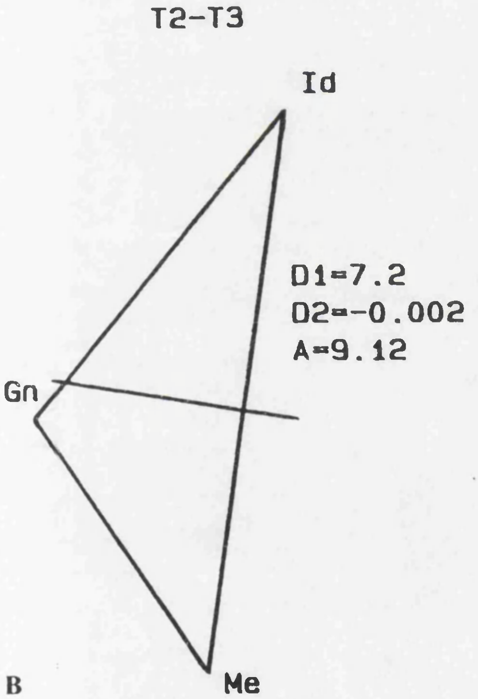


A



B

Fig. 4A & B – Changes after 6-month period.

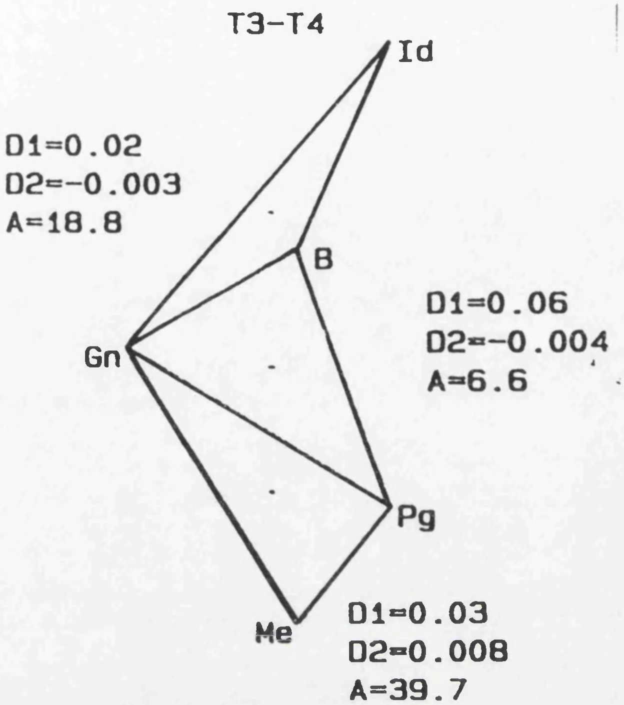


Fig. 5 – One year postsurgical changes.

superior surface and the posterior inferior corner of the advanced segment.

3. 6 month to 1 year follow up (T3-T4) (Fig. 5)

The minimal changes detected in all the elements were within the method error.

DISCUSSION

Stability of the advanced genial segment is usually reported as very good, irrespective of the method of fixation. However, determination of changes in osseous position are difficult because both translation of the advanced genial segment and osseous remodelling may occur simultaneously. There are warnings in the literature[6,15] against the use of Pogonion as a reference point when studying the stability of genioplasty. They argue that bone remodelling at this site can invalidate conclusions about skeletal stability since differentiating between changes due to remodelling and repositioning is impossible. In spite of the controversy over the use of Pogonion, it is still the most important landmark to be assessed in any genioplasty study, because it defines the chin prominence and there is no other landmark that can be substituted.

Finite element analysis is a unique method capable of separating changes due to repositioning from those due to remodelling. Repositioning is failure of the bone segment to maintain its position in relationship to adjacent bones. This repositioning may be unrelated to the direction of the movement occurring during surgery. Remodelling is a combination of bone resorption and apposition causing shape change rather than positional change. Bone remodelling can be monitored by changes in the relationship of nodal points (landmarks) to each other in a given finite element whereas repositioning is identified by changes detected in the adjacent elements with shared nodes. Despite the bone apposition at Pogonion seen in the element Pg-Me-Gn (T2-T3), Pogonion position is also affected by repositioning of the whole genial segment. Changes at Pogonion due to repositioning of the advanced segment can be identified through the element Id-Me-Gn. Infradentale and Genion are relatively fixed points and are not affected by genioplasty, and thus any change in the element Id-Me-Gn is due to positional change at Menton which has moved away from Genion. This can only be explained by a rotation of the genial segment about its contact with the anterior surface of the mandible. The major deformations of the elements Gn-Pg-Me and Gn-Id-B are approximately parallel to each other due to bone apposition at B point and Pogonion. The direction of the major deformation in the Gn-B-Pg element is about 12° different from these. This indicates that the angle of rotation of the genial segment is approximately 12°. Thus Me point also has rotated in an anti-clockwise direction during the first 6 months postsurgery. This is a rotation of the genial segment upward and forward, and occurs with a minimal vertical component. This affects the position of Pg point and the dilatation seen in the element B-Pg-Gn is interpreted as a mixture of local remodelling (apposition) and repositioning of Pg point (Figs 6A & B). This postsurgical forward and upward rotation of the genial segment may the result of postero-superior action and shortening of the mentalis muscles. These muscles were stripped from the underlying genial bone during surgery and became reattached to the advanced segment. Scarring and shortening of this muscle is a possible explanation of the mechanism by which rotation of the genial bone segment occurred and could also explain the bone resorption seen radiographically at the superior surface of the advanced segment. McDonnel *et al.*[4] found variable remodelling patterns of the advanced segment with bone resorption at Pogonion and bony apposition at B point. Our findings are in agreement with this study regarding bone apposition at B point, however bone apposition was also detected at Pogonion. These findings are in harmony with the results of Bell's study.[16] A similar pattern of bone remodelling has been reported when a special bone plate was used for fixing the advanced segment.[17] However, these bone plates may modify the pattern of local bone remodelling at Pogonion so that the changes could be different from other genioplasty fixation techniques. Bone resorption was detected radiographically at the superior surface and the postero-inferior corner of the advanced genial segment. This finding is in agreement with previous investigations of bony changes following advancement genioplasty.[7,12,18] This bone resorption may be due to periosteal and soft tissue pressure.[6,19]

Many investigators have attempted to establish criteria for predicting changes following genioplasty by means of cephalometric tracings. To obtain and determine a reliable result, it is imperative to use reference planes or landmarks that are not altered by

