THE DISTRIBUTION OF OCCLUSAL LOAD IN THE HUMAN MANDIBLE:

A PHOTOELASTIC STUDY.

VOLUME 1

of

TWO VOLUMES

by

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PREFACE

The work on which this thesis is based has been performed over the past three years at the Glasgow Dental Hospital and School, University of Glasgow, at the University of Strathclyde, and at the Dental School, University of California at Los Angeles. Some of the material contained in the study has been published, accepted for publication, or presented to scientific meetings.

Publications

1. Analysis of stress patterns in the human mandible.
   (with A.A. Caputo)
   J.Dent. Res. (in press)
2. Photoelastic studies in the edentulous human mandible.
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Presentations to Scientific Meetings

1. Occlusal load distribution within the human mandible.
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   52nd General Session, International Association for Dental Research, Atlanta, Georgia, March 1974.
2. Photoelastic studies in the edentulous human mandible.
   British Society for the Study of Prosthetic Dentistry, Canterbury, April 1974.
3. Stress distribution in replicas of the dentate and edentulous human mandible.
   (with A.A. Caputo and J.P. Standlee)
   53rd General Session, International Association for Dental Research, London, April 1975.

DEFINITIONS and TERMS

The following is a list of general terms used in this study. Other relevant terms are defined and discussed in later sections.

occlusion	contact between the masticating surfaces of maxillary and mandibular teeth.
balanced occlusion	a condition in which there are simultaneous contacts of the occluding surfaces of the teeth on both sides of the opposing dental arches.
balanced articulation	a condition in which there are simultaneous contacts of the occluding surfaces of the teeth on both sides of the opposing dental arch during movement of the mandible within the functional range.
intercuspation	the interdigitation of cusps or parts of the cusps of opposing teeth.
vertical dimension	a vertical measurement of the face between any two arbitarily selected points which are conveniently located, one above and one below the mouth, usually in the mid line.
occlusal vertical dimension	the vertical dimension of the face when the teeth or occlusion rims are in contact.
centric jaw relation	the relationship of the mandible to the cranium at the occluding vertical dimension which exists when the condyles are in the most posterior position in the mandibular fossae of the temporal bones.

stomatognathic system	the combination of all the structures involved in speech and in the receiving, mastication and deglutition of food.
complete denture	a denture replacing the entire maxillary or mandibular dentition and part of the supporting structures of the teeth.
partial denture	a denture replacing one or more, but less than all, of the natural teeth and supporting structures.
denture bearing area	the oral structures which bear the loads applied to a complete denture.
denture base	that part of a denture which rests on the oral mucosa and to which teeth are attached.
isometric contraction	an increase in muscular tension at the same muscle length, as in clenching the teeth together.
median plane	a vertical plane drawn through the mid line of the body dividing the body into right and left halves.
sagittal plane	a vertical plane through the body parallel to the median plane.
coronal plane	a vertical plane at right angles to the sagittal plane dividing the body into anterior and posterior portions.
Frankfort plane	a horizontal plane passing through the lowest point in the margin of the orbit and the highest point in the margin of the auditory meatus.
osteon	the unit of bone structure: the bone cell and its surrounding lamellae: the basic unit of the Haversian* system.

*C.HAVERS, Anatomist. 'Osteologica Nova' 1692.

lamellae — the concentric thin plates of bone which constitute the normal mature form of the tissue.

trabeculae — the meshwork of superimposed lamellae in cancellous bone.

cancellous — spongy or reticular in appearance.

cortical — related to the outer portion of a substance.

isotropic — having like properties in all respects.

force — the agent which produces a change in a body's state of rest or motion.

load — a force which is applied to the outside of a structure.
Load may be in

(a) tension - a force which tends to pull apart.

(b) compression - a force which tends to crush together.

(c) shear - a force which makes one part slide over another.

stress — the corresponding resistance force which is generated within a structure when a particular load is applied to it.

strain — the deformation which arises in a structure when a load is applied to it. Stress and strain thus correspond to the type of the applied load and may be tensile, compressive or shearing.

<u>modulus of elasticity</u>	the ratio of stress over strain for any substance under load.
<u>ultimate tensile strength</u>	the maximum stress that a substance can stand before failure in tension occurs.
<u>thermal coefficient of expansion</u>	the change in length per unit length of a material for a one degree change in temperature.
<u>index of refraction</u>	the angle through which a beam of light is deflected on passage through a transparent substance.
<u>stress (fringe) optical constant</u>	the difference in the level of stress between succeeding orders of fringes in a photoelastic material.
<u>Poisson's ratio</u>	the ratio of transverse to longitudinal stress in a material subjected to tension.
<u>Newton</u>	the force required to give a mass of one kilogram an acceleration of one metre per second squared.
<u>Wheatstone bridge</u>	an electrical circuit containing four resistances in branches or arms, any one of which may be calculated in terms of the other three when the bridge is suitably adjusted.

ABBREVIATIONS AND SYMBOLS

The following is a list of the abbreviations and symbols used in this study.

Fig	figure
o	degrees (angulation)
oF	degrees Farenheit (temperature)
oC	degrees Centigrade (temperature)
%	per cent
mm	millimetre (s)
cm	centimetre (s)
m	metre (s)
gm	gram (s)
kg	kilogram (s)
N	Newton (s)
MN	Mega Newtons (N x 10^6)
GN	Giga Newtons (N x 10^9)

ABSTRACT

This study is an investigation of the distribution of occlusal load in replicas of the dentate and edentulous human mandible by the method of three dimensional photoelastic stress analysis. The study was stimulated by an interest in the occlusion of the teeth and in the relationship between disorders of the occlusion and the development of pain or dysfunction in the stomatognathic system. A further interest was in the association of faults in the design of complete dentures with pain in the oral tissues underlying the denture base.

The distribution of load in any bone is related to the form and structure of the bone and to the type of loading to which the bone is normally subjected. The anatomical and biomechanical techniques which may be used to investigate these factors were developed for the study of the long bones of the limbs and in particular for the study of the human femur. The methods have been outlined, their limitations highlighted and their results compared. The general agreement of the results is quite striking.

The application of these methods to the structural analysis of the human mandible has demonstrated the way in which the bone is reinforced to meet the loads imposed by masticatory function. Relatively few studies have been reported in which the hypotheses developed from anatomical investigations have been tested by other methods. Photoelastic stress analysis was selected as a method which would provide a visual demonstration of the distribution of load in the mandible and which offered the additional benefit that stresses could be studied in sections cut from the photoelastic models.

As one of the interests in this study was the distribution of load in replicas of the edentulous mandible when load was applied in a number of different ways to a mandibular complete denture base, the theories of complete denture design have been reviewed, with emphasis on the

relationship between the design of the dentures and the transmission of forces to the underlying tissues. The anatomy of the mandible and of the muscles of mastication and the temporo-mandibular joint has also been described.

In order to relate the experimental procedures in this study to the clinical conditions under which load is applied to the mandible, it was necessary to construct a frame in which the photoelastic models could be supported in a position simulating centric relation of the mandible to the cranium. The lines of action of these muscles were determined by radiographic and cephalometric methods and a supporting frame was constructed to represent the base of skull, with metal struts aligned to correspond to the angulation of the muscles. While the shortcomings of this method were recognised, the model system provided adequate support for the models and no movement of the models or of the supporting elements was observed during the loading cycle.

The principles of polarisation, birefringence and photoelasticity have been explained in detail. The methods of photoelastic stress analysis have been outlined, the preparation of models described and the techniques of stress freezing and three dimensional stress analysis presented. A detailed description has then been given of the preparation of photoelastic replicas of a dentate and of an edentulous human mandible.

Weights were suspended from the dentate replicas to simulate bilateral loading in the molar region, loading in the incisor region and unilateral loading in the molar region. The same loads were applied to the edentulous mandible through the medium of a complete denture base. The distribution of load beneath an underextended denture base and of a subperiosteal implant were also studied.

Isochromatic fringe patterns were recorded on the right and left halves of each replica and on sections cut from selected areas of the mandibular body and ramus. Isoclinics were studied in sections from the neck of the mandible. Fringe patterns in the hemisectioned specimens of the dentate and edentulous replicas were basically similar and indicated that stress had been generated in those areas of the models corresponding to the sites of major reinforcement of the structure of the mandible.

Changes in the manner of loading were reflected in alterations in the pattern of stress distribution which suggested that greater stresses were transmitted to the condylar region when load was applied in the incisor region or when unilateral loading was used.

Sections through the edentulous models suggested that when the experimental conditions were in accord with accepted principles of complete denture construction, load was distributed to the outer portion of the model, corresponding to the thickened cortical areas of the mandible. The simulation of occlusal faults and the use of an underextended denture base produced unfavourable distribution of load and provided experimental confirmation of accepted techniques of complete denture construction.

A strain gauge study was then undertaken to confirm the results of the photoelastic method and a study of the optical properties of bone was also made, which suggested that a pattern of birefringence exists in bone and that it may be modified by the application of load in a manner similar to that in which fringe patterns are generated in photoelastic models.

Two short appendices have been included. The first of these outlines the construction of the polariscope which was developed for this study and the second provides a comparison between the photoelastic resin materials used for construction of the dentate and edentulous replicas.

SECTION 1

INTRODUCTION

Chapter 1   Background and Aims of the Study.

CHAPTER 1

Background and Aims of the Study.

BACKGROUND AND AIMS OF THE STUDY

1.1 Background

This study developed from a clinical interest in the occlusion of the teeth, both natural and artificial; in the relationships between disorders of the occlusion and the presence of pain or dysfunction in other areas of the stomatognathic system; and in the association of faults in the design of complete dentures with pain in the oral tissues underlying the denture base.

From clinical experience, it had been noted that symptoms of stomatognathic dysfunction in dentate and edentulous patients could be alleviated and frequently abolished by the elimination of occlusal faults, the correction of aberrant muscle function and the establishment of a stable occlusion of the teeth with the mandible in a retruded and regularly reproducible relationship to the maxilla.

The frequent association between occlusal faults and the development of pain or dysfunction had led to an interest in occlusal forces and in the way in which these forces are transmitted to and distributed throughout the mandible. In order to demonstrate the distribution of occlusal load and to relate this distribution to the anatomical reinforcement of the structure of the mandible, it was decided to use the method of three dimensional photoelastic stress analysis, which provided visual demonstration of the effects produced in replicas of the mandible by the application of simulated occlusal loads.

The method also offered the possibility of comparing the transfer of occlusal load to the mandible in the dentate and edentulous conditions and of investigating the relationship between faults in the design and construction of complete dentures and the development of pain in the tissues of the mandibular denture bearing area.

1.2 Aims of the Study

The aims of the study were as follows:

i) to prepare a model of the mandible suitable for three dimensional photoelastic stress analysis.

ii) to construct a supporting frame in which the model could be held in a position simulating centric relation of the mandible to the cranium, by struts representing the principal elevator muscles of the mandible.

iii) to study and compare the stress patterns produced in replicas of a dentate and of an edentulous mandible under simulated occlusal load and to relate these to the known structural reinforcements of the mandible.

iv) to observe the changes produced in the stress patterns in replicas of the edentulous mandible consequent upon changes in the design or method of loading of the mandibular complete denture base and to relate these findings to clinical experience in prosthodontics.

SECTION 2

REVIEW OF THE LITERATURE

INTRODUCTION

The review of the literature is divided into three chapters. The first reviews the methods which have been used to study the mechanical properties of bone and the second is an account of the application of these methods to the study of the mandible. The third chapter deals with theories of complete denture design in relation to the forces transmitted by the denture to the denture bearing area.

CHAPTER 2

The Biomechanics of Bone

THE BIOMECHANICS OF BONE

2.1 Introduction

A knowledge of the physical properties of bone and of the behaviour of bone under functional loading is an important pre-requisite to the design of appliances which will utilise bone for their support and which may modify the forces to which a particular bone may normally be subjected. The physical properties of bone may be studied in sections of bone, in the intact specimen and in replicas.

2.2 The Study of Sections of Bone

The biomechanical properties of bone were first deduced from the study of sections of bone. These were cut in various planes so that the form and architecture of the specimen could be examined and related to the functional demands to which the bone was known or assumed to be subjected. Attention was directed mainly to the orientation of bony trabeculae in the hope of determining their functional significance in terms of stress and strain. These anatomical investigations have been supplemented by mathematical analysis of the structural form of individual bones and also by the determination of the physical and mechanical properties of the component tissues.

2.2.1 Anatomical Techniques

Interest in the mechanical significance of bone structure can be traced to the early part of the nineteenth century. Attention was at first directed to the trabecular arrangement of the cancellous bone and sections have been prepared to demonstrate this feature in a wide variety of bones. Extensive studies have been made of the long bones of the limbs and in particular of the femur.

WARD (1838) produced a simplified diagram of the architectural arrangement of the bone trabeculae in the femur (Fig. 2.1), which he compared to the supporting structure of a lamp bracket. He suggested that the trabeculae represented trajectories which offered resistance to the stresses and strains to which the bone was subjected in function. This idea found support in the work of WOLFF (1870) and ROUX (1885) and formed the basis of WOLFF's monograph 'The Law of Bone Transformation', published in 1892. The trajectorial theory of bone form implies that the trabeculae of cancellous bone are laid down along the lines (or trajectories) of maximum internal stress in the bone, that they arise at right angles from the inner surface of the bone and intersect also at right angles. Criticisms of the theory may be made on the grounds that the bones under study are not homogeneous and therefore may not behave in a predictable mechanical fashion (KUNTSCHER 1934), and that the trabeculae are not always aligned in a manner which coincides with the trajectories which have been described (CAREY 1929).

2.2.2 Mathematical Analysis

This method was first used by KOCH (1917) in his paper 'The Laws of Bone Architecture'. He obtained the femora of an accident victim and prepared 75 cross sections at quarter inch intervals throughout the length of the right femur, (serial frontal sections were prepared from the left femur). KOCH believed that the mechanical influence of the body weight was more important than muscle action in determining bone architecture and he ignored the latter in his calculations. Assuming a load of 100 pounds in standing, 160 in walking and 320 in running, KOCH made mathematical calculations of the maximum tensile and compressive stresses throughout the length of the bone. He found tensile stresses on the superior aspect of the neck and lateral aspect of the shaft of the bone, except in the distal third of its length.

Compressive stresses were located on the inferior aspect of the neck, the medial aspect of the shaft throughout its length and on the lateral aspect of the shaft in the distal third. He found the highest values for tensile and compressive stress in the entire bone in the middle of the femoral neck and the highest values in the shaft at the junction of proximal and middle thirds.

These calculations were based on the engineering formula for bending, which assumes that the object under study is composed of homogeneous isotropic material of uniform cross section. In calculating bending stress in beams composed of two dissimilar materials, the materials are equated on the basis of their relative moduli of elasticity. The difficulty of applying this procedure to the mathematical analysis of the bending stress in bone is that the modulus of elasticity of cancellous bone is not known (EVANS 1957).

The quantitative results can therefore be criticised on the grounds that they are based on formulae which were devised for the study of structures of uniform shape and composed of homogeneous materials, and which take no account of the variations in bone shape and of the hetero-geneity and varying proportions of its principal component tissues. They also assume an even distribution of force throughout each cross section, a condition which may not occur in bone.

2.2.3 Engineering Techniques

Engineering techniques for the study of small standardised test pieces have been applied to the study of the biomechanical properties of bone. As a method, it has the advantage of eliminating the variables caused by irregularities in the form of bones which can present serious problems in mathematical analyses of bone structure.

EVANS and LEBOW (1951, 1952) tested cortical specimens from the femur and found increased values in dried bones for modulus of elasticity, ultimate tensile strength and hardness. Reduced values were recorded for elongation and shearing strength. They stated that drying appeared to reduce the capacity of the bone to absorb energy, a property which is an important safety factor in the resistance of bones to stress and strain. DEMPSTER and LIDDICOAT (1951) reported similar findings and stated that their stress/strain curves for dry bones were approximately linear, whereas those for fresh specimens deviated from linear beyond the proportional limit. It thus appears that moisture is important in bones for the maintenance of the capacity to absorb energy and to resist shearing loads and for the recording of accurate values for tensile and compressive strength, surface hardness and modulus of elasticity. Physical values are also affected by preservative methods, temperature, the orientation of the specimens and the areas from which they are taken. The age, sex and race of subject and the duration, frequency and rate of loading are also important variables (EVANS 1973).

2.3 The Study of Intact Bones

The study of parts or sections of bone provides information about the physical form and mechanical properties of the bone which may be used as the basis for predictions of the biomechanical behaviour of the intact specimen. Study of the intact bone may be undertaken by the anatomical investigation of split line patterns in the cortical bone, by the application of strain sensitive lacquers, or by the placement of electronic strain gauges on selected areas of the bone surface.

2.3.1 Split Line Impregnation Technique

This method was devised by BENNINGHOFF (1925) and consists of partial decalcification of the bone and impregnation of the surface layers with Indian ink. The ink penetrates along minute cracks in the cortical lamellae to form a series of lines on the surface of the bone. The pattern so produced (Fig. 2.2) was interpretated by BENNINGHOFF as indicating the orientation of the Haversian systems which he believed to lie in the line of resistance to tensile and compressive forces. Trajectorial diagrams were devised which complemented those produced for the cancellous trabeculae and BENNINGHOFF further believed that the interstitial lamellae contributed to the absorption of stresses in such a way that a bone could be considered functionally as a homogeneous structure.

This interpretation was accepted by KUNTSCHER (1934) and he considered that his studies with strain sensitive lacquer provided an experimental confirmation of the functional significance of the split line patterns. PAUWELS (1950), quoted by EVANS (1957), conducted a similar study but felt that there were discrepancies between the split line pattern and the tensile and compressive trajectories which developed following the application of axial load to a femur which had been coated with strain sensitive lacquer. He felt that the lacquer revealed the true functional trajectories, while the split line pattern gave an indication of the influence of tension in the growth and development of the bone.

2.3.2 Strain Sensitive Lacquers

The use of a strain sensitive lacquer for the study of stress and strain in bones was reported by KUNTSCHER (1934). He used the resin Colophonium, which was heated to 40°C and applied to the surface of the bone to form a film of approximately 1 mm thickness. Calibration strips were used to determine the sensitivity of the lacquer, (quoted in inches per inch), which was 0.001 inches.

Erratum Page 26 , last line should read 'inches per inch'.

Thus a crack would appear in the lacquer each time the underlying bone was stretched 0.001 inches. Using this method, it was possible to demonstrate tensile strain by means of a series of cracks which appeared as the load was gradually increased and which were transverse to the direction of the tensile strain. Compressive strain would also be demonstrated by the cracks which appeared in the lacquer after the removal of the applied load, when those parts previously under compression would undergo stretching in recovering to their normal dimensions.

Using this technique, KUNTSCHER demonstrated tensile strain on the superior aspect of the neck of the femur when the bone was subjected to axial loading. With increase in the load, a second group of cracks appeared in the lacquer overlying the lateral aspect of the shaft, just below the lesser trochanter (Fig. 2.3). The cracks in the neck region were transverse to the long axis of the neck, but under increasing load they extended downwards towards the shaft. A similar change took place in the shaft, where with increased load, the cracks extended laterally and then curved inferiorly. The superior aspect of the neck of the femur was the area of highest tensile strain as the first cracks appeared in this area. Compressive strain was demonstrated in the inferior aspect of the neck of the femur and on the medial aspect of the shaft.

From the uniformity of the strain patterns obtained in his tests, KUNTSCHER concluded that the intact bone, in spite of the diversity of its anatomical structure, behaved functionally as a homogeneous structure. He regarded the strain patterns as experimental confirmation of BENNINGHOFF's theory (1925) that the Haversian systems of bone are functionally related to the stresses and strains to which the bone is subjected. He regarded trabeculae in the region of the femoral neck as representing a continuation of the lines of the Haversian system and as being directly related to the direction of tensile strain in the neck of the femur.

The development of the 'Stresscoat' method (DE FOREST and ELLIS 1940), simplified the procedures of applying strain sensitive lacquer to bones and the material is a great deal more sensitive than Colophonium. The use of this material has been described by EVANS and his co-workers in a series of studies on the human femur. Static loading was applied (EVANS and LISSNER 1948) and the deformation patterns described. Their results confirmed KUNTSCHER's earlier findings that the areas of highest tensile strain were the superior aspect of the femoral neck and the lateral aspect of the shaft just below the lesser trochanter. During these tests the intact femur, when subjected to non-fracturing loads, behaved like an elastic body, returning to its original shape and dimensions when the load was removed.

The great advantage of these lacquers is that they demonstrate the entire distribution of the stresses produced in the object under controlled conditions of loading and orientation. The result may be recorded photographically, the resin removed and replaced, and a new test carried out. This allows a comparison of the type and distribution of strain caused in the same object by various loading situations. In addition, an indication can be given for the placement of sensitive strain gauges, which will permit accurate measurement of the magnitude of the strain.

2.3.3 Electronic Strain Gauges

Anatomical investigations, theoretical analyses and laboratory studies of the musculo-skeletal system suffer because of the necessary separation of the components under consideration from the dynamic environment in which they normally function. However convincing the information derived from such investigations may be, it is never possible to be certain that the results are directly applicable to the clinical situation and a great deal of work has gone into the development of techniques for mechanical strain and force measurements in vivo.

Improvements in the range, sensitivity and insulation of electronic measuring devices and the miniaturisation of many of their components have opened up the prospect of undertaking such studies. COCHRAN and his associates (1971) have reported the development of two devices for the direct measurement of forces in the experimental animal, the first being a standard foil strain gauge insulated in a polyimide capsule and the second a pressure transducer. They have suggested the possible use of these devices for the evaluation of implant materials and for the mechanical comparison of various surgical procedures in orthopaedics.

2.4 The Study of Replicas of Bone

The first record of the use of a replica to study stress and strain in bone was that of ROUX (1885) who made a rubber model of an ankylosed knee joint. He coated this with paraffin, subjected it to load and used the cracks which developed in the paraffin as the basis for trajectorial diagrams. He related these stress trajectories to the alignment of the bony trabeculae and postulated that the trabeculae of the cancellous bone are laid down along the lines of maximum internal stress in the bone and thus have a functional significance in the behaviour of bone under applied load. His model system can be criticised, as the deformation of his replica was considerable and must have influenced his results.

2.4.1 Photoelastic Replicas

In recent years a number of investigations of stress/strain phenomena in bones have used the technique of photoelastic stress analysis which is used in industry for the analysis of machine parts. In this method a plastic replica is prepared of the structure to be analysed and is loaded so as to simulate known conditions of load in the prototype. The stress patterns which are generated in the model may then be studied by means of polarised light. By careful control of the applied load distortion of the replica may be avoided.

HALLERMAN (1934) used simplified delluloid models of tibia and fibula and subjected them to axial loading. He studied in particular the effect which osteotomy of one bone produced in the pattern of stress of its partner. He regarded his method as suitable for the qualitative study of bone mechanics but not for dynamic studies, due to the difficulty of demonstrating the effect of velocity in loading.