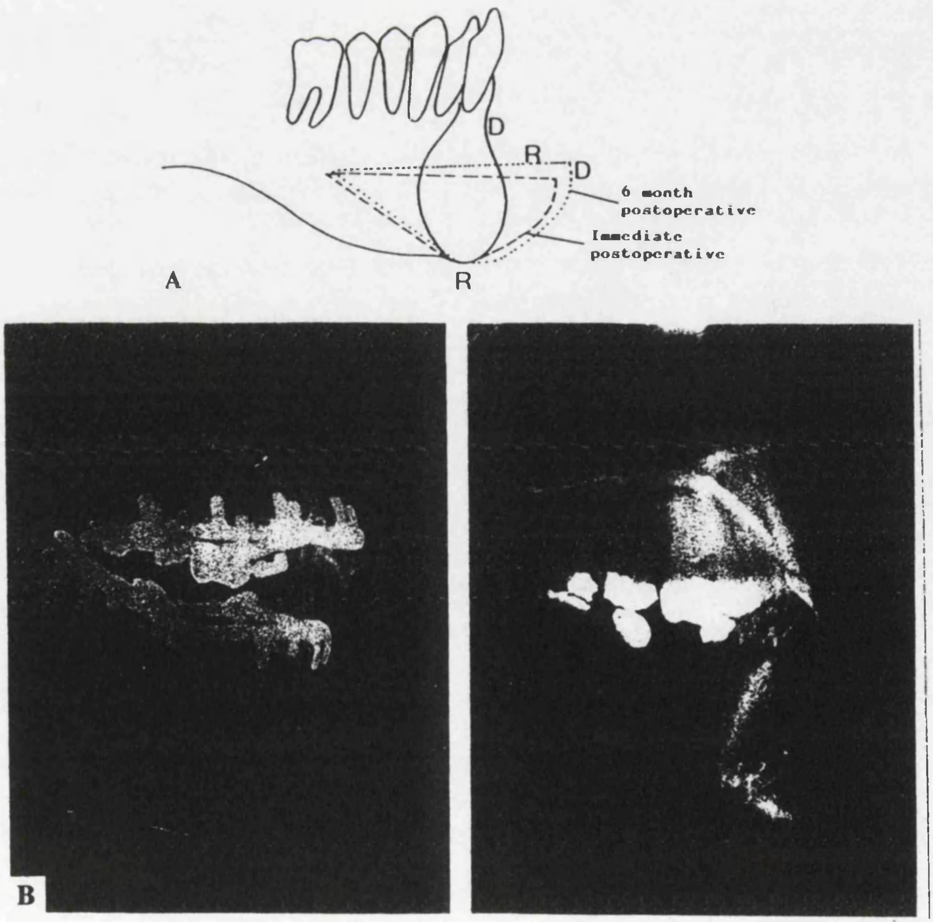


Fig. 6 – Changes of the advanced genial segment during the first 6-month post surgery. (A) The interrupted line shows the immediate postoperative changes, the dotted line shows the change in the segment position after six month period. (B) Radiographic appearance of remodelling and repositioning of the advanced genial segment showing bone apposition at Pogonion and B points, bone resorption at the posterior-superior and posterior-inferior corners of the advanced segment.

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surgery. In the literature several methods have been described that depend on reference planes of doubtful reliability to determine hard and soft tissue changes related to chin surgery. Cranial base superimposition is a method used to determine and predict overall surgical changes of the jaws. However, this method creates problems in the study of dimensional changes of the hard and soft tissue of the chin because concomitant jaw surgery can affect mandibular position. Therefore superimpositions based on cranial reference planes such as the Frankfort or S-N planes are not suitable for determining dimensional differences in the chin area unless the rest of the mandible maintains its position in spite of surgery.

The finite element method is able to separate changes at the chin occurring through genioplasty from the effects of other adjunctive surgery. The method does not depend on a remote frame of reference; the superimposition of the elemental structures is on their centroids, so eliminating the effect of other surgery on the chin shape and position.

This study has shown that the standard advancement genioplasty produced excellent results and bony stability was generally very good, no matter what other orthognathic surgery was also carri d out. Finite element analysis is a very sensitive tool for assessing shape changes. It can also differentiate repositioning from remodelling and separate the changes of genioplasty from those of other adjunctive orthognathic surgery.

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The practicability of finite element analysis for assessing changes in the craniofacial morphology from cephalographs

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Running title: Practicability Of Finite Element Analysis

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Summary

This study investigated the usefulness of a Finite Element Analytical (FEA) method for studying changes in facial form. The material was lateral cephalographs of nineteen patients who had undergone surgical correction of the chin. Finite element analysis was used to assess changes in bony form brought about by surgery. Replicate digitization of cephalographic landmarks was used to minimise measurement error. Random and systematic errors were examined and their influence on the finite element method was assessed. However, the sensitivity of FEA is such that the level of residual measurement error affects the reliability of the method and makes the technique unsuitable for individual cases. However, for pooled data from a group of cases the effect of measurement error is reduced and the reliability of the analysis is satisfactory for inter-group comparison.

Introduction

There is a considerable debate about the usefulness of traditional cephalometric analysis (linear and angular measurements) as a tool for assessing changes in facial form. Moyers and Bookstein (1979) showed that conventional cephalometric analysis using linear and angular measurements is deficient as a tool for morphometric analysis. It misinforms by fabrication, camouflage and confusion. Changing the plane of cephalograph orientation, e.g from Sella-Nasion to Frankfort plane will also alter the perception of any shape changes of the jaws that occur. This effect is described as fabrication. Traditional cephalometric analysis amalgamates changes of landmark positions as a statistically intractable composite of translation and remodelling, which is another source of fabrication. Since fabrication occurs through using orientation planes so the perception of shape change determined by superimposition of a series of cephalographs on registration planes provides a camouflaged view of the changes. Each registration gives a different perception of the shape changes. It is not possible to decide whether any registration is concealing or camouflaging crucial co-variation.

Centroid point superimposition methods (Johnson 1960, 1978, 1979 and 1982) and Trenouth (1989) have been shown to be the most stable of the reference plane methods. However, centroid methods, in common with all other methods involving establishing superimposition planes are dependent on the concept of fixed local frames of reference. In all reference frame dependent methods, changes in form are plotted relative to a reference system which should be independent of changes in form. None of the reference frames is absolutely constant and each one gives different perception of shape change. While centroid points are relatively invariant by comparison with cephalometric "anatomical" landmarks they will still be subject to change if the shape form which they are derived changes.

Rabey (1971 and 1977) developed his Morphograph for craniofacial analysis. This is a very sophisticated system of establishing an external frame of reference. Any interpretation of shape changes can only be related to this frame of reference and it therefore suffers from the same problem as other reference frame methods.

More sensitive analytic techniques are needed to improve understanding of changes in facial form. One possible method is finite element analysis.