MILCH (1940), using two-dimensional plastic models of the femur, demonstrated the stress patterns produced under compressive load and related them to the trabecular structure seen in longitudinal sections of the bone (Fig. 2.4). He also demonstrated alterations in the alignment of the stress patterns in a number of simulated clinical situations. He believed that the stress patterns confirmed the relationship between the anatomical structure of the bone and its mechanical behaviour under load and that they provided further proof of the laws of bone growth and transformation as propounded by ROUX (1885) and WOLFF (1892). His findings have been criticised by EVANS (1957) on the grounds that the stress patterns consisted mainly of parallel lines and did not exhibit the interwoven appearance of trabeculae.

The role of articular cartilage in distributing load and reducing the peak stresses on the articulating surfaces has also been studied by means of photoelastic replicas. SPIVEY and MUIR (1971) prepared two-dimensional models of the head of femur, an acetabulum of mild steel and replicas of the articular cartilage in stiff rubber. The model system was assembled to simulate extension of the hip joint, a load of proportionate physiological magnitude was applied and the model was examined in polarised light.

Erratum Page 30 line 3 - read c for d in 'celluloid'.

The effect of reduction in the thickness of the rubber disc was to increase the concentration of the stresses which developed in the replica of the head of femur. This suggested that the area of contact between the articular surfaces had been reduced and that the load was thus concentrated on a smaller area, with consequent increase in stress. This was seen at its most extreme when the disc was removed altogether as the opposing surfaces were congruent over only a very small area.

Comments

The arrangement of the trabeculae of cancellous bone, as demonstrated either by sections cut through the bone or by radiographic techniques, has a complexity that almost defies description (Fig. 2.5). And yet there is quite clearly a pattern of alignment and reinforcement in particular areas and this pattern is understandable when considered in relation to the functional demands made on any particular bone. Descriptions of the trabecular architecture inevitably over-simplify the structural reinforcement of the bone and yet they are valuable aids to our understanding of bone mechanics. A similar over-simplification can be detected in mathematical analyses of bone structure, as the arrangement of the trabeculae is more complex than any calculations would predict.

Study of the intact bone and of its behaviour under load follows naturally from the investigation of the structural reinforcement as demonstrated in sections or radiographs. The patterns produced in the cortical layers by means of the split-line impregnation technique give a general picture of the reinforcement of the cortical bone and complement the findings recorded in trajectorial analyses of the trabeculae of cancellous bone.

Impregnation with ink of every crack in the cortical surface would produce a pattern which would be almost impossible to interpret. A degree of simplification is therefore present and a multiplicity of bone elements are represented by a few crevice lines which indicate the orientation of the cortical lamellae.

When strain sensitive lacquers are used, tensile and compressive trajectories are constructed at right angles to the surface cracks which develop in the lacquer when the bone is subjected to load. Loading usually simulates a restricted group of clinical situations and the representation of muscle function and attachment is necessarily a compromise. The limitations of the investigative method are reflected in the results, which confirm that the stress trajectories develop in those areas of the bone where structural reinforcement is known to be present, but which do not reflect the complexity of the bony architecture.

Replicas of bone may be criticised on the grounds that they are usually homogeneous models in which no attempt is made to duplicate the complex structural arrangement of the tissues. Loading is usually subject to limitations similar to those encountered in the use of strain sensitive lacquers and a direct relationship cannot be established between the fringe patterns and the internal structure of the bone. Nevertheless, the fringe patterns which are produced in photoelastic replicas under simulated functional loading indicate that stresses are generated in the models in those areas in which reinforcement of the bone structure has been demonstrated by other methods.

Each investigative method thus has its limitations, but they have produced results which are comparable in qualitative terms. Theoretical calculations based on observations of the anatomical structure of bones or on the behaviour of intact bones, sections or replicas under various experimental conditions have been valuable in directing attention to the biomechanical aspects of bone physiology. They have played a significant part in increasing our understanding of the relationships between form and function and of the way in which forces are absorbed and distributed throughout the skeletal system and they have led to significant advances in operative procedures in orthopaedic surgery and in the design of implants and prosthetic appliances.

CHAPTER 3

Structural Analysis of the Human Mandible

STRUCTURAL ANALYSIS OF THE HUMAN MANDIBLE

3.1 Introduction

Interest in the structure of the mandible and in the relationship between the form and function of the bone dates from the time of similar investigations in the long bones of the limbs and many of the methods which were devised for this latter purpose have been applied to the study of the mandible. The biomechanics of mandibular function have attracted particular attention because the bone has a thick layer of compact bone, with little cancellous material internally, which suggests that considerable reinforcement of the structure exists. In addition, the bone is freely movable against the skull, from which it is suspended by a group of powerful muscles which can generate considerable forces in occluding the maxillary and mandibular dentitions.

3.2 The Study of Sections of the Mandible

As in the study of the structure of the femur, the earliest investigations of the reinforcement of the mandible used anatomical techniques. Sections of the bone were prepared in various planes and radiographs, which are effectively sections through the bone, have also been used.

3.2.1 Anatomical and Radiographic Techniques

WALKHOFF (1900, 1902), who is credited with recording the first dental radiograph, studied the morphology of the mandible in relation to the forces acting upon the bone in function. He analysed the internal trabecular structure of the mandible, as revealed in sections of the bone and also in radiographs, and attempted a mathematical and mechanical analysis of the structural components in an effort to relate form and function. He compared the gross external appearance of the mandible with its inner trabecular structure and claimed that the major structural reinforcements were found at the places where the largest forces were exerted. He described a system of trajectories which could be seen in foetal mandibles and which persisted, with modification during the various stages of tooth development and eruption, until the adult form of the mandible was fully established after eruption of the third molars (Fig. 3.1.A). The organisation of this trajectorial architecture, in the alveolar region, was eventually lost in the edentulous mandible, reflecting the loss of the teeth and the altered functional demands made on the bone. LEWIN (1913), quoted by SEIPEL (1948), conducted a similar study and improved on WALKHOFF's trajectorial system by eliminating much of the confusing detail in the region of the condyle and at the angle of the mandible (Fig. 3.1.B). He concurred in the interpretation of the significance of the structural elements in terms of the laws of mechanics.

SEIPEL (1948) also quoted the work of two investigators who drew attention to the compact layers of the mandible. DAVIDA (1915), prepared serial sections to study the Haversian canal systems in the undecalcified bone and analysed the trajectorial arrangement of these structural elements in mechanical terms. WINKLER (1921) also tried by means of saw cuts to build up a picture of the mandibular Haversian systems and emphasised the importance of the cortical bone in reinforcing the structure of the mandible.

Most of these studies concentrated upon the dentate mandible, and in all of them, the emphasis was directed to the arrangement of the calcific element of the bone structure and to the mapping out of trajectories to withstand the stress and strain to which the mandible might be subjected in function. The trajectorial diagram (Fig. 3.2) first published by SICHER and TANDLER (1928), and reproduced in the most recent edition of 'Oral Anatomy' (SICHER and DU BRUL 1970) summarised the findings of these workers and indicated the existence of structural reinforcement along the inferior border of the body and up the posterior border of the ramus of the mandible, obliquely through the body and ramus to the condyle and also up the anterior border of the coronoid process.

The form of the edentulous mandible was studied by NEUFELD (1958) and compared to that of the dentate mandible. In a study of 65 specimens, he reported that the edentulous mandibles demonstrated fewer trabeculae and had thinner layers of cortical bone than the dentate specimens. He also found that the edentulous mandibles had smaller dimensions and that there was an incomplete cortical surface on the residual alveolar ridge crest. There was random variation in the alignment of the bony trabeculae in the edentulous specimens in contrast to the ordered trabeculation of the dentate mandibles. This was in agreement with the findings of TRIEGER and HERZBERG (1969) who reported that the regular ordered arrangement of trabeculae seen in radiographs of the dentate mandible was absent from the edentulous mandible, probably because of a reduction in functional demand.

3.3 The Study of the Intact Mandible

3.3.1 Split Line Impregnation Technique

The interplay of soft and hard tissues in determining the behaviour of the bone under load had received little attention until the development by BENNINGHOFF (1925) of the 'Spaltlinie' method which paved the way for such studies. In this technique, the bone is decalcified and desiccated and the fine cracks in the surface layers of the organic matrix are impregnated with Indian ink. BENNINGHOFF (1925), DOWGJALLO (1932) and SEIPEL (1948) have all used this method to study the cortical structure of the jaws and have published schematic drawings of the trajectorial arrangement of the cortical layers, which with minor discrepancies, are in good agreement.

BENNINGHOFF (1925) presented the split-line impregnation technique and demonstrated the alignment of trajectories in the dentate skull and mandible. These complemented the trajectories previously described from investigations of the trabecular pattern of the cancellous bone. DOWGJALLO (1932) used the technique outlined by BENNINGHOFF and studied the split-line patterns on dentate and edentulous mandibles. He described the arrangement of the osteons and stated that they formed a number of well defined systems in the dentate mandible:

1. From the condyle, obliquely through the ramus and body towards the mental protuberance.
2. Down the posterior border of the ramus.
3. Along the inferior border of the body.
4. Between the condyle and the coronoid process.
5. From the coronoid process, down the anterior border of the ramus to unite with the system running obliquely through the ramus and body from the condyle.
6. A specialised system surrounding the sockets of the teeth.

Between these groups of lamellae, a number of areas were found where no appreciable stain was picked up. These were designated neutral zones.

In the edentulous mandible, DOWGJALLO observed changes in this pattern, which he ascribed to the altered shape of the bone and the reduced functional demands of the edentulous state. Alveolar resorption led to the disappearance of the alveolar system which was replaced by a lamellar arrangement running parallel with the inferior mandibular border.

The systems based on the coronoid process were also markedly reduced in prominence, with a corresponding emphasis on the condylar systems, and the neutral zones appeared to be enlarged. It was suggested that this re-arrangement was a reflection of the loss of the teeth, reduced muscle function, particularly of the temporalis muscle, and a change in the working relationships of the mandibular condyle.

The technique was further developed by SEIPEL (1948) who combined the split-line impregnation method with low power micro-dissection of the deeper layers of the cortical region. This modification was developed in order to study those areas where the impregnation method did not give a clear picture of the arrangement of the lamellar structure. This occurs where resorption or deposition of bone is taking place and also where the surface lamella is thin, particularly if the area also serves as the site for a muscle attachment. SEIPEL's schematic drawings illustrated the differences in the results obtained with the two techniques (Fig. 3.3). The impregnation method produced a series of well defined lines throughout the cortical structure of the mandible but may have exaggerated the directional arrangement of the minute structural elements: microdissection revealed a grain-like pattern indicating the flow or organisation of the connective tissue matrix. These are differences in detail and degree, but the main structural elements in the mandible were demonstrated consistently by either method.

On the basis of his findings, SEIPEL analysed the mechanical significance of the architecture of the mandible. He described a system of trajectories (Fig. 3.4) and proposed a theory to explain their significance in terms of resistance to tensile and compressive forces.

3.3.2 Strain Sensitive Lacquers

KÜNTSCHER (1934) used Colophonium to demonstrate an area of tensile strain in the body of the mandible in a direction parallel with its long axis. He did not, however, give any information about the load which he applied to the bone. In a study on deformation in the mandible, EVANS (1953) used Stresscoat lacquer to demonstrate strain patterns under two loading situations. He applied a load of 59 pounds to the point of the chin in a direction parallel to the long axis of the mandibular body and produced tensile strain in the long axis of the inferior border of the body of the mandible and in the neck of the condyle. In a second specimen, he suspended a load of 175 pounds from a rod which was laid across the occlusal surfaces of the molar teeth. Tensile strain was produced along the mylohyoid line and also along the superior margin of the mandibular notch.

SICHER and DU BRUL (1954) used Stresscoat lacquer and simulated the action of the lateral pterygoid muscles by applying digital pressure bilaterally in the region of the condyle neck. They demonstrated tensile strain in the region of the mandibular symphysis and used this to support their argument that the human chin had developed in order to provide reinforcement of the mandible against the forces exerted by the medial pull of the lateral pterygoid muscles during forceful forward thrust of the mandible.

SHARRY et al (1956, 1960) applied Stresscoat lacquer to a series of edentulous skulls, for which they had constructed complete dentures. The skulls were held in a frame and a series of pulleys and weights were used to simulate muscle action and to apply load through the dentures to the underlying bone. They found that the stress patterns produced in this way were less regular in arrangement and more difficult to interpret than similar patterns demonstrated by other workers on long bones.

Nevertheless, there was clearly a distribution of stress from the body of the mandible towards the condyle and coronoid process.

3.4 The Study of Mandibular Replicas

This type of study appears not to have been used to any great extent in analyses of the structure and function of the human mandible. Only in recent years have any reports of the use of mandibular replicas appeared in the literature, and these have involved the use of photoelastic replicas.

3.4.1 Photoelastic Replicas

Simplified two dimensional models prepared from strips of a photoelastic resin material were used by MOLITOR (1969) to demonstrate the effect of variation in the position of the occlusal load relative to the mandibular elevators, and of variation in the height of the ascending ramus upon stresses in the temporo-mandibular joint. He then prepared a two-dimensional model of the jaws and skull, with inserts of photoelastic material on the mandibular occlusal surface and in the region of the neck and head of condyle. He used this to demonstrate his contention that when occlusal load was applied in normal intercuspal closure no load was transmitted to the region of the temporo-mandibular joint, and the pattern of stress distribution in his photoelastic insert (Fig. 3.5) is similar to the orientation of trajectories in this area described by other methods. LEHMAN (1972) prepared a three-dimensional photoelastic replica of the mandible and also of the maxilla and skull base. He applied load to the mandibular model and demonstrated lines of stress in the areas corresponding to the commonest sites of fracture of the bone.

3.5 Analysis of Muscle Function

Any attempt to relate structural analysis of the mandible to the study of mandibular function must also take account of the activity of the associated muscles. In such studies, the actions of the various mandibular muscles have been demonstrated, either directly on clinical or cadaveric material, or indirectly on working models. Calculations of the line of action or resultant of these muscles in relation to various anatomical planes of reference have frequently been an integral part of such demonstrations.

3.5.1 The Alignment of the Muscles of Mastication

LORD (1913, 1937) attached strings in the line of muscle pull to a human skull and jaw with an intact dentition. He then added a system of pulleys and levers which would simulate the movement of the jaw produced by individual muscles or groups of muscles. Interest in his studies was directed to the way in which movements of the mandible were influenced by the alignment of the various muscles.

The accurate determination of muscle alignment is also necessary for calculation of the forces exerted by the muscles. MAINLAND and HILTZ (1934) marked the mid-points of origin and insertion of masseter, medial pterygoid and temporalis muscles and measured the position of these points relative to the Frankfort and sagittal planes in order to determine the line of action of each muscle in a series of nine cadavers. They measured the physiological cross-sectional area of the muscles, derived values for the total forces exerted and related these forces to their planes of reference. CARLSOO (1952), in a series of five cadavers, used the surface outline of the muscles to determine their lines of action, which he related to the sagittal and transverse planes prior to calculating the forces exerted by each muscle. He also used radiographs as a means of relating these muscle resultants to a series of reference points on the skull. This information was used to establish the alignment of the muscle resultants in radiographs of a group of volunteers in his electromyographic investigation. The angulations of the muscles derived from these two studies are listed in Fig. 3.6.

Comments

As in the studies of the femur which were reported in Chapter 2, the results of the various methods of structural analysis of the human mandible are in good agreement. Anatomical investigations, whether by the study of sections or radiographs, or by means of split-line impregnation techniques, have indicated the reinforcement which exists in the structure of the bone, both in the cancellous trabeculae and in the compact cortical portion. The trajectories which have been postulated as a result of these studies suggest that whatever method is used, the pattern of reinforcement which emerges is essentially the same. Confirmation of the need for this reinforcement can be found in those studies in which strain-sensitive lacquers have been used and where stresses have developed along the line of the theoretical trajectories.

The evidence of the two photoelastic studies which have been reported suggests that photoelastic replicas might provide further confirmation of these theories. The fringe patterns presented by MOLITOR (1969) showed similarities to the trajectorial arrangement in the mandibular ramus described in the anatomical studies. LEHMAN's claim (1972) that the major stresses in his replicas accumulated near the commonest sites of fracture of the mandible, also suggests that resistance to possible fractures would require reinforcement of the bone at right angles to the common fracture lines. This is in fact the anatomical pattern which exists, where reinforcement of the inferior and posterior mandibular borders and along the oblique line resists the tendency to fracture of the angle and neck of the mandible.

The visual display of stresses is the major benefit of the photoelastic method. In the study of the distribution of occlusal load in the mandible, the technique offers the prospect of visual comparison between the stresses generated in the replicas and the structural reinforcement which has been described by other methods.

Three dimensional photoelastic stress analysis offers the additional benefit that the distribution of stresses may be studied in sections cut from selected areas of the models.

It was recognised that if the information derived from the study of stress patterns in photoelastic replicas of the human mandible was to have any validity in terms of clinical practice, the method of applying the occlusal load and of supporting the models against this load should simulate the clinical situation as closely as possible and that the supporting elements should be aligned to correspond to the mandibular musculature.

The use of the centre of the cross-sectional area of the individual muscles or of the centres of their areas of origin and insertion, as a means of deriving the line of muscle action, may be criticised on the grounds that it is arbitary and that it fails to take account of the way in which the functional units of each muscle may interact to produce controlled variations in posture. This is particularly so in the case of the temporalis, which arises from a wide area of the skull and converges towards its insertion on the coronoid process of the mandible. Yet, with his working model based on this arbitary method for the determination of the lines of muscle action, LORD (1913, 1937) was able to simulate a wide range of jaw movements with reasonable precision. This method was therefore used in designing the supporting system for this study.

CHAPTER 4.

The Distribution of Load under Complete Dentures

Page

THE DISTRIBUTION OF LOAD UNDER COMPLETE DENTURES

4.1 Introduction

Success in the wearing of complete dentures depends upon the ability of the patient to adapt to a major change in the oral environment, to modify his habitual patterns of speech and mastication and to acquire an increased range of neuromuscular control. If the dentures stay in place during functional movements, if the opposing dentitions meet evenly and at a comfortable height and if the dentures have a good appearance and do not cause discomfort, the patient should have a strong incentive to persevere in their use (Fig. 4.1).

Retention of complete dentures depends upon accurate impressions to record the detail of the tissue fitting surfaces and to adapt the shape of the peripheral areas to accommodate the movable tissues of the labial vestibule and floor of mouth. Resistance to displacement by unfavourable muscular and occlusal forces requires the correct placement of the teeth and shaping of the polished surfaces, the recording of true centric relation of the jaws and the provision of adequate excursive balance in the articulation of the opposing dentitions. A satisfactory appearance depends upon the selection of teeth of a suitable size, shape and colour and upon the setting of the teeth so that they are in harmony with the facial features and so that maximum support for the labial soft tissues is achieved. Resistance to the vertical forces arising from the occlusion of the teeth depends upon all the factors previously mentioned and also upon the consistency and morphology of the underlying bone and the quality of the investing soft tissue. Where pain or discomfort has resulted in intolerance of complete dentures, THOMSON (1967) has suggested that it is relevant to consider the conditions under which load is applied to the dentures.

4.2 The Nature of the Load

In the natural dentition, occlusal loads are transmitted from the teeth to the alveolar bone by the specialised tissues of the periodontal membrane which are arranged into a series of fibre groups which suspend the teeth in their sockets (Fig. 4.2) and transmit the occlusal forces as tension to the bone (RAMFJORD and ASH 1966). The elongation of the roots of the natural dentition and the specialised nature of their attachment to the alveolar bone also provides a resistance to the horizontal components of stress which may be imposed by the steep inclination of the cusps of the posterior teeth and by close contact between maxillary and mandibular incisors and canines. Load in complete dentures is transmitted as compression on the bone and overlying soft tissue. The mucoperiosteum, which exists as a protective covering for the bone, is itself covered by a foreign material and subjected to load (Fig. 4.3). Thus the wearing of complete dentures leads to a change in the type of load to which the bone is subjected and to the employment of soft tissues which are not designed primarily to bear load. In addition, the form of the supporting tissues affords little resistance against horizontal forces.

4.3 The Magnitude of the Load

There has been considerable interest for many years in the clinical study of the vertical forces applied in mastication and in clenching to the natural dentition and to dentures, both partial and complete. A number of attempts have been made to measure these forces, with an increasingly sophisticated range of devices and almost without exception these studies have confirmed the findings of the earlier workers, that the range of forces exerted in any particular group is very wide and that the forces which can be exerted in the sound natural dentition are far in excess of those found among denture wearers.

BLACK (1895) noted a wide variation in the values recorded by his test group of patients when asked to exert clenched load upon his gnathodynamometer (Fig. 4.4). He was unable to find any meaningful relationships between physical strength and the maximum values recorded and he concluded that the limiting factor in the magnitude of the applied load was the onset of periodontal pain. He examined a small number of complete denture wearers and found that they were able to exert only a fraction of the forces recorded in the natural dentition. However, he commented that it was unreasonable to draw conclusions from these figures as the recording device interfered with normal control of the dentures.

BOOS (1940) attempted to overcome this problem and developed a device for the measurement of vertical load in the edentulous mouth (Fig. 4.5). The instrument consisted of a tripod frame, which was mounted on the mandibular trial denture base, and a central bearing point, which contacted a steel plate located in the palate of the maxillary denture base. The height of the central bearing point could be altered and the instrument was calibrated in pound registrations. Three hundred edentulous patients were examined and it was found that for each patient there was a degree of vertical separation of the jaws at which a maximum force was exerted. The height and force were found to be constant for each patient and this position was taken as the resting vertical dimension in the construction of complete dentures. The maximum power varied in the groups studied from 13 pounds to 100 pounds, with males averaging 60 to 65 pounds and females 25 to 30 pounds and differences of as much as 16 pounds pressure were noted in a change of 2 millimetres in the occlusal vertical dimension.

The measurement of the forces transmitted to the tissues under complete dentures has been attempted by FRECHETTE (1955) and also by STROMBERG (1955). FRECHETTE constructed a set of cobalt chromium complete denture bases which incorporated three movable flaps in the molar region on either side, over the crest of the residual alveolar process and on the buccal and lingual aspects. Strain gauges were applied to these flaps to measure their deflection under occlusal load. A series of interchangeable posterior tooth segments was prepared, consisting of two forms of cuspless teeth and two cusped forms, with 20° and 30° inclines respectively. The performance of these occlusal forms under load was studied and the forces transmitted to the tissues recorded.

The 30° teeth were found to exert the least pressure on the crest of the residual alveolar process and the greatest pressure in three out of four lateral areas. They were also found to be the most efficient in chewing performance. The 20° teeth generated greater pressure over the crest of the alveolar process and less in the lateral areas, while both varieties of cuspless teeth demonstrated marked differences in loading between the right and left side, producing the highest values recorded in the right alveolar and palatal regions and the lowest values in all other areas. The most efficient distribution of occlusal forces was thus found when teeth with a 30° cusp incline were used, although the patient felt that the cusps restricted free movement of the jaws and encouraged food packing, and he expressed a preference for the 20° teeth which were marginally less efficient but provided a greater degree of balance in function.

Similar results were reported by STROMBERG (1955) who also used a displaceable insert on the tissue fitting surface and recorded the pressures produced by cusped and non cusped posterior teeth during mastication of selected foodstuffs. He recorded very high values under the denture base on the balancing side when cuspless posterior teeth were used and he attributed this to movement of the denture bases during function. He suggested that anatomical tooth forms may contribute to the stabilisation of the denture bases.

These methods have been criticised by LAWSON (1960) on the grounds that the movement of the inserts in the denture base would result in some displacement of the recording strain gauges, with inevitable shifting of the load. In addition, on the basis of his own experimental work, he pointed out that variations in the thickness of the oral mucosa may lead to variation in the load recorded and he suggested that the wide variations which exist in the thickness of the oral mucosa would make calibration of the gauges impossible.

The magnitude of the loads which were recorded may thus be open to criticism, and these studies again highlight the difficulty of quantifying occlusal forces. However, it is interesting to note that posterior teeth with an anatomical form were efficient in masticatory performance and distributed the occlusal load more uniformly to the underlying tissues.

4.4 Characteristics of the Oral Mucosa

The hard palate and the attached gingivae around the teeth are covered by masticatory mucosa, a tough keratinised mucosa, tightly bound down to the underlying periosteum and capable of withstanding a degree of load in function (ORBAN 1966). Following the removal of the teeth this tissue provides coverage for the residual alveolar process and is subjected to load under the complete denture base. The masticatory mucosa blends, at the level of the muco-gingival junction, with the lining mucosa of the labial and lingual sulci, which is thin and non-keratinised and is loosely attached to the underlying tissues. Lining mucosa is less well adapted for bearing load and yet is subjected to load under complete dentures, as the denture bases must be extended to the full functional depth of the sulci to ensure retention of the dentures and the distribution of occlusal forces over the widest possible area of bone.

The thickness of the mucosal tissues in the denture bearing area has been estimated by KYDD and his colleagues (1971).

They used an ultrasonic echo ranging device to measure the thickness of the masticatory mucosa and reported values in the edentulous maxilla ranging from 1.1 mm in the anterior region to 4.3 mm in the area of the maxillary tubursity. In the mandible the corresponding thickness in the anterior and posterior regions were 1.9 mm and 2.5 mm. They estimated that this tissue was compressed to between 45 and 55% of its resting thickness under occlusal load.

Coverage of the oral soft tissues by a complete denture base also produces a change in the environment of the mucosa. The quality of the tissue deteriorates due to a number of histological changes. OSTLUND (1958) has demonstrated the thinning and eventual disappearance of a well defined keratinised layer in the palatal mucosa under maxillary complete dentures. AVERY (1966) has postulated that there is a diminution in the blood supply to the underlying connective tissue and diminished mitotic activity in the stratum germinativum, which leads to decrease in cellular turnover and in the rate of replacement of the surface mucosal cells. In addition, the insulating effect of coverage by a complete denture base inhibits the activity of the specialised sensory receptors which are present throughout the oral mucosa and proprioceptive feedback from the tissues is thus diminished. The oral mucosa is also affected by disturbances in hormonal and vitamin metabolism. These conditions are frequently present in edentulous patients in the older age groups and may lead to further reduction in the capacity of the tissues to withstand the forces imposed by the wearing of complete dentures (BERRY & WILKIE 1964).

The importance of initiating treatment, either systemic or local, to improve the condition of the oral soft tissues before undertaking the construction of dentures has been emphasised by MATTHEWS and his colleagues (1961), in their examination of the problems associated with complete dentures. They also recommend that due consideration should be given in the design of complete dentures to the resilient and dynamic nature of the underlying soft tissues.

Erratum Page 51 line 4 - read 'tuberosity' for 'tubursity'.

4.5 Characteristics of Alveolar Bone

The physiological process of healing and bone remodelling which follows the extraction of teeth has been studied in great detail, but the process of bone resorption which then ensues is poorly understood. Bone is a labile tissue and its behaviour varies widely in different individuals, so that the total amount and rate of resorption is variable and, indeed, the rate may vary for any individual at any given time (TALLGREN 1957, 1972, ATWOOD 1962).

ORTMAN (1962) pointed out that after the loss of teeth, the alveolar bone can no longer be subjected to stimulation internally, via the fibres of the periodontal membrane. The nature of the load is therefore changed from tensile to compressive and the magnitude of the load is reduced to that which can be tolerated by the oral mucosa. ORTMAN suggested that the alteration in proprioceptive feedback caused by these changes would lead to a disuse atrophy, which he described as a condition in which no new protein matrix, and hence no new bone, was laid down while resorption continued at a normal rate, leading to a net loss of bone structure. He also suggested that pressure from a denture base may produce ischaemia of the underlying mucoperiosteum and may promote resorption by interfering with the periosteal blood supply of the bone. ATWOOD (1962) agreed that when the teeth have been removed, alveolar bone is no longer subjected to the type of load for which it is designed and that in these circumstances remodelling is to be expected, so that the bone may assume a form which will best withstand the applied load.

The effect of this resorption is that a smaller area of bone is available for the support of the loads transmitted by complete dentures and these changes take place to a greater extent in the mandible than in the maxilla, a fact which was noted by TALLGREN (1972) in a longitudinal study of alveolar resorption in complete denture wearers over a period of 25 years.

The form of the mandibular alveolar ridge was also altered, progressive reduction in height leading in extreme cases to a concavity in the superior surface of the body of the mandible. In addition, NEUFELD (1958) reported that there was an incomplete cortical surface covering the residual alveolar ridge in a series of edentulous mandibles which he examined, and thus the surface was composed, in places, of cancellous trabeculae.

4.6 Denture Design in relation to Load

In order to reduce the effect of the occlusal load on the underlying tissues, maximum extension of the denture bases must be achieved, the teeth must be placed in the correct bucco-lingual position so that no undue lateral component of force is present and the occlusal width of the posterior teeth must be kept to the minimum compatible with efficient comminution of food and the development of balance in occlusion and articulation.

WATT and his colleagues (1958) demonstrated that the area of mucosa which is left to withstand occlusal loads under dentures is much less than the area of periodontal attachment of the missing teeth. On this basis they calculated that almost three quarters of the potential area of support is lost and they suggested that this helped to explain the reduction in the levels of masticatory and clenched loads in their partially edentulous patients when compared to the values recorded in a control group with sound natural dentitions. The functional deficit was thus a consequence of the support deficit and dentures should be so designed as to ensure the efficient distribution of occlusal loads to the available support.

The results of their work suggest that every effort should be made to achieve maximum extension of the denture base in mucosa borne sections of partial dentures and a reduction in the bucco-lingual width of the occlusal surfaces of the artificial posterior teeth. The application of these principles is even more important to the success of complete dentures as these are entirely dependent for their support on alveolar bone and mucoperiosteum. MYERSON (1953) advocated maximum extension of denture bases and argued that teeth be set in balanced articulation to ensure simultaneous bilateral contact in function. He also advocated the use of non-anatomical posterior teeth to eliminate any possibility of lateral stress components in occlusion, though the later studies of FRECHETTE (1955) and STROMBERG (1955) suggested that there was a more even distribution of forces when teeth with anatomical cusps were used.

The value of balanced occlusion and articulation was also recognised by FISH (1948), who pointed out that premature contact in the incisor or in the molar region of complete dentures could lead to instability of the dentures, and suggested that as many teeth as possible should meet and be in use simultaneously so that the reciprocal pressure between the dentures could be directed favourably to the underlying tissues. He also emphasised the importance of the correct bucco-lingual placement of the artificial teeth and advocated the use of a narrow occlusal table. Further support for reduction of the width of the occlusal table can be found in the work of BEARN (1971). He used a series of occlusal inserts of gradually diminishing width in a maxillary complete denture and recorded a progressive reduction in the forces transmitted through the opposing mandibular complete denture by means of a hydraulic insert in the mandibular denture.

4.7 Failures of Denture Design

LAWSON (1959) examined a group of 200 patients who had been unsuccessful in their attempts to wear complete dentures and analysed the commonest causes of failure of the dentures. The commonest fault was inadequate peripheral extention. The vast majority of mandibular dentures were underextended in all border areas and LAWSON commented that very few of the dentures utilised more than a small fraction of the available supporting area and that in many cases the area of the denture base could have been more than doubled.

Erratum Page 54 line 29 - read s for t in 'extension'.

The maxillary anterior teeth had been positioned too far lingually in 70% of cases. In addition to producing an unsatisfactory appearance and interfering with tongue movements in speech, this fault was a major factor in limiting freedom of articulation. Lack of occlusal balance was found in 62% of cases and in 53% free sliding movements of the opposing occlusal surfaces were completely obstructed, protrusive movement being prevented by the setting of the incisors and lateral excursion by the canines and first premolars.

These findings were supported by ANDERSON and STORER (1966), who listed the four most common faults in complete dentures as underextension of the denture bases, incorrect positioning of the maxillary anteriors, occlusal imbalance and a lack of articular balance. They commented that in many cases free articulation was prevented by an incorrect incisal relationship which resulted in contact of the anterior teeth as the patient attempted to protrude the mandible.

4.8 Subperiosteal Implants

Some patients are unable, because of discomfort, to tolerate dentures which have been constructed in accordance with well recognised principles. Repeated failure to adapt to apparently satisfactory dentures suggests that the underlying tissues are unable to tolerate the load to which they are being subjected.

The subperiosteal implant was devised by GERSHKOFF and GOLDBERG (1957) in an attempt to overcome this problem by supporting the denture on a framework which is placed directly on the surface of the bone. They recommended that the subperiosteal framework be made to fit a cast from a direct impression of the bone surface and that the framework should be extended over as wide an area as possible for optimum distribution of load.

This technique offers substantial benefit to many patients and a considerable number of successful dentures have been supported on subperiosteal implant frameworks which have been in place for up to 20 years (BODINE 1974). The problems of advanced resorption and discomfort under complete dentures are more frequently encountered in the mandible and this is reflected in the preponderance of mandibular subperiosteal implants.

Comments

In spite of the fact that the residual alveolar bone and its investing soft tissues are less well able to tolerate load than are the tissues which support the natural teeth, clinical experience suggests that when adequate care is taken in the construction of dentures, the reaction of the tissues is not unfavourable and dentures are worn in reasonable comfort, even if mild inflammatory changes are present in the soft tissues.

The variations which exist in the magnitude of load applied to complete dentures, in the condition of the supporting soft tissues, in the rate and degree of resorption, and in the quality of the alveolar bone, make it difficult to assess the level of load which can or should be tolerated by any particular patient. Complete dentures should be designed so that the loads to which they are subjected are kept to the minimum compatible with adequate function and are distributed over the maximum available area. Failure to observe these criteria of denture design frequently leads to the development of pain or discomfort in the area covered by the denture base. This problem is encountered more often in the mandible where there is a smaller area available for the support of complete dentures.

It was therefore decided to subject the edentulous mandibular replicas to a variety of loading situations in order to simulate features of correct and incorrect denture design. In the first instance, the load was uniformly distributed over the area of the occlusal surface and the denture base was extended to cover the maximum available area. The conditions of loading were then modified to simulate faults in the design of the denture base and of the occlusal table in order to demonstrate the changes which this produced in the transfer of load to the underlying structures. The distribution of load under a mandibular subperiosteal implant framework was also studied.

SECTION 3.

DEVELOPMENT OF THE EXPERIMENTAL SYSTEM

CHAPTER 5.

Anatomy

ANATOMY

5.1 Introduction

In this study replicas of the dentate and edentulous human mandible were prepared in a photoelastic resin material and were loaded to simulate a condition of occlusal load supported by isometric contraction of the mandibular elevator muscles, with the jaw in a position of centric relation. In this chapter, the anatomical form and structure of the mandible and the form and function of the principal muscles of mastication and of the temporomandibular articulation are described. A number of anatomical texts have been consulted and, though not quoted individually in this chapter, they have been included in the list of references.

5.2 The Mandible

The mandible consists of a strong horse-shoe shaped horizontal body which carries the alveolar process and teeth and, on either side, is continuous posteriorly with a broad flat vertical ramus (Fig. 5.1). The ramus projects upwards to form two prominent processes, the anterior of which is the muscular coronoid process and the posterior the articular condylar process. These processes are separated by the mandibular notch.

5.2.1 Surface Detail

The external surface of the mandibular body is marked near the mid line, in the upper part by a faint ridge, the symphysis menti, which indicates the line of fusion of the two halves of the foetal bone, and in the lower part by a triangular raised area, the mental protuberance, the base of which is raised on either side to form the mental tubercle.

The lower border of the body, thick and smoothly rounded, extends backwards and laterally from the mental region and is continuous at the angle of the mandible with the posterior border of the mandibular ramus. A faint ridge, the oblique line, arises from the area of the mental tubercles and becomes more pronounced as it passes upwards and backwards to become continuous with the anterior border of the ramus. Below the roots of the premolar teeth and above the oblique line, the mental foramen, from which the mental nerve and vessels emerge, opens on to the lateral surface of the body of the mandible. The upper border of the body is the alveolar part, which is hollowed by the sockets for the roots of the teeth. In the adult mandible the alveolar and subalveolar portions of the mandible are of approximately equal depth. The external surface of the ramus is flat and is marked by a series of elevations in the lower part for insertion of the masseter muscle.

The internal surface of the body of the mandible is divided by an oblique ridge, the mylohyoid line, which commences as a prominent sharp ridge behind the third molar tooth, just below the upper border of the body and runs downwards and forwards, reducing in prominence, to reach the lower border in the mental region. Above the anterior end of the mylohyoid line the inner surface of the bone is raised up to form two irregular tubercles, the mental spines. In the anterior region above the mylohyoid line, a depression, the sublingual fossa, exists for the sublingual salivary gland. Posteriorly, below the mylohyoid line, there is another depression, the submandibular fossa, for the submandibular salivary gland. The internal surface of the ramus presents an irregular opening, the mandibular foramen, just above its centre. This opening leads into the mandibular canal, which carries the inferior dental nerve and vessels. At the anterior margin of the mandibular foramen a triangular bony process, the mandibular lingula, is located. A number of sharp ridges are present just above the angle of the mandible for insertion of the medial pterygoid muscle.

The alveolar process is carried by the mandibular body and differs from it in curvature. The mandibular body is directed laterally in its posterior region and the alveolar process curves medially. Thus the posterior portion of the alveolar process is situated medial to the body and ramus.

The anterior border of the ramus extends from the tip of the coronoid process to the lateral aspect of the third molar tooth, increasing in width and becoming continuous with the oblique line. The upper border is thin and forms the wide mandibular notch or incisure which separates the coronoid and condylar processes. The posterior border is thick and rounded and extends in a gentle curve from the neck of the condylar process to the angle of the mandible. The coronoid is a flattened triangular process whose margins and medial surface give attachment to the temporalis muscle. The condylar process is expanded above to form the head of the mandible which is convex antero-posteriorly and medio-laterally and which articulates with the mandibular fossa of the temporal bone. The constricted portion below the head is the neck of the mandible which is grooved on its anterior aspect by the pterygoid fovea, a depression for the insertion of the lateral pterygoid muscle.

5.2.2 Structure

The mandible has a thick outer shell of compact bone with a relatively small amount of cancellous bone internally. The compact cortical layers are further thickened in the region of the mental protuberance; along the length of the inferior border of the body and posterior border of the ramus; in the region of the oblique line on the external surface and the mylohyoid line of the internal surface; and in the areas of attachment of the principal muscles of mastication. The cancellous bone is found in the mandibular body principally around the roots of the posterior teeth and extends from this area as a thick bar through the body and ramus to the head of the mandible.

The cortical plates of the mandibular body extend upwards to form the external and internal plates of the alveolar process and are united by the interdental and inter-radicular septa which form the sockets of the teeth. In the anterior region, these plates are united, with no intervening cancellous bone, and fenestration of the labial surface is common. Posteriorly, there is considerable thickening of the cortical elements and areas of cancellous bone are present, lingually in the premolar region, buccally and lingually in the first and second molar regions and buccally in the third molar region. In the second and third molar regions, the oblique line of the mandible increases the thickness of the outer cortical plate and in some cases leads to the formation of a broad flat shelf of bone level with the cervical margin of the molar teeth. This cannot strictly be regarded as part of the alveolar process but becomes important in the edentulous mouth, when it is available for extension of the mandibular denture base and for the distribution of load under the mandibular complete denture.

5.3 The Edentulous Mandible

Following the loss of teeth, the alveolar portion of the body of the mandible is resorbed and atrophic changes occur in other parts of the mandible (Fig. 5.2). The process of resorption affects chiefly the thinner of the two alveolar walls and after its completion a linear alveolar ridge is found on the alveolar border of the bone. The labial wall is thinner in the anterior region and the lingual in the posterior region, with the result that the alveolar process lies within the line of the labially inclined incisor teeth and outside the line of the lingually inclined molar teeth, forming a curve that is wider than the curve of the teeth.

Reduction in height of the alveolar process brings the residual ridge into relation with bony structures which are normally remote, such as the mental prominence and genial tubercles anteriorly and mylohyoid and oblique lines posteriorly. The mental foramen may come to lie near the surface of the residual alveolar ridge and the origin of the incisive, mentalis and buccinator muscles on the lateral aspect and the mylohyoid and genioglossus muscles on the medial aspect of the bone may come to lie at the level of the reduced alveolar ridge. The ramus becomes reduced in dimension, with increasing prominence of its processes and narrowing of its antero-posterior width.

5.4 The Muscles of Mastication

Four powerful pairs of muscles are attached to the mandible on each side and are normally described as the muscles of mastication. These are the temporalis, masseter, medial pterygoid and lateral pterygoid (Fig. 5.3) and they are supplied by branches of the mandibular division of the trigeminal nerve. Three of these muscles, temporalis, masseter and medial pterygoid, exert their power in a vertical direction and act as closing muscles of the jaw, or elevators of the mandible. The posterior fibres of the temporalis also play a part in retrusion of the mandible. The lateral pterygoid muscle is situated in a horizontal plane and pulls the head of the mandible forwards in protrusion and lateral excursion.

Temporalis Muscle

This fan shaped muscle arises from a wide area of theinfra-temporal fossa of the skull, involving the temporal surfaces of the frontal, sphenoid and parietal bones and the greater part of the squamous portion of the temporal bone. This field extends from the inferior temporal line down to the level of the infra-temporal crest of the sphenoid bone. In addition, many fibres arise from the inner aspect of the temporal fascia. The muscle fibres converge on the opening between the lateral aspect of the skull and the zygomatic arch to gain insertion into the coronoid process of the mandible. The anterior fibres are almost vertical in alignment, the middle fibres increasingly oblique and the posterior fibres run forwards almost horizontally and then turn over the root of the zygomatic process of the temporal bone to pass down to the coronoid process. The insertion of the muscle occupies the coronoid process and extends down the ramus to the retromolar region. The main action of the muscle is elevation of the mandible, but the most posterior fibres pull the mandible backwards during closure and also play a part in balancing the action of the lateral pterygoid muscle in lateral excursion of the jaw.

Masseter Muscle

This muscle passes as a broad flat plane from the zygomatic arch to the outer surface of the mandibular ramus and can be divided, through incompletely, into a superficial and a deep portion. The origin is from the lower border of the zygomatic arch, forward of the zygomatico-temporal suture line on the outer aspect, and from the entire length of the arch on the inner aspect. The muscle is inserted into the lower third of the posterior border of the ramus, the inferior border of the body as far forwards as the second molar and the outer surface of the ramus in its lower half. The muscle acts as a powerful elevator of the mandible.

Medial Pterygoid Muscle

This muscle is situated on the medial aspect of the mandibular ramus and is anatomically and functionally a counterpart of the masseter. It is a broad flat muscle which arises by two heads, a superficial from the pyramidal process of the palatine bone and the maxillary tuberosity and a deep head from the medial surface of the lateral pterygoid plate. The fibres run downwards, backwards and outwards to be inserted in the medial surface of the mandibular ramus below the mandibular foramen.

Erratum Page 65 line 15 - read 'though' for 'through'.

Lateral Pterygoid Muscle

This muscle arises by two heads, a superior from the infra-temporal surface of the greater wing of the sphenoid bone, anterior to the infra-temporal crest, and an inferior head from the lateral surface of the lateral pterygoid plate. The fibres run posteriorly and converge to gain insertion into the pterygoid fovea on the medial aspect of the condylar neck. A few fibres of the superior group gain insertion into the articular capsule and into the articular disc of the temporo-mandibular joint. The muscle pulls the head of the condyle downwards, forwards and inwards along the posterior slope of the articular eminence.

5.5 The Temporo-Mandibular Articulation

The head or condyle of the mandible articulates with the temporal bone of the skull. The articulating surfaces of the bones are covered in fibro-cartilage and an articular disc of the same material is interposed, dividing the joint into an upper and lower compartment (Fig. 5.4). The mandibular condyle is cylindrical in form, with its long axis directed medially and posteriorly. The articular surface of the condyle is the superior and anterior surface. The condyle is contained within the mandibular fossa of the temporal bone and articulates in function with the eminence which forms the anterior limit of this fossa. The articular surface of the eminence is the posterior and inferior surface.

The joint is bounded by a capsule. This is reinforced laterally to form the lateral or temporo-mandibular ligament, which arises from the root of the zygomatic process of the temporal bone and is inserted into the neck of the condylar process. There are, in addition, two accessory ligaments attached to the internal surface of the ramus: the spheno-mandibular ligament, which arises from the angular spine of the sphenoid and is inserted into the lingula and the lower border of the mandibular foramen;

and the stylo-mandibular ligament, which arises from the styloid process and passes down to the posterior aspect of the angle of the mandible. When the teeth are in the position of maximum occlusal intercuspation, the head of the mandible is normally situated in the mandibular fossa of the temporal bone, in relation to the posterior slope of the articular eminence, with a joint space of approximately equal dimensions anteriorly and posteriorly. This has been defined as the position of centric jaw relation.

CHAPTER 6.

The Model System

THE MODEL SYSTEM

6.1 Introduction

In clinical studies of the function of bones, joints and muscles, a simplification of objectives is often dictated either by the complexity of the biological system or by the limitations of the investigative technique. This was recognised by CARLSOO (1952) in the planning of his study of the function of the mandibular elevator muscles and has influenced the design of many investigations of occlusal loading, muscle function and temporo-mandibular joint movement. The development and use of a model system for a study of this type necessarily imposes further constraints.

In three dimensional photoelastic stress analysis, load must be applied to the replica and maintained while the temperature is increased to a critical value and then slowly allowed to fall to room remperature. A static situation was therefore selected with a pre-determined magnitude and direction of load and a fixed alignment and length of supporting structures, representing a condition of isometric contraction of the mandibular elevators against a constant load.

The first requirement was the construction of a supporting frame from which the mandibular replicas could be suspended by means of struts representing the masseter, medial pterygoid and temporalis muscles and for this purpose it was necessary to determine the line of action of each of these muscles.