Bookstein (1982) introduced tensor analysis as a method of evaluating shape changes. This is a simplification of the more widely recognised method of finite element analysis (FEA), a system of mathematical modelling best known from its applications in engineering. In finite element analysis the structure under investigation is subdivided by a series of imaginary lines into triangular elements, a process called discretization. The three points that define a finite element are called nodes, these may be common to adjacent elements. When applied to cephalographs, anatomical landmarks can be used as a nodes. An analysis of shape changes by the finite element method necessitates accurate location of each node within a Cartesian framework. Elements are observed in matched pairs of reference and target elements e.g pre and post operative (Fig 1A). Elements are superimposed on their centroids with minimisation of the distances between homologus nodes in the reference and target elements. Inside the reference triangular finite element a circle can be drawn so that it touches the three sides (Fig 1A). Changes in the locations of the nodal points of that of the target element will distort the circle into an ellipse (Fig 1B). The ellipse has two axes that are at 90 degrees to one another and these are called the principal axes of deformation. These principal deformation axes are drawn at the centroid of each element (Fig 1C). If the deformation is greater than 1.00 it represents a stretching or dilatation; if less than 1.00 it represents a shrinkage or compression (Fig. 1D).

Carlsson (1967) showed that the greatest source of cephalographic measurement error was in locating cephalometric landmarks. Measurement errors may be caused by lack of clarity of cephalometric landmarks (Gravely and Benizes, 1974). This variability must be quantified in order to validate any method of cephalometric analysis.

The precision of cephalometric landmark identification may be affected by random and systematic errors. Precision is defined as the proximity of repeated measurements to the same value (Sokal and Rolf, 1981). Random error is due to random imprecision in identifying a landmark. Systematic errors arise from differing interpretations of landmark definition, giving rise to consistent differences in location. This can happen when two observers trace or digitize the same radiograph and also when one observer measures the same radiograph on two different occasions.

Centroid point superimposition methods (Johnson 1960, 1978, 1979 and 1982) and Trenouth (1989) have been shown to be the most stable of the reference plane methods. However, centroid methods, in common with all other methods involving establishing superimposition planes are dependent on the concept of fixed local frames of reference. In all reference frame dependent methods, changes in form are plotted relative to a reference system which should be independent of changes in form. None of the reference frames is absolutely constant and each one gives different perception of shape change. While centroid points are relatively invariant by comparison with cephalometric "anatomical" landmarks they will still be subject to change if the shape form which they are derived changes.

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Houston (1983) showed that replicate digitization of the radiographs improves precision both by reducing the risk of gross errors due to incorrect identification of a landmark, and by reducing random errors if replicated measures are averaged. For the highest precision, Houston (1979) advocated immediate redigitization on each of the two separate occasions.

Aim of the study.

The aim of this study was to evaluate the influence of the systematic and random errors of recording cephalometric landmarks on the validity of finite element analysis. As a convenient model for the study data was derived from examining the local changes brought about by chin surgery.

Materials and methods

1. Material

The lateral cephalographs of 19 patients who had advancement genioplasty were used in this study. The immediate preoperative, and immediate postoperative films were used for error evaluation.

2. Cephalometric Methods

For the FEA the anterior part of the mandibular image was subdivided into three triangular finite elements, with the following five anatomical points used as the nodes (Fig. 2).

Infra dentale (Id): The most superior and anterior point of the bony lamella covering the lower central incisors.

Point B (Supramentale): The most posterior point on the concavity on the labial surface of the mandible in the mid line superior to pogonion.

Pogonion (Pg): The most anterior point of the bony chin.

Menton (Me): The most inferior point on the lower border of the mandible.

Genion (Gn): The most superior point of the genial tubercles.

Although the natural head position vertical was recorded from each cephalograph no use was made of this for the analysis. Each landmark was digitized twice, and if the difference in the coordinates between the first and second time of digitization was more than 0.5 mm, the point was redigitized again until this consistency was obtained. The procedure was repeated, by the same operator, not less than two weeks later. The coordinates of the landmarks from each occasion were compared by mathematical superimposition using fiducal point. Fiducal points were only used to relate the point coordinates on the two occasions of digitization to each other. Where gross discrepancies (more than two mm.) between occasions were noted then the process of replicate digitization was repeated until there was a reasonable consistency of landmark location. This is recognised in the orthodontic literature as the best method to minimize cephalometric measurement error (Houston 1983).

A custom written computer program was developed for the finite element analysis. This calculates the average principal strain and the average direction of the principal strain of each element.

The finite elements were defined as follows:

Element 1: Id - Gn - B point

Element 2: B point- Gn - Pg

Element 3: Pg - Gn - Me

3. Error evaluation of the nodal points

The residual landmark location error was calculated as the difference in landmarks coordinate between the first and second occasion of digitization. The differences between the values of the finite element variables (Maximum strain, Minimum strain, Theta) in the first and second occasion were assessed. The influence of landmarks recording error on the finite element method was determined. A one sample t test for each pair of replicates was used to test for systematic error and the index of reliability to measure random error.

Results.

The error in locating fiducal points was assessed by measuring the distance between each pair on the two occasions of digitization. The difference in this distance was never greater than 0.5 mm and at the limits of the accuracy of the digitizer.

Table 1 shows the statistical evaluation of the absolute distances between replicated landmarks when superimposed using fiducal points.

Figure 3 shows the relationship between replicate values of X coordinates of the digitized points. Figure 4 shows the same for the Y coordinates. Both scatter plots are formed from pooling data from all subjects and for all landmarks.

The results (Table 1) show that the reproducibility measurement of the landmarks when superimposed using fiducal points were all very high (Figure 3 and 4). No systematic error in the location of the points was detected at the 90 percent level of confidence.

Table 2 Shows the finite element analysis error assessment. For each element the variables are the maximum and minimum strains which are directed along the fulcrum of minimum and maximum deformations. A third variable "Theta" is the angle between the direction of maximum strain and the natural head position determined horizontal plane of the second film. Theta is derived from the direction of maximum strain with respect to one side of the element and is thus not dependent on any superimposition. However to aid visualisation of the changes the elements were arbitrarliy oriented to the natural head position vertical of the second film before being plotted. There was no systematic error for the finite element components at 90 percent confidence level, however the random errors were very large. This table shows the high sensitivity of the method to small changes in landmark location.

Discussion.

Several studies have been conducted using finite element method to assess changes in craniofacial morphology. Moss et al (1985) studied craniofacial growth in a group of rats. For each element a computer program determined the direction and amount of the maximum and minimum growth changes in relation to the average age of the rats. The authors concluded that finite element analysis provided absolute quantitative descriptions of cranial skeletal shape and shape changes independent of any external local frame of reference. However, the study did not consider the possible errors in cephalometric measurements that may have affected the sensitivity of finite element analysis

Lavelle (1989) applied finite elements analysis to lateral cephalographs of patients before and after orthodontic treatment to assess craniofacial changes. Lavelle distinguished between the measurement of size or shape changes by summing or subtracting the principal strains values and dividing by two. Like Moss et al., he concluded that finite element analysis provides a better understanding of cephalometric form that was independent of specific registration and orientation. The author did not comment on the method used to record the coordinates of the nodal points nor did he assess the possible sources of error and their influence on the finite element analysis. The component of finite element analysis that describes the direction of the principal strain in relation to the element's sides was also not considered in this study.

Our study support the finding that finite element analysis provides a useful description of morphological changes as observed in cephalographs.

Random errors are important in that they add to the natural variability of the measurements and reduce the correlation between variables. The greatest source of random error is the difficulty in identifying a particular landmark. The average absolute distances between repeated digitization of points Id, Gn are higher than for the other points. The superimposition of overlying structures; e.g arch bar fixation for Id point and the bone structure for Gn point; may have affected the accuracy of their identification.

Finite element analysis is sensitive to small changes in landmark location. The precision was poor despite the reproducibility of the cephalometric landmarks being excellent, with indices of reliability of at least 0.98 (Table 1). The small changes in the landmark coordinates between the replicates had a great effect on the calculation of the finite element variables (maximum strain, minimum strain, Theta) because of the computational sensitivity of the method. In order to achieve acceptable levels of precision for the finite element components, the level of precision for locating landmarks has to be increased. This can only be achieved by averaging data from replicate digitization. However, the small error in recording the fiducal points that are used for superimposition, would limit the extent to which replication is useful. It is unlikely that FEA will be useful in assessing single cases because of the number of the replicates needed to obtain stable results. Provided there is no systematic bias the effects of random error are reduced for pooled data as the number of cases used increases. Thus, FEA could be a useful tool for studying groups of like cases.

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Table 1. Absolute distances in mm. between replicated points when superimposed using fiducal points for nineteen subjects.

Point	Mean coordinates X	Mean coordinates Y	Standard Error	"t" value	"p" value	Index of the Reliability
Id	1.1	0.9	1.3	0.209	0.99	0.99
B	0.9	0.7	1.4	0.180	0.99	0.99
Pg	0.8	0.6	1.3	0.208	0.99	0.98
Me	0.9	0.6	1.3	0.200	0.99	0.99
Gn	1.4	1.1	1.4	0.186	0.99	0.99

Table 2. Error analysis for the Finite Element Components.

Finite Element <u>Id-B-Gn</u>	Subject Mean Value	Replicate Mean Difference	"t" Value	"p" Value	Index Of Reliability
Maximum Strain	2.14	-1.52	0.959	0.350	0.296
Minimum Strain	0.09	-0.01	1.049	0.308	0.043
Theta	60.6	-1.03	0.161	0.874	0.473

B-Pg-Gn

Maximum Strain	3.09	-3.60	0.949	0.355	0.298
Minimum Strain	0.03	0.01	0.223	0.826	0.102
Theta	70.1	-13.20	1.263	0.222	0.470

Pg-Me-Gn

Maximum Strain	2.29	7.66	0.918	0.371	0.156
Minimum Strain	0.04	0.01	0.100	0.922	0.667
Theta	14.4	14.7	1.498	0.151	0.125

LEGENDS

Figure 1. Finite Element Analysis.
A. Undeformed element with a circle touching the three sides.
B. The strain ellipse of the deformed element.
C. The principal axes of deformation at the centroid of the element.
D. The deformation values.

Figure 2. Subdivision of the anterior part of the mandible used for the finite element analysis method.

Figure 3. Combined Scatter plot, for all landmarks and subjects, of the first and second replicate values of the X coordinates .

Figure 4. Combined Scatter plot, for all landmarks and subjects, of the first and second replicate values of the Y coordinates .

THE STABILITY OF BIMAXILLARY OSTEOTOMY AFTER CORRECTION OF SKELETAL CLASS II MALOCCLUSION

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ABSTRACT

This study investigated the changes following bimaxillary osteotomy for correction of class II malocclusion. The records of fifteen patients who had simultaneous maxillary impaction and sagittal split ramus osteotomy with rigid fixation were evaluated. Traditional cephalometric analysis as well as finite element and Euclidean distance matrix analyses were used to assess these changes. The maxilla was relatively more stable than the mandible. The maxilla stayed within 1 mm of its postsurgical position whereas the mandibular settling was 2 mm from the achieved surgical changes. The mandible rotated in a clockwise direction during the first six month post surgery. The mandibular plane angle increased by 2.9 degrees. The authors believe this to be, in part, due to posterior condylar displacement during surgery. Theories of mandibular relapse following sagittal split advancement osteotomy are discussed. The new methods of morphometric analysis do not require cephalograph superimposition and are able to separate maxillary from mandibular changes.

Introduction

As orthognathic surgery has grown more sophisticated, it has allowed the surgeon to address deformities that were previously untreated. Stability of changes resulting from these surgical procedures has been an area of concern since both aesthetic and functional improvement are related to postsurgical stability.

Early studies of single jaw surgery showed that mandibular relapse tended to be greater than maxillary relapse.[1,2] Advances in the surgical techniques allows simultaneous mobilization of both the maxilla and mandible. Assessment of double jaw surgery has indicated less mandibular relapse but more maxillary relapse occurred than for the same procedures performed independently.[3] One recent study[4] tended to confirm these initial impressions, while others have reported relapse comparable to those found in single jaw surgery.[5,6]

Brammer et al.,[3] evaluated 12 patients for postoperative stability eight month after combined maxillary and mandibular osteotomies. Interosseous wire fixation was used. The results showed little maxillary change and a strong correlation between the amount of mandibular advancement and degree of relapse. The direction of the surgical movement varied greatly between the patients and this may affect the interpretation of the results.

In a preliminary study by LaBanc et al,[7] a 100 cases of simultaneous surgical repositioning of the maxilla and mandible were reviewed. The authors observed more relapse than with single jaw procedures, but neither cephalometric measurements nor the review intervals were reported. Ninety seven percent of the patients underwent Le Fort I osteotomy, and 82% had concomitant sagittal split ramus osteotomies. Fixation technique varied between patients. This study was subjective rather than quantitative.

In 1982 Turvey[8] reviewed 31 patients who had undergone simultaneous Le Fort I and sagittal split ramus osteotomies. All had superior repositioning of the maxilla, 16 with a mandibular set-back and 15 with mandibular advancement. The author reported, without quantification, that relapse had occurred in some patients but all still had acceptable results.