6.2 Determination of the Lines of Muscle Action

A radiographic method was used to determine the lines of muscle action in this study. Two dried skull specimens were selected, a dentate specimen with an intact natural dentition in good occlusion and an edentulous specimen in which the mandible had a well formed alveolar process with two areas of recent tooth loss. The dentate mandible was related to the skull by placing the opposing dental arches in the position of maximum occlusal intercuspation, with the condyles in the centre of the articular fossae of the temporal bones. A similar centric relation of the edentulous mandible was achieved and compound occlusal rims, which had been trimmed so that the residual maxillary and mandibular alveolar processes were approximately parallel, were used to establish the occlusal vertical dimension.

The areas of origin and insertion of the masseter and medial pterygoid muscle and of the posterior segments of the temporalis muscles were outlined on both skulls and the mid point of each area clearly marked. Metal rods were cut to the exact length for each muscle and were sealed in position so that they joined the mid points of the areas of origin and insertion to indicate the line of muscle action.

A. The Dentate Skull and Mandible

A lateral skull radiograph was recorded and a cephalometric tracing made so that the angulation of each muscle to the Frankfort plane could be measured (Fig. 6.1). This information was used to design the supporting system for the study of the dentate mandible.

B. The Edentulous Skull and Mandible

Modification of the supporting system was undertaken for this study in order to improve the alignment of the supporting struts. Radiographs of the edentulous skull were recorded in lateral, frontal and basal projections and cephalometric tracings were made so that the angulation of each muscle to the Frankfort and sagittal planes could be measured (Figs. 6.2, 6.3, 6.4). This information was used to design the supporting system for the study of the edentulous mandible.

The values which were derived for the angulation of the mandibular elevator muscles in the present study are listed in Figure 6.5 and are comparable to the values recorded by MAINLAND and HILTZ (1934) and by CARLSOO (1952), to which reference was made in Chapter 3.

6.3 Construction of the Supporting System

The information derived from the cephalometric analysis of the lateral radiograph of the dentate skull was used to design the supporting system for the replicas of the dentate mandible. A supporting frame was constructed in aluminium to represent the base of the skull. An outer rectangular frame was made with two movable beams which could be adjusted to the correct intercondylar width and to which could be fitted aluminium blocks providing location for the head of the mandible and attachment for struts representing the elevator muscles. Initially, an aluminium block with a transverse groove was used to locate the head of the mandible, but this was eventually replaced by a block which carried an articular fossa which had been duplicated from the skull base and processed in acrylic resin. Rectangular blocks of aluminium were used to provide attachment for aluminium struts which were used to suspend the models from the framework and to simulate the muscles of mastication. Two rectangular blocks, representing the origins of the masseter and medial pterygoid muscles were positioned on each of the movable beams and two burther blocks, representing the origin of the posterior fibres of the temporalis muscle, were located on the posterior limb of the framework. These blocks were machined to permit free movement along the framework and both the blocks and the adjustable beams were fitted with locking screws, by means of which they could be securely fixed in position.

Aluminium struts, 5.08 mm x 10.16 mm in cross section were used to suspend the mandibular replicas from the supporting frame. They were fitted to the model by means of metal copings which had been cast to fit over the coronoid processes and mandibular angles and which carried projections for the attachement of the struts (Fig. 6.6). In the construction of these castings, a spacer of approximately 2 mm thickness of baseplate wax was

Erratum Page 71 line 20 - read f for b in 'further'.

added to the surface of the mandible over the area to be covered by each coping. The copings were then formed in wax and cast in a technique alloy and were subsequently lined with silicone* before being fitted to the photoelastic models. This method was chosen in order to simulate the resilience of the soft tissues in the attachment of the muscles to the mandible and to avoid the heavy concentration of stresses which direct attachment of the struts to the replica would have caused.

6.3.1 Modification of the Supporting Frame for Replicas of the Edentulous Mandible

The system which has been described was used in the study of replicas of the dentate mandible. Some difficulty had been encountered in locating the models in the supporting frame due to divergence in angulation between the lateral aspect of the mandibular models and the aluminium blocks from which the supporting struts were suspended. In order to improve the alignment of these struts in the coronal and sagittal planes, modification of the aluminium blocks was undertaken and they were machined to match the angles against the coronal and sagittal planes which had been measured for each muscle during the radiographic study of the edentulous skull (Fig. 6.7). Struts and copings were prepared in the manner previously described. The sections of the supporting frame were cut from a sheet of aluminium of 1 cm thickness and the blocks were machined from a rectangular bar of aluminium, 7.5 cm x 2.5 cm in cross-section.

*Xantopren Blue Bayer, W. Germany.

Comments

The criteria for the determination of the lines of muscle action have been outlined in Chapter 3. In this study, it was necessary to provide support for models of the mandible so that a static load could be applied and maintained during the photoelastic stress freezing cycle. It was considered that this could be achieved by means of metal struts positioned in the line of action of the elevator muscles and this line was derived by joining the mid points of the areas of origin and insertion of each muscle.

It is not possible to represent the entire remporalis muscle by a single strut and for the study of muscle function this muscle has normally been divided into anterior and posterior segments on the basis of the alignment of muscle fibres (LORD 1913, 1937, MAINLAND and HILTZ 1934, CARLSOO 1952). This sub-division has been continued in more recent electromyographic studies (MOLLER 1966, 1974) which have confirmed the retrusive activity of the posterior segments of the temporalis muscle. The intention in the present study was to simulate occlusal loading with the mandible in a position of centric relation. It was therefore decided that the strut representing the temporalis muscle should be positioned in the line of the posterior segment of that muscle.

In this way it was hoped to resist any tendency to forward displacement of the head of the mandible when occlusal loads were applied. Vertical resistance to the applied loads was provided by the struts representing the masseter and medial pterygoid muscles. The lateral pterygoid, which pulls the mandibular condyle forwards during protrusion and lateral excursion and which, from histological and electromyographic studies (HONEE 1970) has been identified as a muscle which is active in rapid movements of the mandible rather than in the support of load, was not represented in the model system.

Erratum Page 73 line 10 - read t for r in 'temporalis'.

SECTION 4.

METHOD AND MATERIALS

CHAPTER 7.

Photoelastic Stress Analysis

Errata On pages 78 - 81 the adjective 'principal' has been incorrectly rendered 'principle'. This error also occurs in pages 94, 105 and 108 and also in the title to Figure 7.8 on page 37 of Volume 2.

PHOTOELASTIC STRESS ANALYSIS

7.1 Introduction

Photoelastic stress analysis depends upon the way in which light is altered by passage through transparent materials which have been subjected to load. In this chapter an outline is presented of the properties of light and the way in which these may be altered by passage through suitable media. The principles of polarisation, birefringence and photoelasticity are explained. A description is given of the plane and circular polariscopes and of their use in the study of isochromatic and isoclinic fringe patterns. An explanation is given of the use of these fringes in determining the stresses to which a particular specimen has been subjected and the characteristics of photoelastic models and materials are outlined. A number of standard texts have been consulted and, though not quoted directly, they have been included in the list of references.

7.2 The Polarisation of Light

Light is a form of radiant energy in which the electromagnetic disturbance is displayed in a visual manner. The visible spectrum of light occupies only a short range of wavelengths in the total field of electromagnetic phenomena (Fig. 7.1) and extends from violet through indigo, blue, green, yellow and orange to red (Fig. 7.2). Light of one wavelength is visible as a single colour and is known as monochromatic light. White light is a mixture of light of several different wavelengths.

Natural light consists of a complex mixture of harmonic waves which vibrate in a random fashion in all possible directions perpendicular to the straight line along which the light is propagated (Fig. 7.3), but this random vibration may be modified by passing the beam of light through suitable media.

When light passes from one medium to another it is refracted or subjected to a change of velocity. In passing through a polarising filter light is broken up into two components which vibrate in planes at right angles to each other, one parallel and one at right angles to the plane of polarisation of the polariser. The component at right angles to the plane of polarisation is eliminated. The other is transmitted and consists of light in which all the waves vibrate in only one plane perpendicular to the axis of propagation (Fig. 7.3). Such light is described as plane polarised light and it will pass unchanged through a second polariser whose plane of polarisation is parallel to that of the first. If the second polariser is placed with its plane of polarisation at right angles to that of the first, all light will be extinguished.

Plane polarised light may be converted to circularly polarised light by the use of a filter, known as a quarter wave plate, positioned with its principal axis at an angle of 45° to the plane of polarisation of the polariser. This has the effect of changing the linear vibration of the polarised light waves to a circular orbit along the axis of propagation (Fig. 7.3).

7.3 Birefringence and Photoelasticity

When light passes through an isotropic medium it propagates with the same velocity in every direction. When it enters an anistropic or crystalline medium it is divided or refracted into two plane polarised components of different velocities which vibrate in planes at right angles to each other. This is the phenomenon known as birefringence and the difference in velocity of the emergent rays is known as phase difference or relative retardation.

BREWSTER (1816) discovered that some isotropic materials became optically birefringent when subjected to stress or strain and therefore behaved temporarily as if they were crystals. Almost all transparent materials possess this property which is known as temporary birefringence or the photoelastic effect. In addition, a number of materials may acquire permanent birefringence if subjected to a thermal cycle while under load. The optical effect of birefringence and hence the stress or strain which has produced it, can be analysed if the specimen is viewed in polarised light.

7.4 The Plane Polariscope

A polariscope is an instrument which permits the examination of specimens in polarised light. The simplest form is the plane polariscope, which consists of a light source and two polaroid lenses, a polariser and an analyser (Fig. 7.4). The polariser converts the incident light beam into plane polarised light. If the light is then passed through a stressed birefringent material it is further refracted into two component waves which vibrate in planes at right angles to each other, corresponding to the directions of the principle stresses in the material. The analyser, which is set with its plane of polarisation at right angles to that of the polariser, collects the two emergent rays from the specimen into the same plane and identifies the interference to the light wave caused by passage through the stressed specimen.

Where one of the principle stresses in the material coincides with the plane of polarisation of the polariser a single light component will emerge, having passed unchanged through the polariser and specimen. It will be perpendicular to the plane of polarisation of the analyser and hence will be eliminated by it to give a dark line. This line indicates the direction of the principal stresses and is known as isoclinic.

Where the difference in magnitude of the principle stresses in the material is a constant, the phase difference between the two emergent rays will be an integral number of wave lengths and extinction of light will occur when the rays are collected by the analyser into one plane. The dark lines so formed represent a condition of constant difference in the principle stresses and are known as isochromatics.

Isochromatic and isoclinic fringes are superimposed in the plane polariscope and they must be separated for analysis of the stresses in the specimen.

7.5 The Circular Polariscope

The circular polariscope consists of the following elements: light, source, polariser, first quarter wave plate, second quarter wave plate and analyser, arranged in that order (Fig. 7.5). The polariser converts the incident light beam into plane polarised light and the first quarter wave plate, set with its axis at an angle of 45° to the plane of polarisation, changes the plane polarised light into circularly polarised light. The second quarter wave plate, set with its principal axes at right angles to that of the first, restores the original plane polarised light which then passes to the analyser. If polariser and analyser have their axes crossed and both quarter wave plates also have their axes crossed, all light is eliminated and a dark field results. A light field may be produced by positioning either the polariser and analyser or both quarter wave plates with their principle axes parallel.

If a stressed birefringent specimen is placed between the two quarter wave plates the circularly polarised light is resolved into two linear components at right angles to each other, along the principle lines of stress in the specimen. The second quarter wave plate causes further retardation of the emergent rays and also modifies their angulation. These linear components of light are no longer vibrating in the planes of the principle stresses in the specimen, nor do they coincide with the axis of the polariser and so the orientation of the principle stresses cannot be demonstrated by extinction of light by the analyser. The only condition which produces extinction of light in the circular polariscope is a retardation of a constant wavelength between the two emergent rays from the specimen. Thus the circular polariscope eliminates the isoclinics and demonstrates only the isochromatic fringes. These may be demonstrated against a dark field or against a light field, the light field having the advantage that the outlines of the specimen can be clearly seen.

7.6 Interpretation of Stress Patterns

Alternate use of plane and circularly polarised light may therefore be used to study the two types of fringes produced in stressed birefringent materials. The information which is derived from this study may be used to analyse the distribution of stresses within the specimen.

A. The Study of Isochromatics

In order to study the isochromatic fringes, it is necessary to eliminate the isoclinics from the field, which is done by using the circular polariscope. In monochromatic light, the isochromatics appears as dark lines across the specimen and in white light they appear as a series of coloured fringes.

Retardation of white light as it passes through a birefringent material results in the sequential elimination of the principal colours of which the white light is composed, commencing with indigo, the colour of the shortest wavelength, and the transmission of the appropriate complementary colour. A pattern of coloured fringes is formed in the material when viewed in polarised light and each isochromatic or fringe of uniform colour (Fig. 7.6) represents a line along which the difference of the principle stresses within the material is constant. The colours appear in the same sequence in succeeding orders of fringes, though they become progressively paler until it is only possible to distinguish between a rose pink and a pale green colouration. The development of successive orders of fringes may be observed directly during the course of an experiment or may be calculated by counting the fringes from a point on the surface of the model to which no load has been applied. Monochromatic light is used for the accurate determination of fringe orders and white light for demonstration purposes.

Study of the isochromatics allows the fringe order or number to be determined and gives a qualitative demonstration of the stresses or strains generated in different parts of the specimen. In addition, when the direction of the principle stresses has been determined by the study of the isoclinics, the fringe order allows the value for each stress to be calculated. The fringe order is a series of integral numbers when dark field illumination is used. Half order fringes are demonstrated in a light field system.

B. The Study of Isoclinics

The calculation of the directions of principal stress in a specimen derives from the study of the isoclinic lines. When monochromatic light is used against a dark field in a plane polariscope, both the isoclinic and isochromatic fringes appear as dark lines on the specimen. In white light, however, the isochromatics appear as coloured and the isoclinics as dark lines.

Thus, the isoclinics stand out as dark lines against a background of coloured fringes (Fig. 7.7). At any point on an isoclinic, the directions of the principle stresses are parallel and perpendicular to the plane of polarisation of the polariser and may thus be related to any chosen reference axis (Fig. 7.8). The angulation of the plane of polarisation is known as the parameter of the isoclinic. The system of polariser and analyser may then be rotated simultaneously through a chosen angle, when the directions of the principle stresses may again be plotted in relation to the new parameter. When a series of isoclinics has been studied in this way (Fig. 7.9) stress trajectories may be constructed by drawing curves which are tangential to one of the principle stresses and perpendicular to the other (Fig. 7.10). These constructions are carried out by laying a sheet of tracing paper over a diagram of the isoclinics and using a set square to draw the necessary lines.

7.7 Photoelastic Models and Materials

In photoelastic stress analysis, a model of the object under study is constructed in a transparent material which will demonstrate birefringence when subjected to load and viewed in polarised light. The model may be scaled in proportion to the prototype or may be an exact replica.

Two dimensional models may be assembled by cutting sections of appropriate size and shape from sheets of photoelastic material and are suitable for the study of structures composed of plates or bars. Simplified models representing the outline form of complex objects may also be constructed in this way. Two dimensional models have the advantage that they may be subjected to dynamic loading and thus the development of stresses may be observed directly. However, if a more accurate visualisation of the distribution of stress within an object of irregular shape is desired, a three dimensional model must be prepared. This is done by preparing a mould of the object, pouring a replica in a fluid resin material and curing the resin at high temperature.

The model is loaded and is heated to a critical temperature under carefully controlled conditions while the load is maintained. After the model has cooled to room temperature, the load is removed and the stresses generated by the load are permanently locked into the structure of the model. This is known as a 'stress freezing' technique. The stresses in the entire structure may be studied and sections may be cut from the model, without distortion of the fringe patterns, so that the stresses in particular areas may be analysed.

Most photoelastic model materials exhibit a linear relationship of stress and strain within a certain range of loading and for a certain length of time. Beyond this range of load or time, their stress/strain relation is time dependent. Thus the materials are viscoelastic.

This means that the instantaneous strain which develops in response to the application of load is altered by a gradual increase in strain with time. Removal of the load is followed by instantaneous recovery of part of the strain and by a time dependent relaxation of the remainder, which may result in some residual deformation. Thus it is important to select a material which has a linear stress/strain relationship over the range of load and time to be used in testing, so that no portion of the photoelastic model is loaded beyond the linear range of the material.

Materials used for 'stress freezing' techniques are diphasic polymers. One phase is rigid at room temperature and becomes increasingly fluid at high temperature. The second phase is less rigid than the first, but retains its properties even at high temperature. At room temperature, loads will be carried by the solid phase constituents with relatively small deformations. A load applied above the melting point of the solid phase will be carried by the second phase constituents and the stresses which are generated are much greater than at room temperature. At their critical temperature, such materials behave in a perfectly elastic manner: maximum deformation is reached almost immediately and if the load is removed at this temperature, there is a complete recovery without noticeable delay. If the system is allowed to cool with the load still acting, the first phase constituents will solidify and lock in the stresses generated in the second phase. The fringe patterns are retained permanently in the model, which may be cut in sections without release of the internal stress provided that the temperature does not rise unduly.

Comment

Photoelasticity has the great advantage over other investigative techniques that it allows the stress patterns in the test object to be observed directly throughout the entire structure. The technique is widely used in engineering and is particularly useful when the structure to be studied is irregularly shaped, as it permits examination of the whole stress field, rather than a selection of points. In anatomical studies, it has two major disadvantages. Firstly, loading and support of the specimens must be simulated in a rather idealised fashion and secondly the photoelastic replicas are homogeneous and lack the variety of structural components which exist in bone. However, in a bone of irregular shape which is part of a complex neuro-muscular system and which is subjected to constant variations in the direction and magnitude of load this method allows a series of studies to be undertaken under standardised conditions and provides results which are suitable for direct visual comparison. It was for this reason that photoelastic stress analysis was chosen as the investigative method for this study.

CHAPTER 8.

Study of the Dentate Mandible

STUDY OF THE DENTATE MANDIBLE

8.1 Introduction

A dentate mandible with an intact dentition was selected and was duplicated in a photoelastic resin (Fig. 8.1). This portion of the study was undertaken in California and materials of American manufacture were used. The experimental method was devised to suit the physical characteristics of the photoelastic resin material.

8.2 Production of Photoelastic Replicas

A fluid silicone material* was used to prepare a two-part mould of the dentate mandible. The first section covered the internal surface of the bone, to the height of the occlusal plane anteriorly, and to the level of the mandibular neck in the posterior region. The second section covered the external surface, enclosed the condyles and the tips of the coronoid processes, and overlayed the occlusal surfaces of the teeth (Fig. 8.2). The mould was inverted for pouring and a reservoir was incorporated along the inferior mandibular border to replace resin lost during polymerization contraction.

The model was then cast in a liquid epoxy material**. This resin is characterised by its very low exothermic reaction, which allows large models to be cast without the creation of residual stresses. The material consists of an epoxy resin which is mixed with an anhydride hardener at a temperature of 220°F to produce a homogeneous fluid mixture. A thermostatically controlled heater incorporating a mechanical spatulator was used and mixing was continued for six hours, as recommended by the manufacturer. The resin was then poured into the mould which had previously been heated in an oven to a temperature of 230°F and particular care was taken to avoid the introduction of air bubbles.

* Silicone RTV - Dow Corning, Inc.

** PLM/4. Liquid Epoxy Resin - Photoelastic Inc., Malvern, Pa.

The mould was then returned to the oven and maintained at a constant temperature of 210°F for 36 hours, by which time gelation of the resin had taken place. A programmed thermostatic control was then used to complete the curing cycle, which, for this resin, consists of a gelation cycle of 12 hours at 260°F and a post-cure phase of 48 hours at 280°F with heating and cooling at the rate of 2-5°F per hour. After completion of the gelation cycle, the model, which at this stage was firm and flexible, was removed from the mould and placed on a glass slab which had been dusted with talcum powder. Free movement of the replica was thus permitted, which ensured the release during the post-cure phase of any stresses generated by the moulding procedure. When the curing cycles had been completed and the oven had cooled to room temperature, the model was removed from the oven and examined in polarised light. Only models which were found to be free of stresses at this stage were used in the study.

Three satisfactory models were produced. Excess material was carefully trimmed from the area of the inferior border and the models were then lightly polished and prepared for loading. Any stresses generated by these machining procedures were eliminated by heat during the stress freezing cycle, prior to the application of load.

8.3 Loading and Stress Freezing

Occlusal loading was simulated by suspending weights from metal frames which were lined with silicone and placed on the occlusal surfaces of the teeth (Fig. 8.3). Load was applied to the three dentate mandibular replicas in the following manner:-

Specimen 1. 500 gm loads placed bilaterally in the first and second molar region.

Specimen 2. 500 gm load placed in the incisor region.

Specimen 3. 500 gm load placed unilaterally in the right first and second molar region.

The magnitude of the applied load was selected on the basis of preliminary studies which indicated that loads of up to 1 kg produced distinct fringe patterns without causing measurable distortion of the models.

In each instance, the model was positioned in the supporting frame and placed in the oven. The temperature was raised at the rate of 50°F per hour to 230°F where it was maintained for one hour before the load was applied. Following the application of occlusal load, the oven was maintained at the temperature of 230°F for a further one hour and was then allowed to cool to room temperature under thermostatic control, with the load remaining in position.

8.4 Recording the Results

After completion of the stress freezing cycle, each resin model was sectioned in the mid line and each of the hemimandibular specimens so produced was then examined under polarised light and photographed to record the stress pattern (Fig. 8.4). As the surface details of the specimen tended to obscure the fringe patterns, the models were immersed in a fluid of comparable refractive index*. A series of vertical cuts was then made through the models and sections were obtained, of approximately 2 millimetre thickness, from the region of the central incisors, first premolars, first molars, second molars, mandibular angle and neck of mandible (Fig. 8.5). These sections through the body of the mandible were polished, using successively finer grades of sandpaper and copious amounts of mineral oil. The sections were then examined in the field of a circular polariscope (Fig. 8.6). Isochromatic fringe patterns were recorded using both colour and black and white photography.

*Cedarwood Immersion Oil, Matheson, Coleman and Bell, Norwood, Ohio.

CHAPTER 9.

Study of the Edentulous Mandible

Page

STUDY OF THE EDENTULOUS MANDIBLE

9.1 Introduction

This portion of the study was completed in Glasgow. Materials of British manufacture were used and as these differed to some degree in physical characteristics from the materials which had been employed in the study of the dentate mandible, the technique which had been developed for that study was modified in a number of ways for the study of the edentulous mandible.

9.2 Production of Photoelastic Replicas

The edentulous mandible, which was used in this study (Fig. 9.1) had a well formed alveolar process, with two areas, the right premolar and molar regions, where the sockets of the teeth could be clearly seen. No changes were necessary in the method of preparing the silicone* mould of the mandible, which again was made in two sections, one covering the internal surface of the bone and the other the external surface plus the condyles and the tips of the coronoid processes. The model was inverted for pouring and a reservoir was again incorporated along the inferior mandibular border.

The mixing and curing techniques recommended by the manufacturers of the fluid resin material** which was used to pour the models of the edentulous mandible differed from the system used in the previous study. This material, like the resin used in the first study, consists of an epoxy resin which is mixed with an anhydride hardner, at a temperature of 110°C, to form a homogeneous fluid mixture. The proportion of resin to hardner is 100 parts to 30 parts by weight and the usable life of the mixture at 110°C is one hour.

*Silcoset 105. ICI Stevenston, Ayrshire.
**Araldite CT200. CIBA Geigy (U.K.) Ltd.

The resin was heated to the required temperature by means of a thermostatically controlled heater which incorporated a magnetic stirring device. When the resin was completely fluid, stirring was commenced and the hardener was added. After solution was complete, stirring was continued for a further 30 minutes and the mixture was then carefully poured into the previously heated mould.

The mould was returned to the oven and maintained at a temperature of 105°C for 2 hours and then at 110°C for a further 24 hours. The oven was allowed to cool, at the rate of 7°C per hour, over a period of 12 hours to reach room temperature. The model was then removed from the mould. Excess material at the inferior border was carefully ground away and the surface of the model was smoothed and lightly polished (Fig. 9.2). The replica was then returned to the oven so that any stresses generated during processing or polishing could be eliminated by annealing.

The model was placed on a glass slab, which had been lightly dusted with French Chalk to permit minor changes in the shape of the model consequent upon the release of strain. The temperature of the oven was raised to 150°C over a period of hours. It was maintained at this level for 2 hours and was allowed to cool to room temperature under thermostatic control. The model was removed from the oven and was examined in polarised light (Fig. 9.3). Only those models which were found to be free of stress at this stage were used in the study and five satisfactory replicas of the edentulous mandible were produced.

9.3 Preparation for Loading

Load was applied to replicas of the edentulous mandible through the medium of a mandibular complete denture base. Three bases were constructed in cobalt-chromium alloy,* two mandibular complete denture bases and one mandibular subperiosteal implant framework.

*Wisil Fried Krupp, Essen.

A. Construction of mandibular complete denture bases.

A layer of baseplate wax was applied to the alveolar process of the edentulous mandible and was extended to cover the entire denture bearing area. Over the crest of the residual alveolar process, the wax was built to a thickness of approximately 4 mm and was progressively reduced in thickness to approximately 1.5 to 2 mm over the remainder of the denture bearing area to represent the approximate thickness of the soft tissues which cover the alveolar process of the mandible (KYDD 1971). A cast of the mandibular denture bearing area was then produced in dental stone and two duplicates were prepared in refractory investment material. Two denture bases were then constructed in cobalt-chromium alloy, with vertical posts in the canine and first molar regions on either side. One base covered the full extent of the denture bearing area, covering the mylohyoid line and extending to the oblique line on the external surface of the mandible (Fig. 9.4). The second base covered only the crest of the residual alveolar process (Fig. 9.5). The bases were lined with silicone rubber** and fitted to the photoelastic models. As in the earlier studies of SHARRY and his colleagues (1956, 1960) this resilient material was used to represent the mucoperiosteal covering of the bone.

B. Construction of subperiosteal implant framework

In order to ensure an accurate fit of the mandibular subperiosteal framework, the wax form was laid down on a refractory cast duplicated directly from one of the photoelastic mandibular replicas. The outline of the framework was carried to the full extent of the denture bearing area and was kept clear of the crest of the alveolar process except at the posterior border on either side and also in the canine and first molar regions, where vertical posts were located. The implant framework was fitted directly to the surface of the photoelastic model, without any intervening resilient material (Fig. 9.6).

**Xantopren Blue Bayer, W. Germany.

9.4 Loading and Stress Freezing

The denture bases were fitted to the photoelastic models, which were then positioned in the supporting frame. Occlusal loading was simulated by suspending weights from a metal frame which was positioned over the vertical posts on each denture base. Load was applied to the five edentulous mandibular replicas in the following manner:-

Specimen 1. 500 gm load applied over all four posts on the fully extended denture base (Fig. 9.7), a condition of bilateral occlusal load, simulating balanced occlusion.

Specimen 2. 500 gm load applied to the two canine posts on the fully extended denture base (Fig. 9.8), to represent incisal load and simulate occlusal imbalance.

Specimen 3. 500 gm load applied to the canine and molar posts on the left side on the fully extended denture base, to represent unilateral occlusal load and simulate occlusal imbalance.

Specimen 4. 500 gm load applied over all four posts on the underextended denture base.

Specimen 5. 500 gm load applied over all four posts on the subperiosteal implant framework.

In each instance the model was positioned in the supporting frame and placed in the oven. The load was applied at room temperature and maintained during the stress freezing cycle. The temperature was raised at the rate of 15°C per hour to 150° C, where it was maintained for one hour. The oven was then allowed to cool to room temperature under thermostatic control with the load remaining in position.

9.5 Recording the Results

After completion of the stress freezing cycle, each resin model was sectioned in the mid line and each hemimandibular specimen was immersed in a fluid of comparable refractive index* and examined in polarised light. Isochromatic fringe patterns were then recorded photographically in white and monochromatic light.

A series of vertical cuts was then made through the models and sections were obtained of approximately 2 millimetre thickness from the incisor, premolar and molar regions. In addition, from Specimen 1, longitudinal sections were cut on the left side of the model, just above the inferior border and just below the alveolar border. The sections were polished by means of successively finer grades of sandpaper and were lubricated during the polishing process by the application of mineral oil. The sections were then examined in the field of a circular polariscope and isochromatic fringe patterns were recorded photographically in order to study in more detail the development of stress in the areas related to the denture bases.

Sections were also cut from the region of the neck of the mandible and isochromatic fringe patterns were recorded in order to identify the areas in which stresses had been generated. The direction of the principle stresses in these sections was computed from the study of the isoclinic fringe patterns. The polariser and analyser were rotated, the development of the isoclinics was recorded photographically at intervals of 20^{o}, and principle stress trajectories were constructed.

*Oil of Cedar Wood, BDH Chemicals, Poole, Dorset.

SECTION 5.

PRESENTATION OF RESULTS

CHAPTER 10.

The Dentate Mandible

THE DENTATE MANDIBLE

10.1 Hemisectioned specimens

Three specimens of the dentate mandible were tested. The first was subjected to bilateral occlusal load, the second to incisal load and the third to unilateral occlusal load. In the description of the stress patterns in these models, areas of the model will be identified by the anatomical name of the corresponding area of the mandible.

Specimen 1.

The first model was loaded bilaterally in the first molar region. The fringes which developed within the model formed a number of well defined groups on both halves of the replica in the following areas (Fig. 10.1):-

1. Along the inferior border of the mandible, around the angle and up the posterior aspect of the vertical ramus to the condyle.
2. Obliquely through the body of the mandible and ramus, from below the molars to the condyle.
3. From the molar region, up the anterior border of the ramus towards the tip of the coronoid process.
4. Along the margin of the sigmoid notch, between the condyle and the coronoid process.

Specimen 2.

The second model was loaded in the central incisor region. Again a symmetrical pattern of fringes developed, with two distinct groups predominating (Fig. 10.2):-

1. Along the inferior border of the mandibular body and up the posterior border of the ramus.
2. Through the body of the mandible, below the teeth, and then up along the anterior border of the ramus to the tip of the coronoid process.

Specimen 3.

In the third model, the load was applied unilaterally in the right first molar region. The fringes again formed recognisable groups within the model and there was an interesting variation between the two halves of the replica (Fig. 10.3). On the right side, two distinct groups of fringes developed:-

1. Along the inferior and posterior borders towards the condyle.
2. From below the molars, up the anterior border of the ascending ramus.

On the left side, a single trajectory predominated and ran from below the teeth, obliquely through the body and ramus to the condyle.

In all of the specimens there was some concentration of stresses in the region of the angle of the mandible, corresponding to the location of the coping which provided attachment for the struts representing the masseter and medial pterygoid muscles. Stresses also developed in the model around the teeth which had been loaded and some fringes were seen running through the crowns of the adjacent teeth. In all cases there was a basic similarity between the fringe patterns when viewed from both the lateral and medial aspects.

10.2 Transverse sections - Body of Mandible

These sections were supported on the inferior border and viewed from the anterior aspect.

Specimen 1.

The sections of the first model demonstrated a basically symmetrical stress pattern (Fig. 10.4). On both lateral and medial aspects of the bone, the fringes were grouped around the cortical area. Laterally, the greatest concentration of stresses was along the inferior border in the anterior region, moving upwards to the superior border at the angle of the mandible. Fringe distribution was uniform throughout the medial surface.

Specimen 2.

The second mandible also showed a symmetrical stress pattern, with fringes of comparable intensity present in the cortical areas on both the lateral and medial aspects, throughout the length of the mandibular body (Fig. 10.5).

Specimen 3.

The third model showed marked fringe formation within the body of the mandible, and around the inferior border, in the central incisor region (Fig. 10.6). Distally, the fringes were concentrated in the cortical areas on both the lateral and medial aspects. On the right side, the fringes on the medial aspect were more prominent and tended to differentiate into superior and inferior groups, particularly in the region of the mandibular angle (Fig. 10.7.A). On the left side, the stresses were more uniformly distributed throughout the lateral and medial cortical areas (Fig. 10.7.B).

10.3 Transverse sections - Neck of Mandible

In both the first and second specimens, stress concentration in the region of the condylar neck was minimal. A few fringes developed around the anterior margin in the first model and around the anterior and posterior margins in the second. The greatest concentration of fringes was seen in those sections from the third model (Fig. 10.8). On the right side there was marked fringe formation throughout the section centred around two areas of major stress concentration, one in the anterior and one in the posterior region of the neck of the condyle. On the left side a similar differentiation of anterior and posterior concentration was noted, though the fringe pattern was of diminished intensity.

CHAPTER 11.

The Edentulous Mandible

THE EDENTULOUS MANDIBLE

11.1 Hemisectioned specimens

Five replicas of the edentulous mandible were tested. The first three were subjected to load through the medium of a fully extended mandibular denture base. A denture base of reduced extent was used to apply load to the fourth model and a subperiosteal implant framework was fitted to the final model of the series. In the description of the fringe patterns, areas of the model will be identified by the anatomical name of the corresponding area of the mandible.

Specimen 1.

The first model was subjected to a load of 500 gm distributed uniformly over the denture base area. The fringes which developed in response to this load formed a number of well defined groups in the hemi-mandibular specimens (Fig. 11.1):-

1. Along the inferior mandibular border and up the posterior aspect of the ramus to the condyle.
2. From below the alveolar process, obliquely upwards through the ramus to the condyle.
3. From below the alveolar process, up the anterior border of the ramus to the coronoid process.
4. Between the condyle and the coronoid process.

There was considerable accumulation of stress in the area underlying the denture base and also in the region of the mandibular angle, where the coping, providing attachment for the pterygo-masseteric sling was located. This pattern was demonstrated on both halves of the model and was similar whether the specimen was viewed from the lateral or from the medial aspect.

Specimen 2

This model was subjected to a load of 500 gm applied to the two canine posts on the fully extended denture base.

The stresses which were generated in the model under these conditions led to the development of a group of fringes (Fig. 11.2) which ran from the inferior border in the anterior region, obliquely upwards through the body and ramus to the condyle and to the tip of the coronoid process. There was minimal fringe formation in the posterior aspect of the ramus and this pattern was demonstrated on both halves of the model.

Specimen 3.

In this model, a load of 500 gm was applied to the left canine and molar posts on the fully extended denture base. The fringes which developed in response to this load were grouped as follows (Fig. 11.3):-

A. Left-Side

1. Along the inferior mandibular border and up the posterior border of the ramus to the condyle.
2. From below the denture base, obliquely upwards through the body and ramus to the condyle.
3. From below the denture base, up the anterior border of the ramus to the coronoid process.
4. Between the condyle and the coronoid process.

B. Right-Side

1. From the inferior border of the body in the anterior region, obliquely through the body and ramus to the condyle.
2. Up the posterior aspect of the ramus and neck of mandible.

There was also a considerable accumulation of stress in the area underlying the denture base, extending from the left side, where the load was applied, round to the right premolar region.

Specimen 4.

This model was subjected to a load of 500 gm distributed uniformly over the denture base area. The denture base in this instance was of reduced extent, covering only the residual alveolar process. The hemisectioned specimens (Fig. 11.4) demonstrated stress fields basically similar to Specimen 1. Fringes were grouped as follows on both halves of the model:-

1. Along the inferior mandibular border and up the posterior aspect of the ramus to the condyle.
2. From below the alveolar process obliquely upwards through the body and ramus to the condyle.
3. From below the alveolar process, up the anterior border of the ramus to the coronoid process.
4. Between the condyle and the coronoid process.

There was a concentration of stresses in the alveolar region in this model, particularly in the molar and premolar regions, and fringes could be seen, on the right side of the model, around the molar sockets.

Specimen 5.

This model was subjected to a load of 500 gm distributed uniformly over a mandibular subperiosteal implant framework which had been carried to the full extent of the denture bearing area. Hemisections of this model demonstrated groups of fringes on both halves of the model in the following areas (Fig. 11.5.A):-

1. Along the inferior mandibular border and up the posterior aspect of the ramus to the condyle.
2. From below the area covered by the framework, obliquely through the body and ramus to the condyle.
3. Up the anterior border of the ramus to the coronoid process.
4. Between the condyle and the coronoid process.

Fringes were absent from the alveolar portion of the model, except at the posterior border of the framework and in the areas where the posts were located (Fig. 11.5.B).

11.2 Transverse sections - Body of Mandible

These sections also were supported on the inferior border and viewed from the anterior aspect. During this part of the study, the polariscope described in Appendix A became available and there was no longer any need to support the specimens for photographic purposes. The same orientation has, however, been maintained for all the sections described in this chapter.

Specimen 1 - Bilateral occlusal load

Transverse sections were cut from the right half of this model, in the mid line, in the region of the mental foramen and in the area of the molar sockets. These demonstrated the development of fringes around the cortical area of the specimens, with minimal internal stress (Fig. 11.6). Longitudinal sections were cut from the left half of this model, just above the inferior border and just below the alveolar crest. These also demonstrated stress concentration in the cortical areas of the specimen (Fig. 11.7).

Specimen 2 - Incisal load

Sections cut from the mandibular body of this replica demonstrated the development of internal stress, particularly in the anterior region (Fig. 11.8) where fringes were seen extending from the crest of the alveolar process internally into the specimen.

Specimen 3 - Unilateral occlusal load.

Sections from this model displayed fringes in the cortical region, with minimal development of internal stress (Fig. 11.9). On the left side where the load was applied, fringes developed in the region of the residual alveolar process and the major concentration of stress was on the medial aspect of the model. On the right side, fringes developed particularly along the lateral aspect and around the inferior border of the specimen.

Specimen 4 - Underextended denture base

This model demonstrated the development of fringes in the region of the alveolar process and extending internally into the specimen (Fig. 11.10).

Specimen 5 - Subperiosteal implant

Stresses were concentrated in the cortical areas of this specimen with minimal fringe formation either internally or in the region of the alveolar crest (Fig. 11.11).

11.3 Transverse sections - Neck of mandible

The orientation of these specimens is identical to that of the specimens from the dentate mandible, which were supported on the posterior border and viewed from the inferior aspect.

A. Isochromatic fringe patterns

Sections from all models displayed isochromatic fringes. These consisted of two distinct groups, one centred on the anterior and one on the posterior border of the sections (Fig. 11.12), which confirmed the observations made on the hemi-sectioned specimens, that stresses were transmitted to the mandibular condyle along the anterior aspect of the condylar neck and also up the posterior border of the ascending ramus.

B. Isoclinic fringe patterns

Study of the isoclinics revealed that stresses in the region of the mandibular neck tended to spread internally and also along the cortical areas of the model (Fig. 11.13). Stresses which originated near the anterior border spread inwards and along the lateral aspect of the sections: stresses which originated near the posterior border spread inwards and along the medial aspect of the sections. The principle stress trajectories (Fig. 11.14) were therefore aligned approximately parallel and perpendicular to these surfaces.

SECTION 6.

DISCUSSION

Chapter 12 Analysis of Results

CHAPTER 12.

Analysis of Results

ANALYSIS OF RESULTS

12.1 Introduction

When a complete analysis of stress is undertaken using only photoelastic data both the isoclinic parameters and the isochromatic fringe order must be determined at a number of points. If the results which such an analysis produces are to be directly applied from the model to the prototype then it is necessary that the model, both in its construction and in the conditions under which load is applied to it, must be an exact replica of the original.

The models used in the present study were a replica only of the shape of the mandible and did not reproduce the variety of its structural components. The loading system was selected as a simulation of occlusal loading against isometric contraction of the mandibular musculature. Not all of the muscles were represented and it was not possible to take account of the variation in forces exerted by the individual muscles of the selected group. The load applied was selected on the basis of experiment as one which produced demonstrable fringe patterns on the models rather than as a representation of clinical occlusal load.

For these reasons a detailed quantitative analysis of the photoelastic results was not undertaken. In all of the studies reported, the loading conditions were strictly comparable and qualitative comparison of the results is therefore valid. Isochromatic fringe patterns were used as the basis for these comparisons in the hemisectioned specimens and in most of the transverse sections of the models.

Isoclinics were studied only on sections from the region of the neck of the mandible in the edentulous models and the principle stress trajectories for these sections were constructed. These results also have been presented in a qualitative form.

12.2 Hemisectioned Specimens

12.2.1 The Dentate Mandible

The areas of stress concentration in the hemisections of the replicas of the dentate mandible corresponded to the trajectories described by SEIPEL (1948) and also by SICHER and DU BRUL (1970), which are representative of the studies outlined in Chapter 3.

Thus although the models were homogeneous and did not have the variety of structural components which exist in the mandible itself, their behaviour in this experimental situation suggested that a bone with the basic shape and dimensions of the mandible would require reinforcement in precisely those areas where that reinforcement seems to exist.

The three models showed some interesting differences. The first two mandibles showed a symmetrical pattern of fringe formation, with greater concentration of stresses in the first model, which was more heavily loaded. The third model showed a clear difference in fringe formation between the loaded and unloaded sides, indicating perhaps that the unilateral application of load caused some degree of torque in the structure of the model. This model also demonstrated a much greater development of fringes in the condylar region, suggesting that greater stresses may be transmitted to the condyles when the load is applied in this manner.

12.2.2 The Edentulous Mandible

The stress fields which developed within the models of the edentulous mandible and which were demonstrated in the hemisectioned specimens also showed a strong similarity to the trajectories which have been described on the basis of anatomical investigation of the mandible.

Stresses in the photoelastic replicas appeared to be concentrated in precisely those areas where the cortical structure of the mandible is reinforced, along the inferior border and at the symphysis, along the oblique and mylohyoid ridges, at the angles and up the anterior and posterior borders of the ascending ramus.

Thus, although the model was a homogeneous structure, it appeared to develop stress in those areas where the bone itself demonstrates structural reinforcement.

The replicas to which symmetrical bilateral occlusal loads were applied (Specimens 1, 4 and 5) demonstrated stress patterns which were very similar and which closely resembled the distribution of stresses in the hemisections of the first model in the dentate series. In the second specimen, there was minimal stress development along the inferior border of the mandibular body and posterior border of ramus, and in the third specimen, unilateral load produced a marked difference in fringe formation between the loaded and unloaded sides. This difference may reflect an alteration in the distribution of load, with the transfer of greater stresses to the region of the mandibular condyle when occlusal imbalance was simulated.

Comments

The most notable features of the hemisectioned specimens were the basic similarity which existed in the pattern of stress distribution in all models studied, and the strong resemblance which was noted between the photoelastic stress patterns and the alignment of the structural trajectories within the mandible which have been described by other workers. The fringe patterns were modified by changes in the point of application of the load, but in each case the stresses were still distributed along pathways corresponding to the location of anatomical trajectories, suggesting that the reinforcement which exists in the mandible can cope with variations in the loading situation. It also seems likely that occlusal load is distributed in a similar manner throughout the body and ramus of the dentate and edentulous mandibles. If this is so, then the differences noted by DOWGJALLO (1932), NEUFELD (1958) and TRIEGER and HERZBERG (1969) probably represent minor modifications of the reinforcing structure reflecting the reduction in the level of occlusal load in the edentulous condition.

Stress concentrations in the replicas were consistently noted on the anterior and posterior aspects of the mandibular neck, along the inferior border of the body of the mandible and along a line running obliquely through the mandibular body and ramus to the condyle. This last group corresponds in alignment to the major buttressing system of the mandible, designated by SICHER and DU BRUL (1970) as the dental trajectory. Close inspection of the isochromatic fringes in this area against dark ground illumination (Fig. 12.1) revealed that they consisted of two groups, superior and inferior to a dark band. This dark band is known as the zero order fringe and it represents an area of the model where there is no stress present. It therefore indicates a neutral zone in the specimens and suggests that the development of strain within the body and ramus of the mandible is resisted along a line corresponding to the dental trajectory. A similar zero order fringe can be seen in the region of the inferior mandibular border.

12.3 Transverse sections - Body of Mandible

12.3.1 The Dentate Mandible

Sections from the mandibular body of these specimens demonstrated the development of fringes in the cortical areas of the models. The absence of any differentiation of teeth, periodontal tissues and bone, however, made it impossible to visualise the transfer of occlusal load from the teeth to the bone.

Sections from the region of the angle of mandible illustrated the transfer of stresses from the area of the body towards the ramus in two main groups, located above and below the mandibular canal and corresponding to the anterior and posterior groups of fringes in the sections from the region of the condylar neck.

12.3.2 The Edentulous Mandible

Transverse sections from the edentulous replicas were studied in relation to the anatomy of the bone and also in relation to the principles of complete denture construction.

A. Anatomy

The transverse sections from Specimens 1 and 5 were studied in order to relate the distribution of occlusal load in the replicas to the structural reinforcement of the mandible which can be demonstrated by anatomical techniques.

When symmetrical bilateral occlusal load was applied to the models through the medium of the fully extended denture base and through the subperiosteal implant framework, the stresses were distributed throughout the cortical area of the models, which corresponds to the thickened cortical layers revealed by transverse section of the body of the mandible (Fig. 12.2) or by radiographic examination (Fig. 12.3). The area of the residual alveolar process was almost entirely free of isochromatic fringes.

B. Complete Denture Construction

Transverse sections from the remaining edentulous specimens were studied in order to demonstrate the changes in the distribution of occlusal load when the experimental situation was modified to simulate faults in the prosthodontic technique. Occlusal imbalance in complete dentures may be caused by premature contact of the anterior teeth or of the posterior teeth, on one or both sides and may cause discomfort by preventing the uniform distribution of load to the area of the denture base. Inadequate peripheral extension is another common fault in the construction of mandibular complete dentures and is frequently associated with discomfort and with trauma to the soft tissues overlying the alveolar process.