Hiranaka and Kelly[4] studied the short term stability (during IMF) in 18 patients who underwent simultaneous bimaxillary orthognathic surgery. Seven patients had class II, six patients had class III, and four patients had class I occlusion and one patient had facial asymmetry. Patients were treated by a variety of mandibular surgical techniques and the maxilla was repositioned in different directions. Using routine cephalometric analysis, they concluded that stability of mandibular surgery is increased by concomitant maxillary impaction. They also found a positive correlation between the magnitude of mandibular advancement and the amount of postsurgical relapse. Mandibular advancement showed greater relapse than mandibular set back. There was great variability in the deformities and the corrective surgical procedures. The analysis used in this study cannot differentiate between mandibular changes and the effect of the maxillary changes on the mandible.

Hennes et al.,[5] investigated 24 patients who had undergone simultaneous maxillary impaction and mandibular advancement osteotomies with internal rigid fixation. Despite variation in individual response, the authors claimed an optimum level of skeletal stability. No significant correlations between surgical movements and postoperative changes were found. The authors did not distinguish between orthodontically related postoperative changes and those due to skeletal stability. The method used to analyse the lateral cephalographs could not separate remodelling (Bone apposition and resorption) from repositioning at the osteotomy sites.

At the moment there are no studies that have quantitatively assessed the stability of bimaxillary surgery and were able to separate the maxillary and mandibular changes.

Moyers and Bookstein[9] showed that conventional cephalometric analysis using linear and angular measurements is deficient as a tool for morphometric analysis. To overcome these deficiencies Bookstein[10] introduced tensor analysis for evaluating shape changes. This is a simplification of the more widely recognised method of finite element analysis (FEA). A system of mathematical modelling best known from its applications in engineering. In finite element analysis the structure under investigation is subdivided by a series of imaginary lines into triangular elements, a process called discretization. The three points that define a finite element are called nodes, these may be common to adjacent elements. When applied to cephalographs, anatomical landmarks can be used as nodes. An analysis of changes using finite element method requires accurate location of each node on each occasion using Cartesian coordinates. Elements are observed in matched pairs e.g pre and post operative. Inside the first triangular finite element a circle can be drawn so that it touches the three sides (Fig 1A). Changes in the locations of the nodal points of the element will distort the circle into an ellipse (Fig 1B). The ellipse has two axes that are at right angles to each other and these are called the principal axes of deformation. These principal deformation axes are drawn at the centroid of each element (Fig. 1C). If the deformation is greater than 1.00 it represents a stretching or dilatation; if less than 1.00 it represents a shrinkage or compression (Fig. 1D).

Euclidean Distance Matrix Analysis (EDMA) for the comparison of forms was proposed by Lele[11] in 1991. It has been applied in several studies of craniofacial morphology.[12,13] EDMA uses landmark coordinate data to calculate all possible linear distances between landmarks. The matrix that describes a form based on landmark data is called a Euclidean distance matrix or form matrix. The relative location of the landmarks can be reconstructed entirely from landmark coordinate data or from the Euclidean distance matrix.

In applying EDMA for comparing biological shapes, there are two Euclidean distance matrices. One represents the initial morphology, the other represents the second shape. EDMA compares these Euclidean distance matrices by systematically using pairs of homologous linear distances to form ratios. Figure 2 is a simple example of EDMA. . The matrix of these ratios is called a difference matrix. Inspection of the difference matrix allows determination of how the two shapes differ. If all ratios of the difference matrix are equal to one then there is no difference between the shapes being compared. Those ratios less than one show that the linear distance is smaller in the second shape. Ratios greater than one show a larger distance in the second shape. If across the matrix all the ratios are equal, but not equal to one then the difference between the shapes can be attributed exclusively to size change. When the difference matrix consists of varying values, differences between the shapes are due to both size and shape changes. The ratio of the greatest increase to greatest decrease in distances provides an index of shape difference and can be tested the statistical significance by the method described by Lele and Richtismeier.[14]

Aims of the study

These were:

1. To evaluate the stability of 15 patients who underwent simultaneous mobilization of the mandible and the maxilla for correction of Class II dental relationship with associated facial skeletal disproportion.

2. To compare routine cephalometric analysis, Finite element analysis, and EDMA for evaluating the changes following surgery.

Materials and Methods

1. Patient Data

Fifteen patients (3 male and 12 female), with mean age 23 who received bimaxillary osteotomy to correct class II skeletal disproportion. The cases underwent simultaneous mobilization of the maxilla and mandible. The maxilla was impacted about 4 mm anteriorly (range 3 to 5 mm) and 2 mm posteriorly (range 1 to 3 mm). Twelve patients had simultaneous advancement genioplasty of an average of 3 mm (range 2 to 4 mm). Standard lateral cephalometric radiographs were obtained using the same cephalometer with the same magnification for each patient. The preoperative cephalograph (T1), immediate postoperative (T2), six month (T3), and one year (T4) postoperative cephalographs were used in the analysis. Cases of segmental osteotomy, cleft lip or palate and craniofacial syndrome patients were excluded from this study. All the patients had presurgical orthodontic preparation and postsurgical orthodontic adjustments to obtain maximum occlusal interdigitation.

2. Surgical Technique

Each patient underwent bimaxillary surgery with rigid internal fixation. The maxilla was down-fractured at the Le Fort I level and orientated to the mandible using an intermediate splint prepared at the time of model surgery. Intermaxillary wire fixation was applied temporarily to position the maxilla in a predetermined relation to the mandible. The mobilized maxilla was then repositioned and stabilized with Champy plates, two on each side at the piriform apertures and the zygomatico-maxillary buttresses. Once the maxilla was stabilized, the intermaxillary fixation and intermediate splint were removed. Intra-oral sagittal split ramus osteotomies were then carried out. The distal segment was stabilized with maxillo-mandibular fixation to a final inter-occlusal splint. The proximal mandibular segment was left in its preoperative position. Proximal and distal segment were then rigidly fixed using three bicortical position osteosynthesis screws per side. The occlusal splint is usually left fixed to the maxilla to guide the mandible into the new occlusion.

3. Cephalometric analysis

The changes following surgery were evaluated by comparing the immediate preoperative (T1), immediate postoperative (T2), six months (T3) and one year postoperative (T4) cephalographs. Cephalographs were taken in the natural head position, this was only used to provide a reference horizontal plane to orient the elements of the FEA. One author carried out all the digitization. Each landmark was digitized twice and if the difference in the coordinate between the first and second time of digitization was more than 0.5 mm the point was redigitized twice until satisfactory accuracy was obtained. The whole procedure was repeated not less than two weeks after the first occasion and the average of the two occasions used in the study. The points shown in table 1 were used in the evaluation and were defined according to Rakosi.[15]

Table 2. Shows t.e linear and angular measurements used in this analysis and the following elements were used for the finite element analysis.

Element 1. S-ANS-PNS (Figure 3)
Element 2. S-N-Gn (Figure 4)
Element 3. S-N-Cd (Figure 5)
Element 4. S-N-Go (Figure 6)
Element 5. N-Cd-Go (Figure 7)
Element 6. Cd-Go-Gn (Figure 8)

A custom written finite element analysis computer program was developed for the study. The average principal strains and the average direction (Theta) of the principal deformation of each element were calculated. Detailed analysis of the error of the method has been submitted for publication elsewhere.

Euclidean Distance Matrix analysis was carried out using a custom written computer program. The statistical significance of differences in shape was tested by the method described by Lele and Richtsmeier.[14]

<u>Results</u>

Table 2 shows the immediate and six months postoperative changes using linear and angular measurements.

Table 3. Shows components of the matrices used to conduct the Euclidean distance matrix analysis. Each entire matrix has 19 by 19 components and there are four distance (one for each occasion) and three difference (ratios between occasions) matrices. Thus it is impractical to publish them in full and only components highlighted in the discussion are presented. The index of shape difference for the surgical changes was statistically significant with $p<0.004$. For the immediate to six months postoperative period, the changes were also statistically significant with $p<0.01$. The changes from six month to one year postsurgery were not statistically significant with $p=0.164$.

Figures 3 to 8 are the elements used to evaluate immediate, six months, and one year postoperative changes.

Figure 10 is for one of the cases that shows significant clinical relapse following mandibular advancement.

A. MAXILLARY CHANGES

<u>1. Surgical changes (T1 - T2)</u>

The maxillary impaction was 4 mm anteriorly (4mm decrease in the upper anterior facial height) and 2 mm posteriorly (2 mm decrease in upper posterior facial height). The maxilla rotated in an anti-clockwise direction 1.3 degrees upward from the presurgical maxillary plane. Element S-PNS-ANS (Fig 3) shows the principal maxillary movement. The principal deformation of the element is parallel to S-ANS line which is due to more anterior maxillary impcation than posteriorly.

2. Changes during first six months post surgery (T2-T3)

The maxilla rotated in a clockwise direction, with an increase in the anterior upper facial height of 1 mm. The centre of rotation was close to PNS with no changes detected at the posterior end of the maxilla. The SNA angle decreased by 0.7 degrees.

3. Changes at one year follow up (T3 - T4)

The small changes detected were within the measurement error and not statistically significant.

B. MANDIBULAR CHANGES

1. Surgical changes (T1 - T2)

The mandible autorotated about 7 degrees following the maxillary impaction. This is shown by the decrease in both the ramus and mandibular plane angles. The angle between the proximal and distal segments (gonial angle) was unchanged.

The Distal Segment:

The distal segment was advanced about 7 mm increasing the total mandibular length (Cd - Gn) by 7 mm. The net increase of the facial depth (S - Gn) was 4.6 mm. The mandibular plane angle decreased by 6.7 degrees with a five degree increase in SNB angle. Element S-N-Gn shows the combined rotation and advancement of the distal segment (Figure 3).

The Proximal Segment:

The length of the proximal segment (Cd - Go) increased by 2.5 mm. The ramus angle (S-N/ Cd-Go) decreased by 6.5 degrees. This change is shown by the element S-N-Cd (Figure 4), and the distances S-Cd and N-Cd were increased by 0.6 mm and 1.4 mm. This shows the condyle has been pushed posteriorly during surgery. The principal deformations in element S-N-Go (Figure 5) illustrate the changes at Go. The element N-Cd-Go (Figure 6) traces the rotation of the proximal segment in relation to the base of the skull. The element Cd-Go-Gn (Figure 7) shows the changes between the proximal and distal segment arising from surgery. The principal dilatation was almost parallel to the Go-Gn line showing there was very little angular change between the proximal and distal segments.

2. Changes during the first 6 months postsurgery (T2-T3).

The mandible rotated in a clockwise direction with increase in the mandibular plane angle by 2.7 degrees and the ramus angle by 2.9 degrees. No change in the gonial angle was detected. The lower posterior facial height decreased by 3 mm. The condyle rotated and shifted anteriorly, this shift is shown in the element S-N-Cd (Figure 4). The condylar anterior shift follows the same angle as that of condyle's posterior distraction during surgery. The decrease in the Euclidean distance Cd-Go and the principal deformations of the elements S-N-Cd and Cd-Go-Gn demonstrate the remodelling changes of the proximal segment. The deformations of the element S-N-Cd and the change in S-Cd distance are interpreted as local bone resorption at condylion. The element Na-Cd-Go (Figure 6) illustrates the changes of the proximal segment, which are a mixture of remodelling and repositioning.

3. Changes at one year follow up (T3 - T4)

The small changes detected were within the measurement error and not statistically significant.

Discussion:

This study showed that the maxilla is relatively more stable than the mandible following bimaxillary surgery. The maxilla relapsed in a clockwise direction with an increase in the upper facial height by 1 mm and decrease in SNA angle by 0.6 degree. The posterior maxilla showed only slight vertical settling and the maxilla stayed within 1 mm of its postsurgical position. While these figures are relatively small, they were greater than those reported by Satrom et al.[16] However, the average magnitude of the maxillary impaction in their sample was about 50% less than the impaction in our cases. Proffit et al.,[17] studying single jaw maxillary impaction also found good stability after superior repositioning with intra-osseous wires. They reported 0.33 mm of maxillary inferior settling, compared with the 0.8 mm reported by Satrom et al.,[16] who used additional infraorbital suspension wires for the maxilla. This data seems to show that Le Fort I impaction is generally a stable procedure and postsurgical changes are small whatever the fixation method.

During mandibular surgery the proximal segment was pushed posteriorly in the glenoid fossae. The principal dilatation on the S-N-Cd element and the increase in the distances S-Cd, N-Cd illustrate this change. Similar findings were reported by Kundert and Hadjianghelou.[18] They measured the temporomandibular joint spaces anteriorly, posteriorly and cranially to document the condylar changes during surgery in 14 cases of mandibular advancement. They noted that in 75% of the condyles studied, there was a narrowing of the joint space concomitant with posterior condylar displacement. Posterior displacement of the condyles was detected in our cases and probably contributed to mandibular relapse.