An attempt was made to simulate these clinical errors by changing the point of application of the occlusal load and by altering the design of the denture base. Occlusal imbalance was represented by the application of incisal load and of unilateral occlusal load. When incisal load was applied, there was considerable development of internal stress in the model, particularly in the incisor region. Load had thus been transferred from the denture base mainly to the alveolar portion of the model. This is an area of the edentulous mandible where structural reinforcement is lacking (NEUFELD 1958) and the application of load is not well tolerated. Unilateral application of occlusal load did not lead to the development of internal stresses in the model, but produced an asymmetrical distribution of stresses throughout the cortical areas. When load was applied to the model through the medium of the underextended denture base, internal stresses were found under the entire denture bearing area, which again indicated that load had been transferred from the denture base mainly to the alveolar portion of the replica.

These findings emphasise the importance of occlusal balance and adequate peripheral extension in distributing the occlusal load to the cortical areas of the model, which correspond to the thickened cortical layers of the mandible, and reinforce the need for attention to these two features in the design and construction of mandibular complete dentures.

12.3.3 Transverse Sections - Neck of Mandible

Sections from the area of the condylar neck in all specimens demonstrated the development of isochromatic fringes in two distinct groups, one near the anterior border and one near the posterior border. Study of the isoclinics from the edentulous replicas confirmed the existence of these two groups and related the anterior group to the reinforcement of the external and the posterior group to the internal surface of the mandible.

12.4 Conclusions and Indications for Further Study

12.4.1 Conclusions

It is considered that the aims expressed in the opening chapter have been fulfilled in the course of this study:-

1. The use of a fluid resin in a two part silicone mould has proved reliable in the production of models of the mandible suitable for three dimensional photoelastic stress analysis. After the trimming of excess material and the use of the appropriate annealing procedure, no difficulty was encountered in rendering the models free of stress before commencing the experimental procedure.
2. As a representation of a static loading situation, the model system was satisfactory. The metal struts provided adequate support for the models against the simulated occlusal loads and maintained the relationship of condyle to articular fossa established at the outset of each study. No movement of the models or of their supporting elements was observed during the loading cycle.
3. The hemisectioned specimens of the dentate and edentulous mandibular replicas demonstrated fringe patterns which were basically similar and which indicated that stresses had been generated in the models in areas corresponding to those parts of the mandible in which structural reinforcement has been demonstrated or predicted by other methods.

Sections from the edentulous models also demonstrated the transfer of load from the denture bases to the underlying structures. When the loading situation was in accord with the normally accepted principles of complete denture construction, the load was distributed to the outer portion of the model, corresponding to the thickened cortical areas of the mandibular body. The transfer of load from the teeth to the model in the dentate series could not be demonstrated, as a single homogeneous model was used to represent teeth, periodontal tissues and bone. Sections from other areas of the dentate models, particularly the neck of mandible, showed a pattern of stress distribution similar to that seen in the edentulous models.

4. Changes were demonstrated in the stress patterns in the edentulous mandibular replicas when the experimental situation was modified to simulate faults in complete denture design. Departure from a situation of occlusal balance altered the distribution of the occlusal load throughout the mandibular body and ramus. Unfavourable loading of the alveolar region was noted after the application of incisal load and also when a reduced denture base was used. This provides experimental confirmation of accepted techniques of complete denture construction, as lack of occlusal balance and underextension of complete denture bases are frequently associated with pain in the tissues underlying the dentures and with dysfunction in the stomatognathic system.

12.4.2 Indications for Further Study

In an attempt to overcome some criticisms and shortcomings of the photoelastic method and to establish a more convincing relationship between the results of this investigation and the anatomical and clinical features under study, a number of further studies were undertaken:-

1. It was recognised that it would be necessary to make a

model using different materials to represent individual teeth, periodontal membrane and bone in order to demonstrate the method of load transfer from the teeth to the bone in the dentate replicas. This has, indeed, now been done, in association with Dr. A. Caputo and Dr. J.P. Standlee of the Dental School, University of California at Los Angeles. The results of this further study were presented to the 52nd General Session of the International Association for Dental Research, in Atlanta, Georgia, in March 1974.

2. In order to counter the possible criticism that stresses in the transverse and longitudinal sections of the mandibular replicas may be produced or affected by the sectioning procedure, a stress-free edentulous model was sectioned in the manner previously described. Figure 12.4 is a section cut from the incisor area of this model, demonstrating that no stresses had been generated during cutting or polishing.

3. The reproducibility of the results may be questioned, as each model had to be sacrificed in order to demonstrate the stress patterns. To meet this objection and also to seek confirmation of the photoelastic results by another experimental method, it was decided to undertake a further study using electrical resistance strain gauges. This study was reported in Chapter 13.

4. A further criticism of the method may be made on the grounds that the models are homogeneous. However, the suggestion has been made (BENNINGHOFF 1925, SEIPEL 1948) that some degree of homogeneity must exist in bone to account for its behaviour under load. In view of this fact and in an effort to find a method of relating the photoelastic patterns more convincingly to the behaviour of bone under load, a further study was undertaken of the optical characteristics of bone. The results of this study are presented in Chapter 14.

Erratum   Page 116 line 22 - read 'is' for 'was'.

SECTION 7.

SUPPLEMENTARY STUDIES

CHAPTER 13.

Strain Gauge Study

STRAIN GAUGE STUDY

13.1 Introduction

The photoelastic models of both the dentate and edentulous mandibles had consistently demonstrated the development of stress in the region of the neck of the mandible on both the anterior and posterior aspects. Stresses were also generated along a line running obliquely through the mandibular body and ramus to the condyle and also along the inferior border of the mandible. When the stress freezing technique is used, it is difficult to observe the development of fringes within the model. In addition, each model has to be sacrificed in order that the stress patterns may be examined and repetition of any particular experimental situation requires the production of a new specimen.

It was therefore decided to use another method of stress analysis in order to verify the findings of the photoelastic study and to demonstrate the nature of the stresses produced under different conditions of load. Electrical resistance strain gauges were selected and were placed on a photoelastic model of the edentulous mandible in order to record the changes in strain produced by the application of simulated occlusal load.

13.2 Principles of Electrical Resistance Strain Gauges

A strain gauge is a device which is used to measure the degree of deformation of an object consequent upon the application of load. Measurement may be recorded mechanically, optically, electrically, acoustically or pneumatically. By far the widest use is made of electrical strain gauges and in particular of the resistance type of electrical strain gauge. The principle on which this type of gauge is based was discovered by LORD KELVIN (1856) who noted an increase in the electrical resistance of copper and iron wires when loaded in tension.

Changes in resistance are proportional to changes in the degree of strain in the metal and, when calibrated, can be used to measure changes in the degree of strain of other objects.

Metal-foil strain gauges are a form of wire resistance strain gauge in which a grid of very thin metal foil is deposited, usually by a photoetching process, on a thin epoxy resin backing. They have a high sensitivity and accuracy and they range in size down to almost microscopic dimensions. Accurate measurement of the resistance changes in these gauges can be made by linking them to a Wheatstone bridge system.

13.3 Method and Materials

A. Calibration of Material

A test specimen of the epoxy model material was produced and was subjected to load in tension. Values for the tensile strain were recorded and a stress/strain graph was drawn for the material. A stress-free rectangular block 5.08 mm x 10.16 mm in cross section and 7.62 cm in length, was cut from a photoelastic mandibular replica. Four metal foil strain gauges* were cemented in position. They were wired in series to eliminate any possible bending moment and were linked to a strain indicator. A circular perforation was made 5 mm from either end and the block was suspended from a horizontal bar of aluminium. Weights were added in increments of 100 gm up to 1 kg and the strain at each value was recorded. The weights were then removed 100 gm at a time and the strain at each interval was noted. This procedure was repeated on three occasions and a graph was drawn from the average values obtained (Fig. 13.1). This graph was linear over the range tested. Changes in the level of strain produced by the successive addition and removal of weights of 0.5 and 1.0 kg were also recorded. In each case, deflection of the strain indicator was

*NF 2b. Showa Measuring Instruments Co. Ltd., Japan.

instantaneous following the addition and removal of these weights, though the strain recorded was marginally less than that produced by the incremental addition of weights.

B. Experimental Procedure

Four metal foil strain gauges** were cemented to the surface of a photoelastic mandibular replica in the following locations on the left side of the body and ramus:-

1. The anterior aspect of the mandibular neck on the external surface.
2. The posterior aspect of the mandibular neck.
3. The external surface, in the region of the oblique line.
4. The inferior border.

The fully extended mandibular complete denture base was lined with silicone and fitted to the model. The copings for the attachment of the supporting struts were also lined with silicone and fitted to the model which was then suspended from the supporting frame (Fig. 13.2). The gauges were wired to a Wheatstone bridge system (Fig. 13.3) and linked to a strain indicator (Fig. 13.4). A load of 500 gm was found to produce a measurable change in the strain recorded and was therefore retained for this part of the study.

Prior to loading, the strain indicator was balanced for each gauge and the balance was checked on two subsequent occasions at intervals of 5 minutes. The load was then applied and the system allowed to stabilise for 15 minutes before a further series of three readings at intervals of 5 minutes was made. The load was then removed and, after a further interval of 15 minutes, a final three values were recorded.

**FLA-3-11. Tokyo Sokki Kenkyujo Co. Ltd., Japan.

This test procedure was carried out at room temperature and the following conditions of load were used:-

1. 500 gm load distributed uniformly over the denture base, to represent a condition of balanced occlusion.
2. 500 gm load applied to the two canine posts, to represent incisal loading.
3. 500 gm load applied to the left canine and molar posts, to represent ipsilateral occlusal load.
4. 500 gm load applied to the right canine and molar posts to represent contra lateral occlusal load.

13.4 Results

The results are displayed graphically in Figure 13.5.

Gauge 1. Under all conditions of loading, this gauge recorded the development of tensile strain. Incisal load produced higher values than a uniformly distributed load and the highest values were recorded when the model was subjected to unilateral occlusal load.

Gauge 2. Under all conditions of loading, this gauge recorded the development of compressive strain. The magnitude of deflection recorded was comparable for all the loads tested, except for incisal load which produced the highest values for this gauge.

Gauge 3. Under all conditions of loading this gauge demonstrated minimal activity and must be considered to lie in a neutral axis of the model.

Gauge 4. Under a uniformly distributed load and under incisal load, this gauge demonstrated minimal activity. Tensile strain was recorded, however, under both forms of unilateral load.

Comments

The results of this study indicated that under the conditions of this experiment, stress was distributed through the body and ramus of the mandibular replica to the region of the condyle, when occlusal load was applied to the model. This is consistent with the findings of the photoelastic study. In addition, the strain gauges demonstrated that the anterior aspect of the mandibular neck was subjected to tensile and the posterior aspect to compressive strain and that a greater load was transmitted to the condylar region by the application of incisal or unilateral occlusal load.

The suggestion, from the photoelastic study, that the oblique line of the mandible lay in a neutral axis between the forces generated by the occlusal load on the one hand and by the activity of the elevator muscles on the other, was also confirmed by the behaviour of the third gauge, which demonstrated minimal activity under all conditions of load. A similar neutral axis appeared to be present along the inferior border of the model, except when unilateral load was applied. This suggests that under these conditions the model was undergoing some degree of torque. It is interesting that the strain which was recorded in this area was tensile and not compressive, as might have been expected from comparison with the trajectorial analysis of SEIPEL (1948).

CHAPTER 14.

Optical Characteristics of Bone

CHAPTER 14.

Optical Characteristics of Bone

14.1 Introduction

The use of photoelastic replicas in the study of the biomechanical properties of bone has been criticised by EVANS (1957) on the grounds that the models are homogeneous and do not represent the variety of structural components which exist in the bone itself. He has stated that the photoelastic studies demonstrate only the stresses which would develop in an object resembling a bone in outline form.

However, the outline form of any bone is important and WOLFF's law of bone transformation (1892) which states that the outer form and inner architecture of any bone are determined by the forces to which the bone is subjected in function, is widely accepted. In addition, the properties of bone appear to be determined not so much by the physical characteristics of its component tissues as by the precise way in which these tissues are combined. Many investigators have considered bone as a biphasic material, the inorganic mineral phase endowing the structure with resistance to compressive forces and the collagenous organic phase providing the resistance to tensile forces. These elements have contrasting mechanical properties and the resulting structure is stronger than either alone and has properties which could not be deduced from the analysis of either of these major components (EVANS 1973).

Bone demonstrates a homogeneity that would not be predicted from the analysis of the physical properties of its constituent elements and two theories have been put forward to explain this phenomenon.

14.2 Hydraulic Pressure Mechanism

Bone has an inherent ability to form a supporting structure of definite architecture, offering increased resistance to forces in certain directions (WOLFF 1892). In investigating this property, BENNINGHOFF (1925) suggested that in order to exhibit relatively constant mechanical properties in response to particular forces, bone must behave as a relatively homogeneous substance. Bone however, is quite obviously not homogeneous, either in its gross or microscopic form, and SEIPEL (1948) has suggested that the development of trajectories or lines of stress in bone may be in part a hydraulic phenomenon. He stated that organic trajectories differ from fixed lines of stress in an inorganic substance in that they represent only temporarily increased resistance in a certain direction. The vascular components of bone structure, by the contribution they make to the hydraulic pressure mechanism may impart a degree of homogeneity to the structure and may play a significant part in the resistance of the bone to mechanical pressure. This view was supported by SMITH and WALMSLEY (1959) who maintained that the mechanical properties of bone were influenced by the amount of its vascularisation and that high vascularity was usually accompanied by a greater degree of flexibility than could be accounted for by the tensile properties of the bone. FROST (1964) also emphasised the importance of the vascular and soft tissue elements in the distribution of stresses in bone and suggested that the hydraulic pressure mechanism may play a part in the determination of the outer form of individual bones.

14.3 Viscoelasticity

It has long been suspected that bone had certain viscoelastic properties. This phenomenon has been explained in relation to photoelastic model materials and is characteristic of many plastic materials. The viscoelastic properties of bone have been investigated by ROTH, FROST, and VILLANEUVA (1961 a & b). They used fresh cortical specimens from long bones and applied controlled compressive loads to produce indentation of the surface layer.

Under light loading, the indentations were reversible and disappeared once the load was removed. Increased loads caused a permanent distortion of the bone surface. When the surface of the bone was ground to remove the indentations and the specimen treated successively with ethanol, dioxane and nitric acid, a prominence, the reverse of the indentation, appeared on the cut surface.

This was explained on the basis that bone consists of two elastic components, one in the mineral and one in the collagen matrix, which have additive effects under normal loads. Under heavier load, the permanent indentation of the mineral component builds up an elastic strain in the matrix element which has the capacity to correct itself if the effect of the mineral distortion can be removed. BURSTEIN, REILLY and FRANKEL (1973) also investigated the viscoelasticity of bone. They tested specimens of bovine bone and stated that under tension, bone displayed certain characteristics of a plastic material and that residual deformation on successive loading was cumulative. When test specimens began to display plastic deformation, they became lighter if viewed in reflected light and darker if viewed in transmitted light, a phenomenon which is also demonstrated in the crazing of polymers.

These studies suggest that the behaviour of bone under load demonstrates certain characteristics which are normally associated with plastic materials. There may therefore be a greater validity than is normally acknowledged in theories and valuations which assume a homogeneity of structure and also in the use of plastic replicas for the study of the behaviour of bone under load.

Comments

These two theories highlight the importance of the collagenous matrix in the behaviour of bone under load and suggest that the calcified elements exist to provide a degree of rigidity for a structure which has an inherent capacity to absorb load. The theories of bone biomechanics which were outlined in Chapter 2 were developed originally from the study of the distribution of the calcified elements and it was BENNINGHOFF (1925) who first removed the major portion of the inorganic material and demonstrated the arrangement of the organic matrix.

The hydraulic pressure mechanism may play some part in the distribution of stress in bones, particularly in some of the long bones which have large marrow spaces. Many bones, however, are not highly vascular and yet are subjected to considerable forces. The mandible is an example of this type and the viscoelastic properties attributed to the collagen matrix of bone offer a more convincing explanation for the distribution of load within this bone.

It was therefore decided to examine the behaviour of the organic matrix of bone under load and to attempt to relate this to the behaviour of photoelastic replicas, by using a method based on optical birefringence.

14.4 Optical Birefringence in Bone

Substances which demonstrate optical birefringence may do so because:

1. The individual molecules are arranged in a particular alignment. This is known as intrinsic or crystalline birefringence.
2. The submicroscopic particles, even if these themselves are not intrinsically birefringent are orientated in a particular manner. This is known as form or textural birefringence.

3. Their optical characteristics are modified by the application of stress. This is known as strain birefringence and is the foundation of photoelastic stress analysis.

Many biological materials display optical birefringence, either intrinsic or form, when viewed in polarised light and a number of workers have studied this phenomenon in bone. At the microscopic level, ASCENZI and BONUCCI (1964) demonstrated optical birefringence in bone and related it to the orientation of the collagen fibres. EVANS and VINCENTELLI (1968) also used polarised light to examine the orientation of collagen fibres in bone and found that the arrangement of these fibres was related to the shearing strength and modulus of elasticity of their specimens.

Birefringence in a gross specimen, the partly decalcified jaw of a dog was demonstrated by LEHMAN and MEYER (1966). They assumed that this was a strain birefringence and on this basis proposed a very tenuous argument for a relationship between stress and the development of interproximal dental caries.

In order to study this optical effect in bone, the left half of the mandible of a young male baboon was prepared for examination in polarised light using the technique of decalcification, dehydration and clearing outlined by TOMPSETT (1970). The resultant specimen demonstrated birefringence (Fig. 14.1) in the body and ramus of the bone and also in the dentine of the teeth. The pattern of this birefringence, particularly in the ramus of the mandible, showed a striking similarity to the split line patterns described by BENNINGHOFF (1925), DOWGJALLO (1932) and SEIPEL (1948), and it seemed likely that the optical birefringence was related to the orientation of the fibres in the collagenous matrix of the bone. It was therefore decided to undertake a further study in an effort to determine whether the pattern of optical birefringence in bone could be influenced in any way by the application of load.

14.5 Examination of Bone Specimens

Permission was obtained for the removal of the right and left radii from three Baboons which had been sacrificed for other purposes at the Wellcome Surgical Research Institute, University of Glasgow Veterinary School. The radius was selected in preference to the mandible in order to simplify the loading procedure and to avoid the use of a bone whose structure is complicated by the modifications necessary for the support of the teeth. The following method was found to produce the best optical results.

14.5.1 Method

The forelimbs of the baboons were disarticulated and the radii dissected out immediately post mortem. The bones were stripped of muscle, ligaments and periosteum and were immersed in 70% ethanol for 12 hours. This was done in order to promote the release of any strains in the fibres of the collagen matrix of the bone. The bones were removed from the ethanol and one of the pairs was placed on a loading frame (Fig. 14.2) which consisted of a base, with a vertical column of aluminium on which the specimen could be supported in approximately the centre of its length. Load was applied by suspending weights of 700 gm from either end of the bone, approximately 2.5 cm from the extremity. Before the experiment was begun, the frame and the weights were coated in paraffin wax to protect them from corrosion. The loaded specimen and the control were then immersed in normal saline at 37°C for 12 hours prior to fixation. Formaldehyde was then added to the normal saline to make up a solution of 10% formol saline and the temperature was maintained at 37°C throughout the period of fixation.

After 10 days, test specimen and control were removed from the formalin solution. The load was removed and both bones were washed and were then radiographed to show their mineral content (Fig. 14.3). They were then placed in a solution of 4N Formic Acid to decalcify. After 7 days they were radiographed to ensure that the mineral content had been removed (Fig. 14.4). The bones were then bleached in hydrogen peroxide for two days, washed in tap water and dehydrated in ascending ethanol solutions prior to infiltration and clearing by immersion in methyl salicylate.

The specimens were immersed in a glass vessel filled with methyl salicylate, which was placed between the polarising and analysing lenses of a plane polariscope. A source of white light was used and results were recorded photographically in colour and in black and white.

14.5.2 Results

Both bones exhibited optical birefringence when viewed in polarised light (Fig. 14.5). In the control, a uniform pattern was evident throughout the length of the bone and in the test specimen there was intensification of the birefringence in the central area of the bone and a series of alternating light and dark bands arranged parallel to the surface of the bone was clearly visible in the area where load had been applied.

14.6 Photoelastic Study

In order to relate the change in the pattern of optical birefringence which had been demonstrated in the baboon radii to the fringe patterns seen on the photoelastic models, a replica of a radius was made in the material which had been used for the edentulous mandibles. The replica was examined in polarised light to ensure that it was free of stress (Fig. 14.6) and was then subjected to load while supported on the stand which had been used for the bones

(Fig. 14.7). A load of 50 gm was used and was again applied 2.5 cm from either end of the model. The frame was placed in the oven which had been used for the mandibular replicas and the model was subjected to a stress freezing cycle while the load remained in place. The appearance of the replica after loading and stress freezing (Fig. 14.8) was then compared with that of the loaded bone specimen.

14.7 Conclusions

1. Decalcified bones demonstrated optical birefringence when cleared, immersed in a suitable medium and viewed in polarised light. It seems likely that the regular pattern of birefringence observed in the baboon mandible and in the control specimens of the baboon radii is related either to a molecular or to a submicroscopic pattern and is associated with the arrangement of the collagenous matrix.
2. The pattern of birefringence was altered by the application of load prior to fixation of the bone specimens. This suggests that some re-arrangement of the collagenous matrix takes place in response to the application of load.
3. The alternating bands arranged parallel to the surface of the bone which developed in the loaded bone specimen showed certain similarities to the isochromatic fringes which were demonstrated on the photoelastic replica of the radius in response to the application of load in a similar manner. It therefore seems possible that the inherent pattern of birefringence in the bones has been modified by the applied load, by the superimposition of a pattern of strain birefringence.

If this is so, then the use of photoelastic replicas for the study of stress and strain may have a greater relevance than is generally admitted.

SECTION 8.

APPENDICES

Appendix A Construction of Polariscope

Appendix B Comparison of Materials

APPENDIX A

Construction of Polariscope

During the study of the dentate mandibular replicas and in the early stages of the study of the edentulous specimens, a horizontal polarising system was used. This had two disadvantages:

1. Hemisectioned specimens, immersed in cedarwood oil, had to be viewed through the outer wall of the containing vessel which detracted from the optical quality of the results.
2. Sections of the replicas had to be mounted on a stand and positioned in the plane of the polariscope. This was a time consuming and often frustrating procedure.

It was therefore decided to construct a polariscope which would permit the viewing of specimens and recording of results in the vertical axis. The additional interface was thus eliminated from the recording system for the hemisectioned specimens and the small sections could be placed on a sheet of ground glass which was positioned in line with the polarising lenses.

This polariscope is illustrated in Figure A.1. The framework consisted of a wooden base, 30 inches in length and 14 in width, with a vertical backboard, 3 feet in height, supported by bracing struts. Two channels were machined in the backboard to allow vertical adjustment of the component parts which could be locked in any desired position by means of wing nuts.