The unchanged gonial angle suggests a constant angular relation between the proximal and distal segment. However, the distal segment rotated slightly in anti-clockwise direction during its advancement, following the maxillary occlusal plane. This slight rotation brought the lower posterior corner of the distal segment (lingual plate) more inferiorly in relation to the proximal segment. Thus, the increase in the Cd-Go distance seen as a surgical change (T1 - T2) may be explained as an inferior transposition of Gonion point (Figure 9). This type of distal segment rotation would only occur in cases with a deep curve of Spee and a long horizontal lingual bone cut during the sagittal split osteotomy. The increase in the articulare-gonion distance at surgery was explained as surgical oedema in the bilaminar tissue of the temporomandibular joint.[16] Nevertheless, articulare is liable to change with any rotation of the proximal segment so it is unsuitable for measuring changes of the condylar surface.

During the first six months post surgery the mandible relapsed by both remodelling and repositioning.

Resorption occurred at the condyle and inferiorly at gonion. This was demonstrated by the decrease in Cd-Gn and Go-Gn distances and the changes in the element Cd-Go-Gn.

Repositioning occurred by a clockwise rotation of the mandible and a change in condylar position. The mandible rotated 2.5 degrees in a clockwise diection. The change in condylar position was shown by the principal strains in element S-N-Cd.

Different values of mandibular relapse following sagittal split advancement osteotomy have been reporetd in the literature.[19-24] Lake et al.,[19] reported 26% relapse simliar to 25% reported by Schendel and Epker[20] and less than the relapse of 40% reported by Kohn.[21] However, this relapse is greater than 9% reported by Ellis and Gallo[22], but their investigation was during fixation period only. In all these reports the mandibular advancement was with wire fixation only.

In studies of double jaw surgery, mandibular relapse with wire fixation has been reported to be 14% by Brammer et al,[3] 27% by Wade[23] and 20% by Turvey et al.[6] On the other hand with rigid internal fixation, Van Sickels et al[24] reported 8% mandibular relapse and 6% was reported by Satrom et al.[16] These authors used SNB and ANB angles to evaluate mandibular changes. These are insensitive measures of mandibular changes as the mandible may rotate in a clockwise or anticlockwise direction with little change in SNB angle. Primary mandibular changes cannot be separated from secondary effects arising from maxillary repositioning when ANB angle is used.

For the same group of subjects the magnitude of the reported relapase will vary with the measurement used to assess it. In our cases mandibular relapse was 40% of the change in mandibular length (S-Gn), 38% if evaulated using SNB angle, and 26% for alteration in the mandibular plane angle. Percentage of relapse, in isolation from the extent of sugical change, has a potential to mislead.

Clinically the most relevant measures of surgical changes are those relating maxillary and mandibular positions to horizontal and vertical planes defined by natural head position. In our cases the magnitude of the surgical mandibular advancement measured at Gn was 6.9 mm with a superior shift of 3.7 mm. The magnitude of relapse at six month period was 1.7 mm posteriorly and 1.6 mm inferiorly as it recorded at Gn point. The mandible stayed within 2 mm of its postsurgical position.

Ellis and Carlson[25] showed that the supra-hyoid musculature remains attached to the distal mandibular segment and may be stretched by the advancement procedure. The effect of this tension is to cause posterior and inferior displacement of the distal segment. Although, Wessberg et al.[26] proved that skeletal relapse following surgical advancement of the mandible is not significantly influenced by suprahyoid myotomy. In non-rigid fixation cases, these forces may cause opening of the gonial angle. However, they should have minimal effect when rigid fixation is used.[25] Reitzik and Schoorl[27] investigated histologically and biochemically the bone repair in the mandible at the osteotomy site. They concluded that rigid fixation produces a primary bone healing that is denser and stronger than non rigid fixation where relapse is due to the action of distracting muscle forces causing changes at the osteotomy site. Satrom et al[16] reported opening of the gonial angle of about 1.5 degrees for the rigid fixation group and 4.2 degrees for wire fixation group. No change in the gonial angle was detected in our cases.

Wolford et al.,[28] investigated the role of muscles of mastication in mandibular relapse. They described three types of mandibular movements in advancement cases. Type I clockwise and forward movement; Type II straight forward movement; Type III anti-clockwise and anterior movement. Type III mandibular movement cases have been found to have a high incidence of relapse. The muscles of mastication are lengthened in the ramus area. As these muscles attempt to return to their original positions, they rotate the mandible in a clockwise direction. The rigid fixation generally prevents this movement, but it may still occur to a lesser degree. In our sample, the distal segments were advanced and rotated in an anti-clockwise direction (Fig. 9) which may contribute to some extent to the relapse observed. On the other hand, the potential for a greater amount of alteration in the condyle to fossae relationship has been mentioned by Thomas et al.,[29] as the main disadvantage of mandibular rigid fixation. Kundert and Hadjianghelou[18] also reported greater condylar displacement with rigid fixation when compared with wire fixation. Distraction of the mandibular condyles from their functional position in the glenoid fossae results in dramatic relapse immediately upon release of intermaxillary fixation.[20] This relapse occurs because of a discrepancy between the functional occlusal position (centric occlusion) and terminal hinge position (centric relation). Lake et al.,[19] also found the position of the proximal segment to be the predominant influence on postoperative stability.

We believe that skeletal relapse following surgical advancement of the mandible is multifactorial. The suprahyoid muscles, may have been a contributory factor in mandibular relapse. The distraction of the mandibular condyle during surgery was another important mechanism of mandibular relapse. During surgery the proximal segment was manipulated into its presurgical anatomical position. The achievement of this has potential for error.

Finite element analysis allows evaluation of remodelling changes at the proximal segment. Element Cd-Go-Gn (T2 T3) shows the major axes of deformation to be parallel to Go-Gn line and there was 4 mm decrease in the Gn-Go distance. These findings are due to local bone resorption at Go, since Gn was not affected by surgery. The other minor axes of deformation of the same element was interpreted as arising from local bone remodelling (Resorption) at the condylar surface. This finding is supported by the 3 mm. decrease in Cd-Gn distance (T2-T3) and the deformation occurring in element S-N-Cd.

Most of the measuring methods that have been used to assess changes following orthognathic surgery have been based on cranial base superimposition of patients' cephalographs. As has been explained by Moyers and Bookstein[11] changing the plane of cephalographs superimposition, e.g from S-N to Frankfort plane, will alter the interpretation of the surgical changes in jaw bones. Traditional cephalometric measurements cannot separate the primary changes of the mandible from secondary change due to alteration in maxillary position in bimaxillary osteotomy. It also does not differentiate between the clinically important problems of remodelling and repositioning.

The interpretation of surgical changes shown by EDMA or finite element analysis requires both surgical and biological understanding. EDMA is an easier method to understand and apply. It lends itself to statistical manipulation more readily than finite element analysis. However, it cannot be used to assess the rotational changes that are demonstrable with finite element analysis. Like other morphometric techniques, they can be used to test hypotheses or as an exploratory method to gain insight into shape changes. These new methods of morphometric analysis appear to complement rather than replace conventional techniques and are sensitive tools that can aid understanding of surgical changes.

Conclusions:

There were significant changes in facial form due to surgery.

The results of this study are in agreement with previous findings that Le fort I maxillary imapcation is a fairly stable procedure.

The mandibular postsurgical changes were a mixture remodelling and repositioning. Bone resorption occurred at the condyle and at gonion. Repositioning was by a clockwise rotation of the mandible and anterior movement of the condyle.

The preoperative form, the desired magnitude and direction of mandibular advancement are not within the control of the surgeon. However, the position of the proximal segment during surgery is dependent on the surgical manipulation. It is one factor which can be addressed which may improve the successs of the surgery.

If the relative importance of factors influencing relapse is to be better understood then larger scale studies are needed. It may be that multicentre studies will be necessary for this.

Both EDMA and FEA provided additional information that helped in understanding the sugical and post sugical changes.

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Table 1. Definitions of cephalographic landmarks.

Sella: The midpoint of the sella.

Nasion: The most anterior point of the nasofrontal suture in the median plane.

Anterior The tip of the bony anterior nasal spine Nasal Spine: in the median plane.

A point: The deepest midpoint in the curved bony outline from the base to the alveolar process of the maxilla.

Supradentale: The lowest, most anterior point on the alveolar portion of the premaxilla in the median plane.

Upper Incisal Edge: The tip of the incisal edge of the most anterior maxillary central incisor.

Upper Anterior Root Apex: Root apex of the most anterior maxillary central incisor.

Upper Mesial Cusp Tip: The tip of the mesiobuccal cusp of the upper first or second molars.

Posterior Nasal Spine: The dorsal limit of the maxilla.

Lower Incisal Edge: The tip of the incisal edge of the most anterior mandibular central incisor.

Lower Anterior Root Apex: The root apex of the most anterior mandibular central incisor.

Infra dentale: The most superior and anterior point of the bony lamella covering the lower central incisors.

Point B The most posterior position of the concavity on the labial surface of the mandible in the mid line superior to pogonion.

Pogonion (Pg) The most anterior point of the bony chin.

Menton (Me): The most inferior point on the lower border of the mandible.

Genion (Gn): The most superior point of the genial tubercles.

Cemento-enamel Junction of Lower Molar: The most mesial point of the cemento-enamel junction of the lower first or second molar.

Mesial Cusp Tip: The tip of the mesiobuccal cusp of the lower first or second molar.

Gonion: The intersection of the lines tangent to the posterior margin of the ascending ramus and the mandibular base.

Condylion: Most superior point on the condyle.

TABLE 2. Linear and angular measurements from the preoperative (T1), immediate (T2), six month (T3) and one year (T4) postoperative Cephalographs.

Angular Measurements:

Angle	T1	T2	T3	T4

	Mean/Std.Dev	Mean/Std.Dev	Mean/Std.Dev	Mean/Std.Dev
SNA	77.5/3.4	79.5/4.9	79.5/4.6	79.1/4.1
SN/Pg	69.9/4.4	77.0/3.9	75.5/3.9	75.1/3.6
SNB	69.5/3.9	74.8/4.1	73.6/3.9	73.4/3.8
SN/MP	50.1/6.4	43.5/6.1	46.0/6.4	46.6/6.5
GONIAL	130.3/6.5	130.7/5.9	130.5/5.2	132.3/5.3
RAMUS	99.9/4.6	92.1/5.0	96.4/4.9	95.6/4.7
MAXIL.	8.4/5.0	7.8/4.5	7.8/4.7	7.7/4.4
Distances				
UAFH	54.9/4.2	50.9/4.1	51.7/4.3	51.5/4.1
LAFH	77.1/6.4	75.6/4.1	74.2/3.4	74.5/3.8
UPFH	49.4/2.6	47.5/2.9	47.8/2.7	48.0/2.0
LPFH	40.3/3.6	42.1/4.0	39.2/4.7	39.2/4.9
Cd/B	107.6/5.8	117.1/4.3	114.2/4.9	114.8/5.6

UIT (Upper Incisal Tip), LIT (Lower Incisal Tip), MP(Mandibular Plane), UAFH (Upper Anterior Facial Height), UPFH(Upper Posterior Facial Height), LPFH (lower Posterior facial height), Maxil(Maxillary Plane Angle).

Table 3: Components of the Euclidean Distance Matrices

End Point Landmarks		Distances (mm.) on Occasion			Ratios of distances between occasions	
		T1	T2	T3	(T1/T2)	(T2/T3)
S	PNS	49.1	47.3	47.6	0.96	1.01
S	Cd	18.9	19.7	18.5	1.04	0.94
S	Gn	102.7	107.3	105.1	1.04	0.98
S	B	104.1	108.2	106.6	1.04	0.99
N	ANS	54.7	50.7	51.5	0.93	1.01
N	Cd	85.7	87.4	85.9	1.02	0.99
ANS	Me	76.4	75.2	73.9	0.98	0.98
PNS	Go	40.0	41.6	38.8	1.04	0.93
Gn	Cd	92.1	99.3	96.4	1.08	0.97
Go	Cd	50.7	53.1	49.0	1.05	0.92
Gn	Go	57.0	61.5	62.1	1.08	1.01

LEGENDS ACCORDING TO THE APPEARANCE IN THE TEXT

Figure 1. Finite Element Analysis. A, Undeformed element with a circle touching the three sides. B, The strain ellipse. C, The principal axes of deformation at the centroid of the element. D, The deformation values.

Figure 2: A simple illustrative example of Euclidean

Distance Matrix Analysis.

1a. The initial shape - A square A_1, B_1, C_1, D_1 with sides of unit length

1b The second shape - A rhombus A_2, B_2, C_2, D_2, with sides of unit length.

1c The Euclidean distance matrix of the initial shape.

1d The Euclidean distance matrix of the second shape.

1e The difference matrix.

1f The index of shape difference - the ratio of maximum increase to maximum decrease (from 1e).

Figure 3. The element S-ANS-PNS showing changes due to surgery and at six month follow up period

Figure 4. The element S-N-Gn showing changes due to surgery and at six month follow up period

Figure 5. The element S-N-Cd showing changes due to surgery and at six month follow up period

Figure 6. The element S-N-Go showing changes due to surgery and at six month follow up period

Figure 7. The element N-Cd-Go showing changes due to surgery and at six month follow up period

Figure 8. The element Cd-Go-Gn showing changes due to surgery and at six month follow up period

Figure 9. Shows the rotation of the proximal and distal

segments during surgery.

Figure 10: This shows the lateral cephalometric and facial appearance preoperatively, postoperatively and at six months follow up of one of the cases.