Illumination was provided by twin tungsten halogen lamps which were housed in the base of the unit and the sides and front of the unit were boxed in. The components of the polarising system listed from below upwards were:

a sheet of aluminium with a circular perforation of 5 inch diameter, to reduce the beam of light to the area of the polarising lenses.

a sheet of ground glass to act as a diffusing screen.
polarising lens.
platform for specimens.
analysing lens.
camera.

The polarising lenses, of 5 inch diameter, were contained in a circular housing of 8 inch diameter and could be rotated by means of a screw drive. Markings at 10° intervals were placed on the outer casings of these units to facilitate the recording of isoclinic fringes. The housing also contained a recess of 5.5 inch diameter, into which a quarter wave plate could be fitted. The recess was in the upper surface of the housing of the polarising lens and the lower surface of the analyser, to maintain the correct relationship of the quarter wave plates in recording isochromatic fringe patterns.

The camera was mounted so that the centre of the lens was in line with the centre of the polarising system. The camera was a Minolta SRT 101, with autobellows extension and 100 mm lens and the films used to record the results were:

for colour,	Kodak High Speed Ektachrome
	Agfachrome 50 L
for black and white,	Agfa 1 F
	Ilford HP 4

APPENDIX B

Comparison of Materials

The material used in the study of the dentate mandible was an epoxy resin, PLM - 4, manufactured in the United States of America by Photoelastic Inc., of Malvern, Pennsylvania. In the study of the edentulous mandible, an araldite resin, CT 200, manufactured in Great Britain by Ciba-Geigy (U.K.) Ltd., of Cambridge, was used.

With the exception of the recommended mixing times and the procedures suggested for annealing the models after processing, these materials were very similar in handling and in their behaviour under the experimental conditions of the study. The physical properties of the materials are listed in Table B.1 and the values quoted, both at room temperature and at the stress freezing temperature, indicate that the materials are comparable in all respects.

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ATWOOD D. A. (1962) should read '..... to rate of resorption of residual ridges'.

EVANS F. G. & VINCENTELLI R. (1969) should read '..... of collagen fibre orientation .....'

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All the references quoted have been examined personally, except:

PAUWELS (1950) which is quoted from EVANS (1957).

DAVIDA (1915))
LEWIN (1913)) which are quoted from SEIPEL (1948).
WINKLER (1921))
WALKHOFF (1900, 1902))

THE DISTRIBUTION OF OCCLUSAL LOAD IN THE HUMAN MANDIBLE:

A PHOTOELASTIC STUDY.

VOLUME 2

of

TWO VOLUMES

by

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THESIS

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October, 1975.

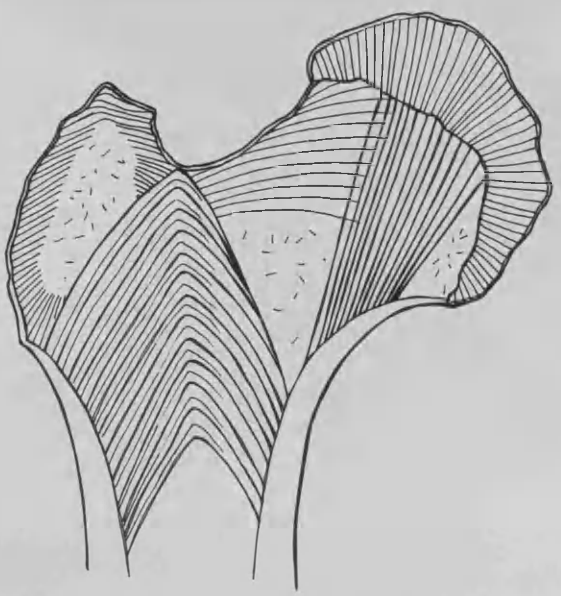
ILLUSTRATIONS AND TABLES

ADDENDUM

In the cephalometric tracings from the skull radiographs, the following abbreviations have been used:

M.	Masseter muscle	F.	Frankfort plane
M.Pt.	Medial pterygoid muscle	S.	Sagittal plane
T.	Temporalis muscle	O.P.	Occlusal plane
		Mand.	Mandibular plane

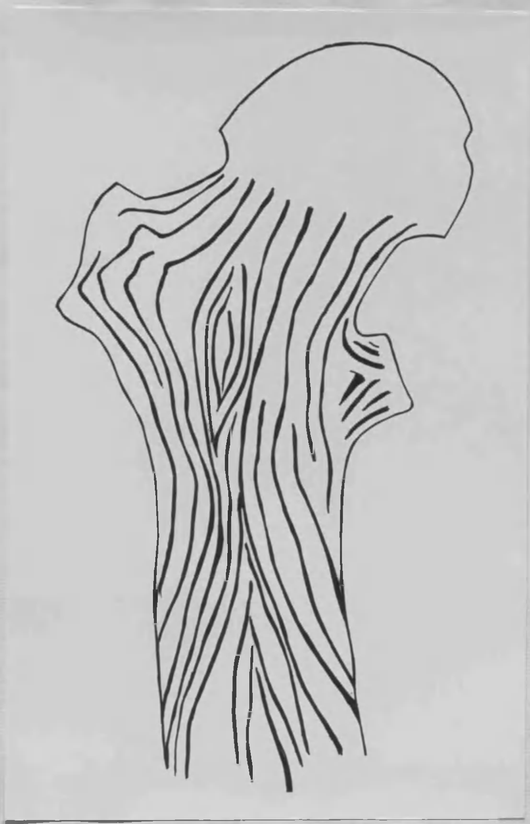
FIGURE 2.1.



Diagramatic representation of the arrangement of the bone trabeculae in the femur.

Redrawn from WARD (1838).

FIGURE 2.2.



Split-line pattern on the decalcified femur.

Redrawn from BENNINGHOFF (1925).

FIGURE 2.3.

Pattern of cracks in lacquer coating on femur.

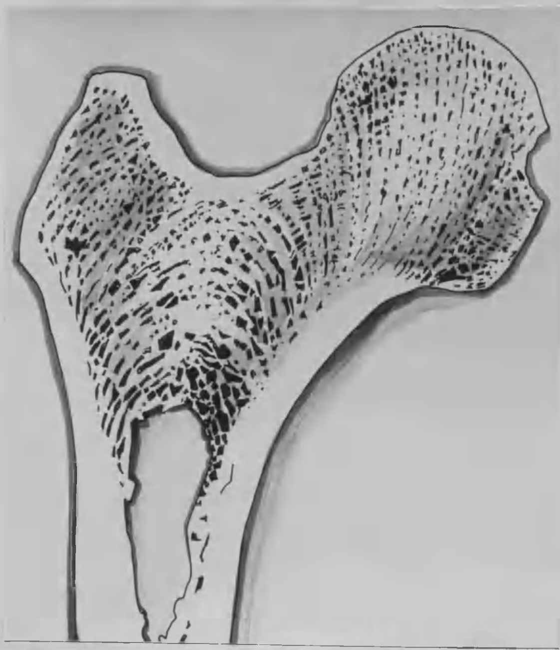
Redrawn from KUNTSCHER (1934).

FIGURE 2.4.

Fringe pattern in photoelastic replica of femur.

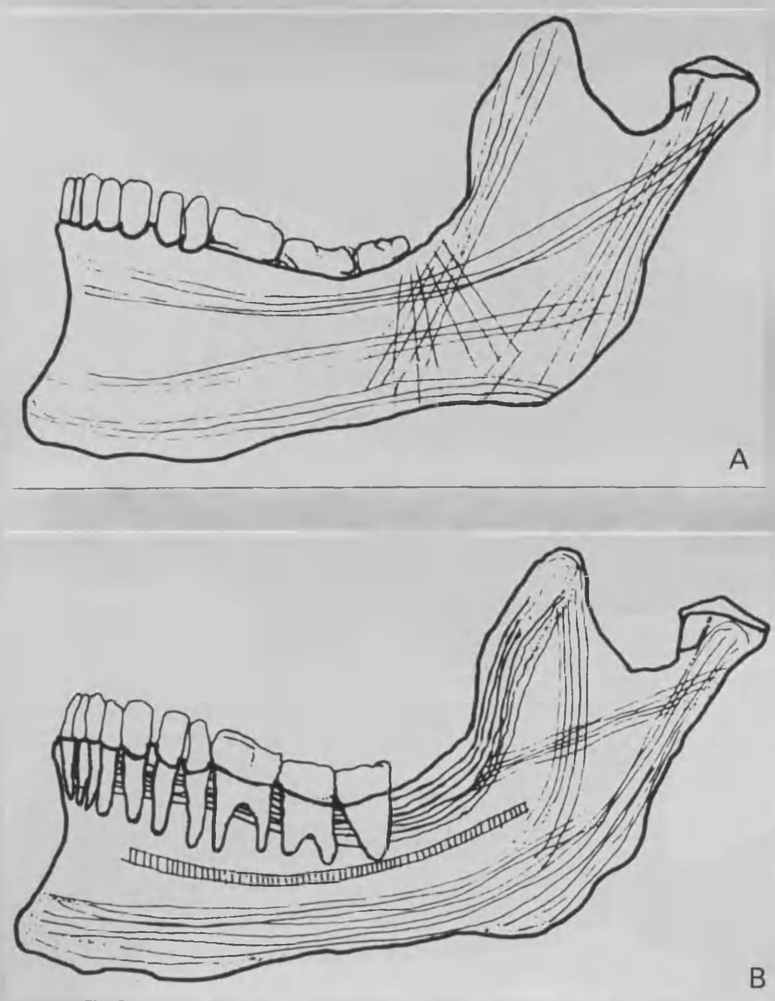
Redrawn from MILCH (1940).

FIGURE 2.5.



The trabecular pattern in the head of femur.

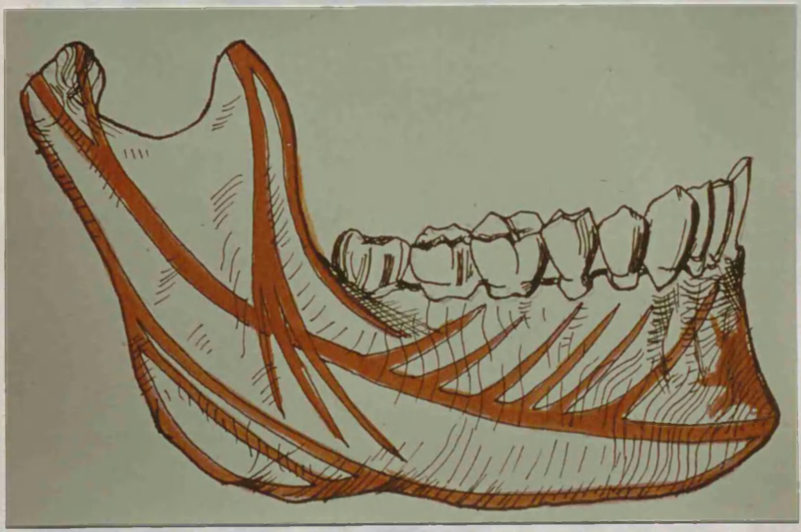
FIGURE 3.1.



Orientation of trajectories in the human mandible as described by

A. WALKHOFF (1900)
B. LEWIN (1913)

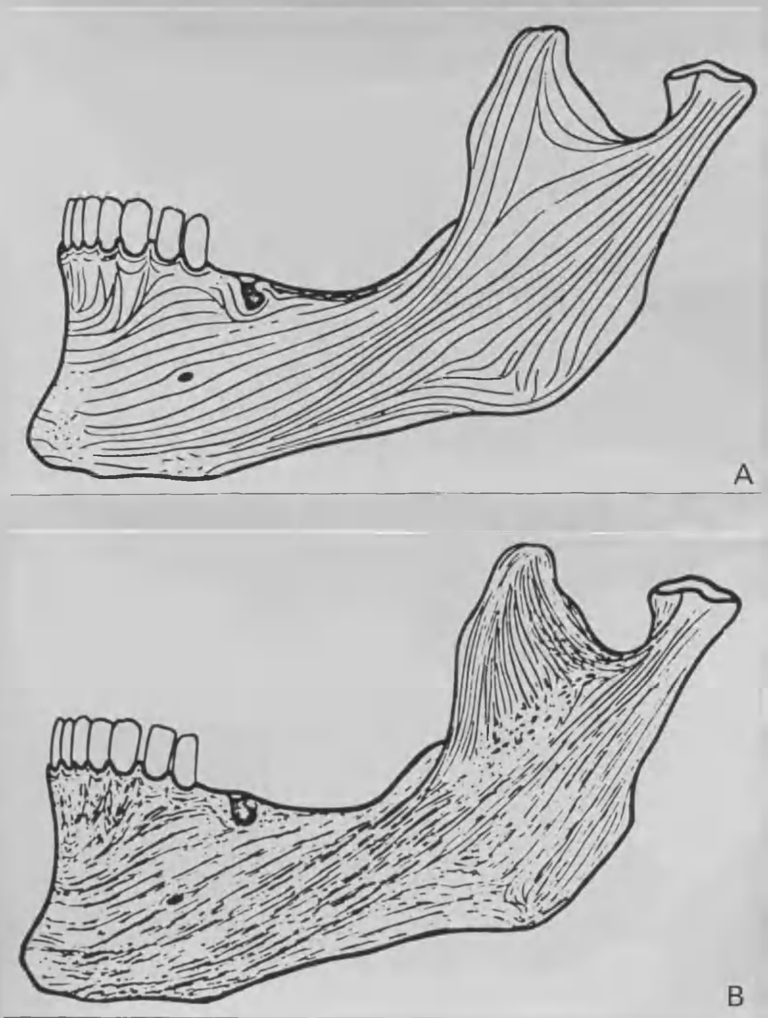
FIGURE 3.2.



Structural trajectories in the human mandible.

Redrawn from SICHER & DU BRUL (1970).

FIGURE 3.3.



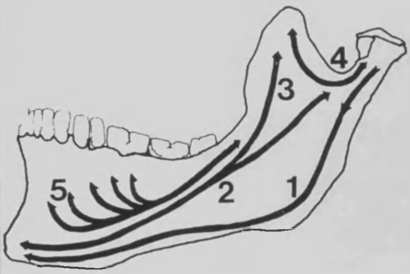
A. Surface architecture of cortical bone demonstrated by split line impregnation technique.

B. Internal fibrous organisation of cortical bone demonstrated by microdissection.

Both redrawn from SEIPEL (1948).

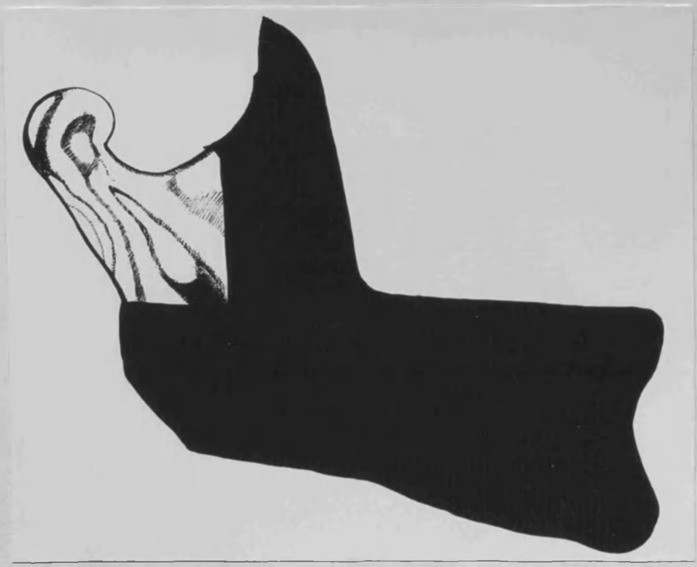
FIGURE 3.4.

Diagramatic Representation of Trajectories
in the Human Mandible as Described by Seipel (1948)



1. Inferior Basal Trajectory (Compressive).
2. External and Internal Oblique Trajectories (Tensile).
3. Temporal Trajectory.
4. Connecting Trajectory.
5. Alveolar Arcade System.

FIGURE 3.5.



Stress patterns in photoelastic mandibular model.

Redrawn from MOLITOR (1969).

FIGURE 3.6.

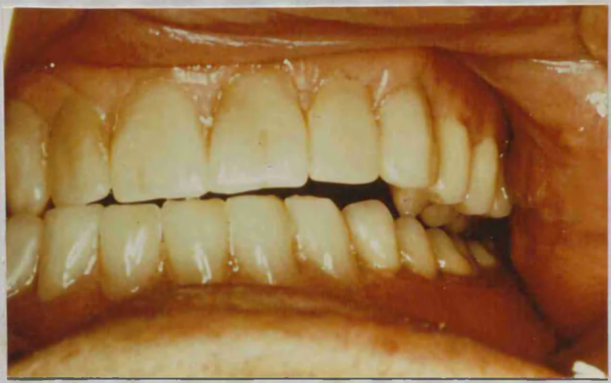
	Angle to Frankfort Plane		Angle to Sagittal Plane
Masseter	$52 - 62^0$	M & H	$7 - 12^0$ C
	$59 - 75^0$	C	
Medial Pterygoid	58^0	M & H	$20 - 26^0$ C
	62^0	C	
Temporalis			$16 - 20^0$ C

The alignment of the muscles of mastication as determined by:-

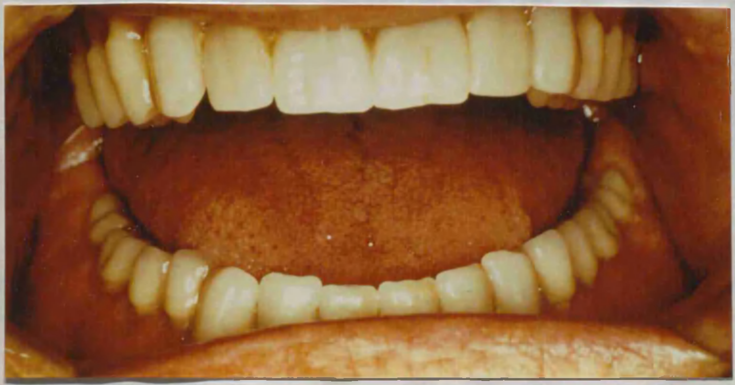
M. & H. MAINLAND & HILTZ (1934)
C. CARLSOO (1952)

FIGURE 4.1.

A



B

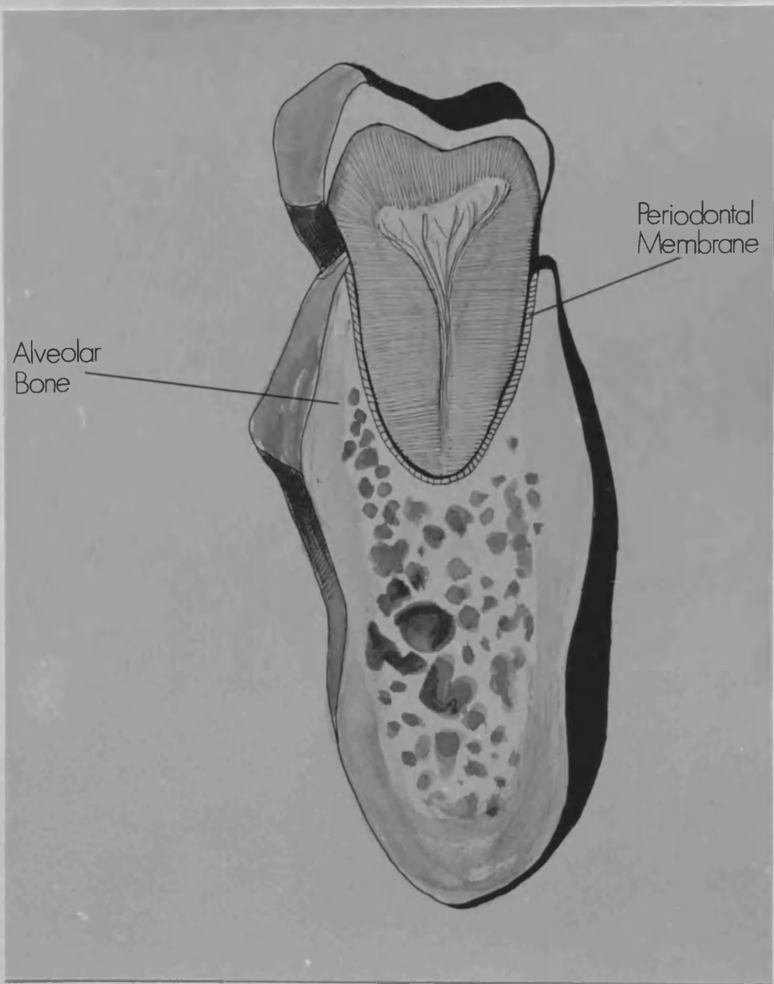


C

Maxillary and mandibular complete dentures demonstrating -

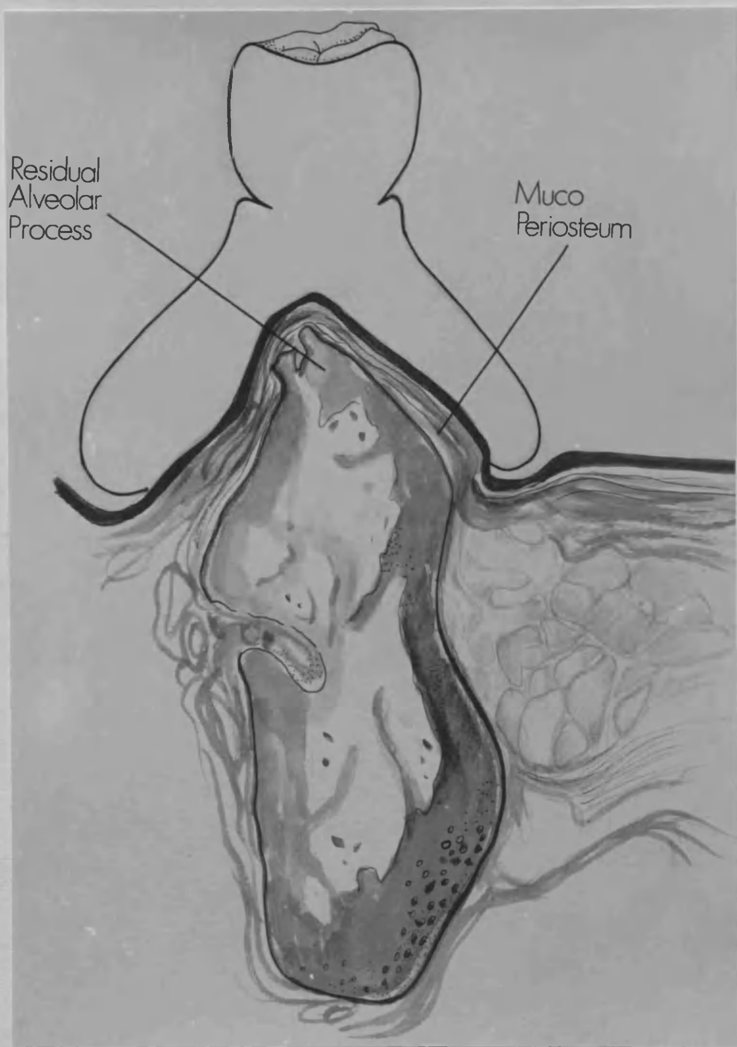
A. Occlusal balance on closure.
B. Balancing contacts during functional movements.
C. Adequate retention on opening.

FIGURE 4.2.



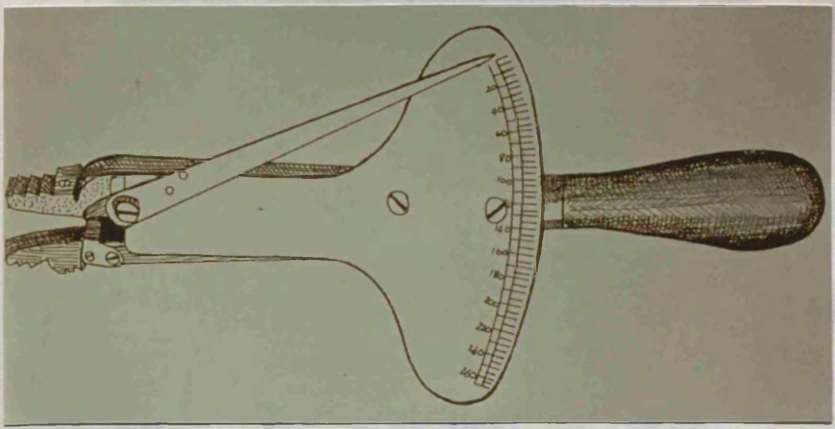
The arrangement of the supporting tissues for the natural dentition in the mandible.

FIGURE 4.3.



The arrangement of the supporting tissues for the mandibular complete denture.

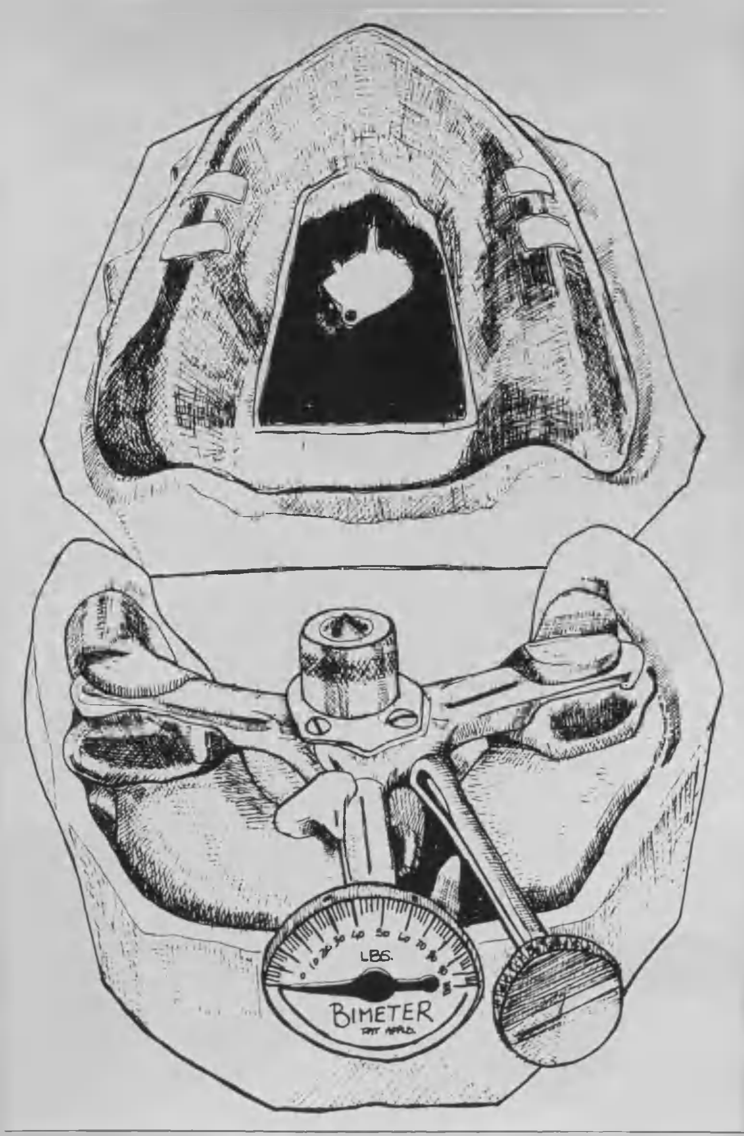
FIGURE 4.4.



Gnathodynamometer.

Redrawn from BLACK (1895).

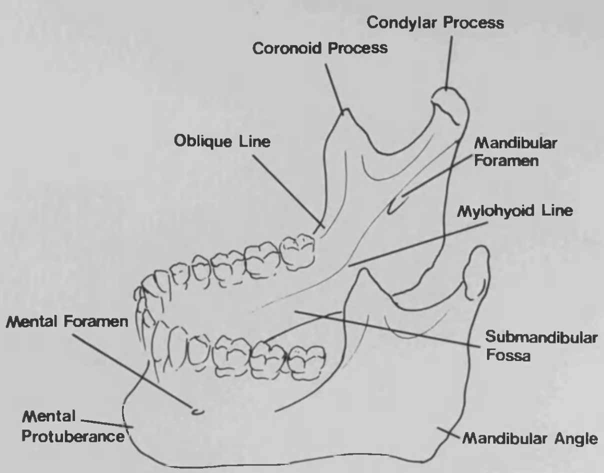
FIGURE 4.5.



The Bimeter.

Redrawn from BOOS (1940)

FIGURE 5.1.



The Dentate Mandible

FIGURE 5.2.

The Edentulous Mandible

FIGURE 5.3.

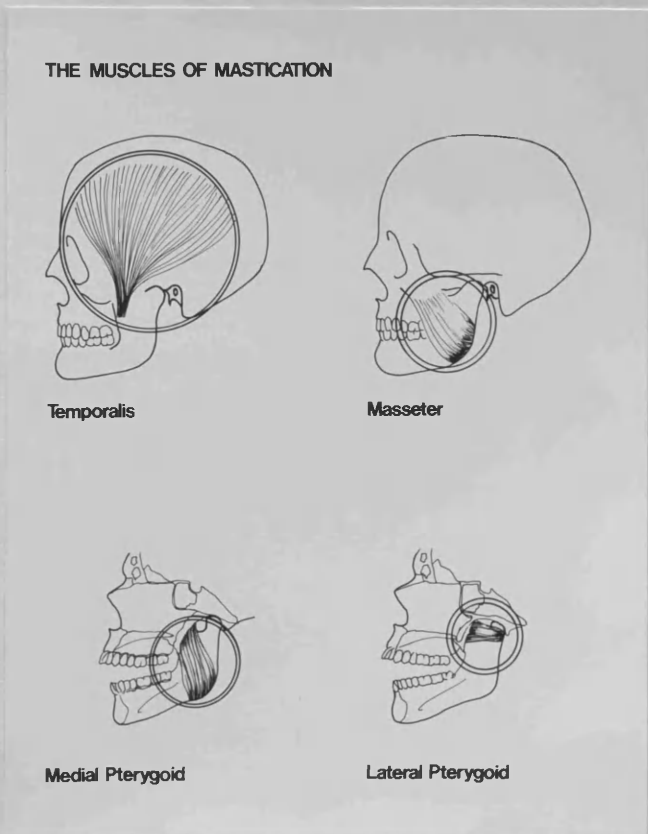
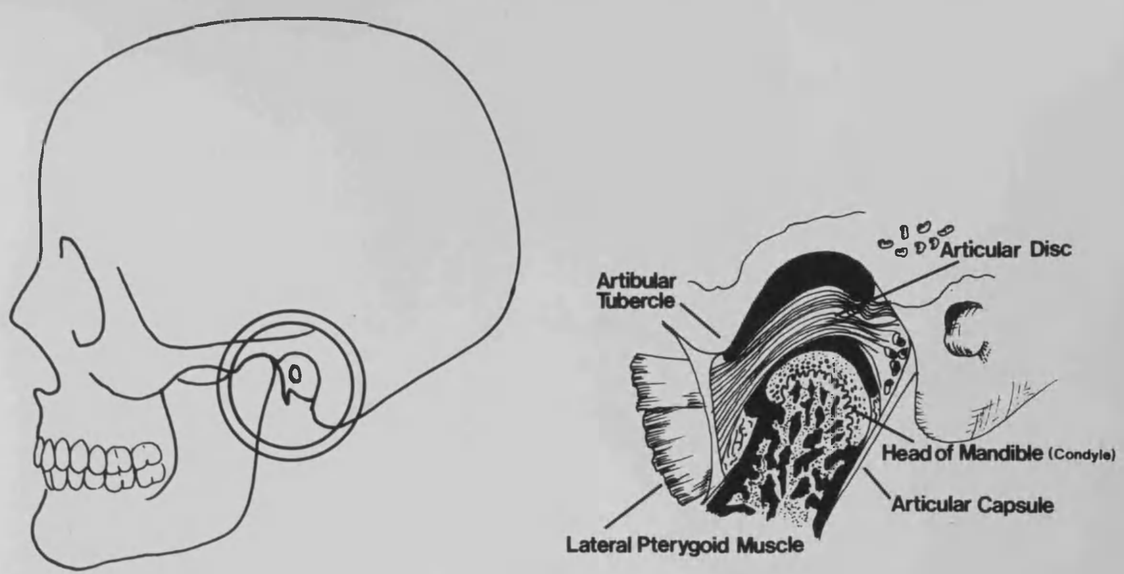
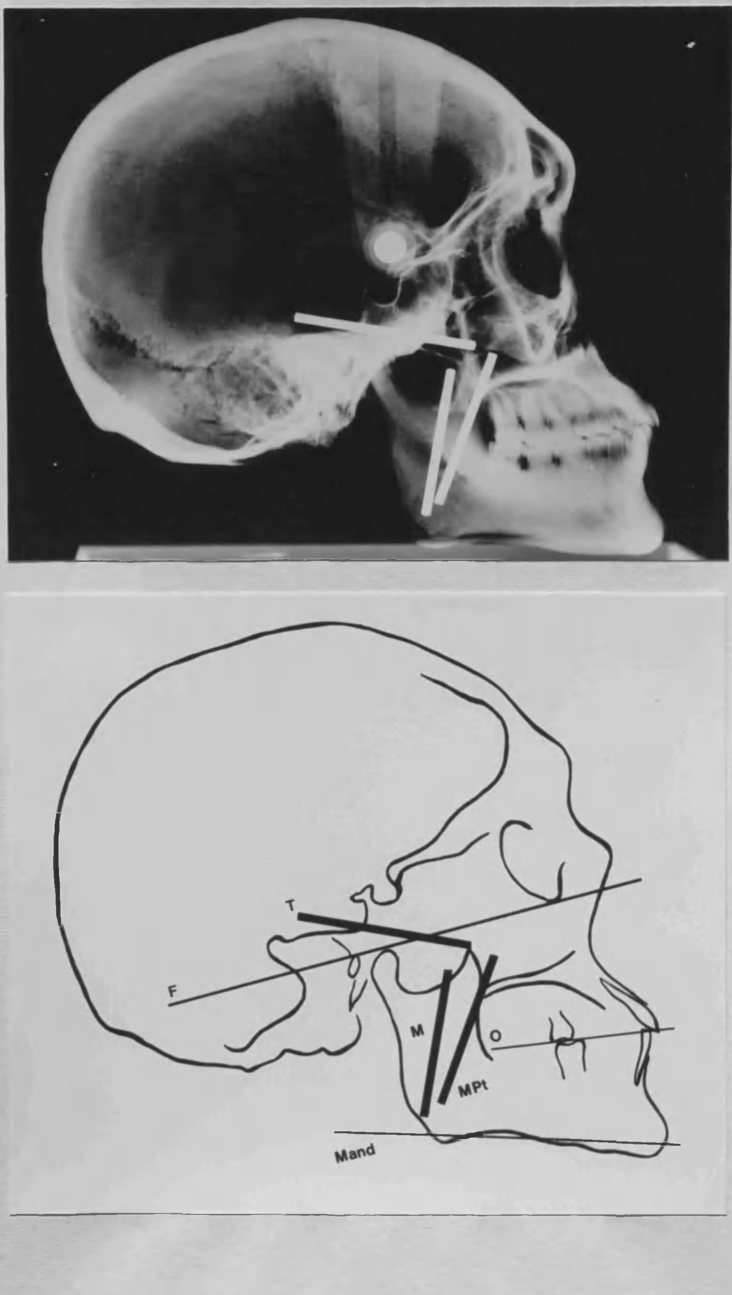

THE MUSCLES OF MASTICATION
Temporalis
Masseter
Medial Pterygoid
Lateral Pterygoid

FIGURE 5.4.



The Temporo Mandibular Articulation

FIGURE 6.1.

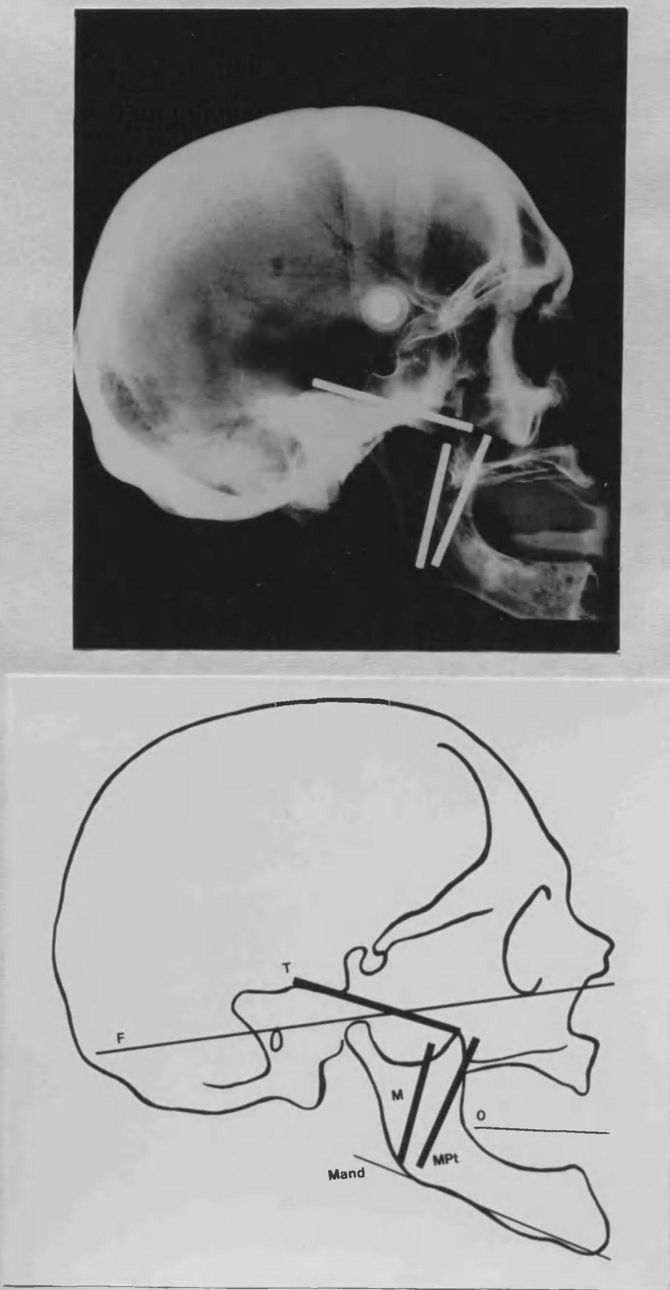


A

B

Lateral radiograph (A) and cephalometric tracing (B) of dentate skull and mandible.

FIGURE 6.2.

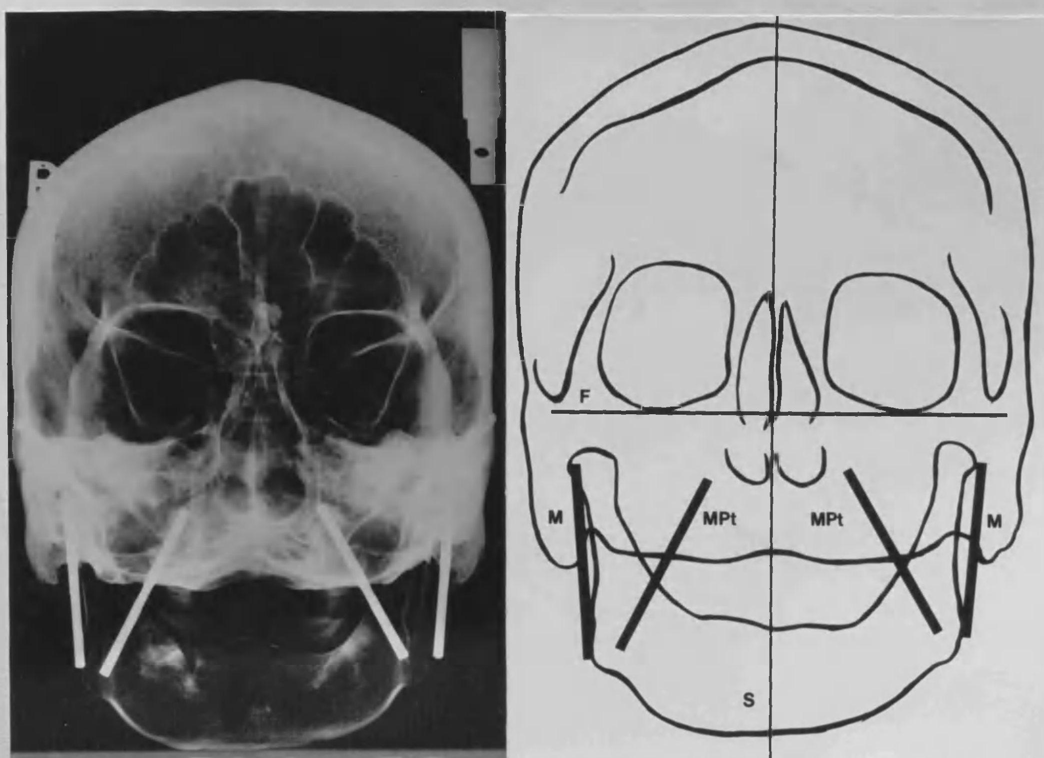


A

B

Lateral radiograph (A) and cephalometric tracing (B) of edentulous skull and mandible.

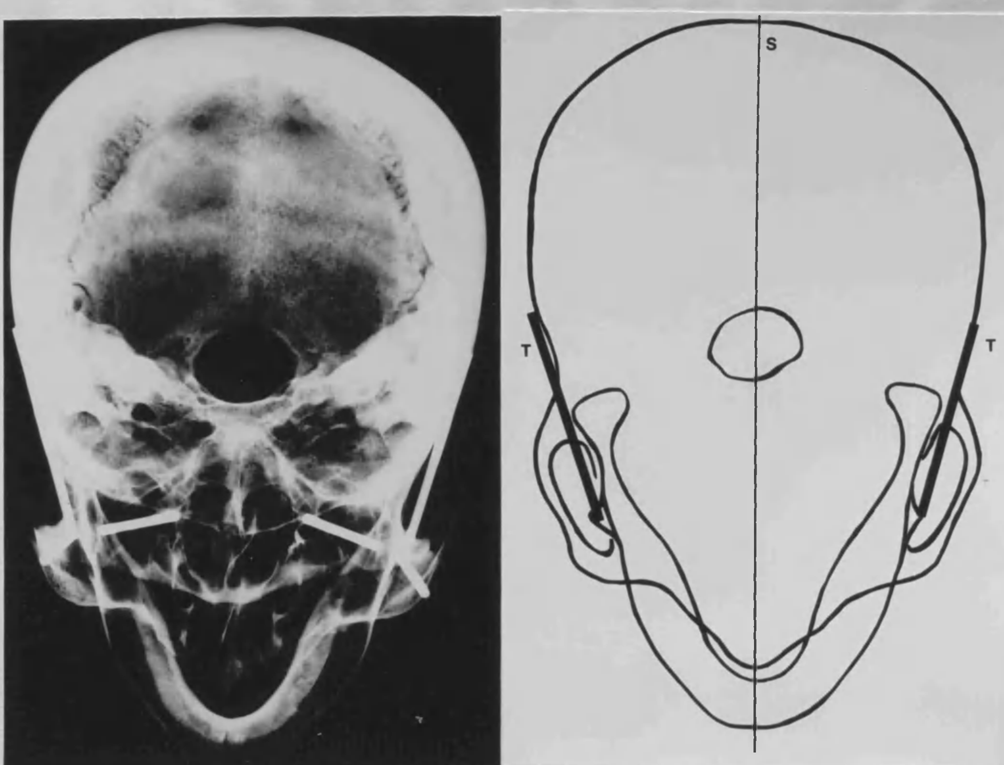
FIGURE 6.3.



A B

Frontal radiograph (A) and cephalometric tracing (B) of edentulous skull and mandible.

FIGURE 6.4.



A B

Basal radiograph (A) and cephalometric tracing (B) of edentulous skull and mandible.

FIGURE 6.5.

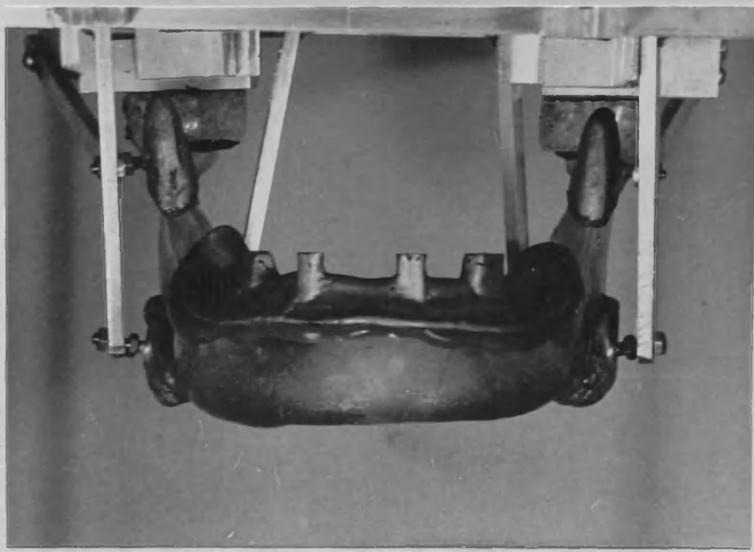
	Angle to Frankfort Plane		Angle to Sagittal Plane	
	Dentate Skull	Edentulous Skull	Edentulous Skull	
			R	L
Masseter	65^0	68^0	6^0	7^0
Medial Pterygoid	56^0	58^0	27^0	30^0
Temporalis	25^0	27^0	18^0	14^0

Angulation of the mandibular elevator muscles measured from the dentate and edentulous skulls.

FIGURE 6.6.

Photoelastic replica of dentate mandible in supporting frame.

FIGURE 6.7.



A

B

Frontal (A) and lateral (B) views of photoelastic replica of edentulous mandible in supporting frame.

FIGURE 7.1.

THE RADIANT ENERGY (ELECTROMAGNETIC) SPECTRUM

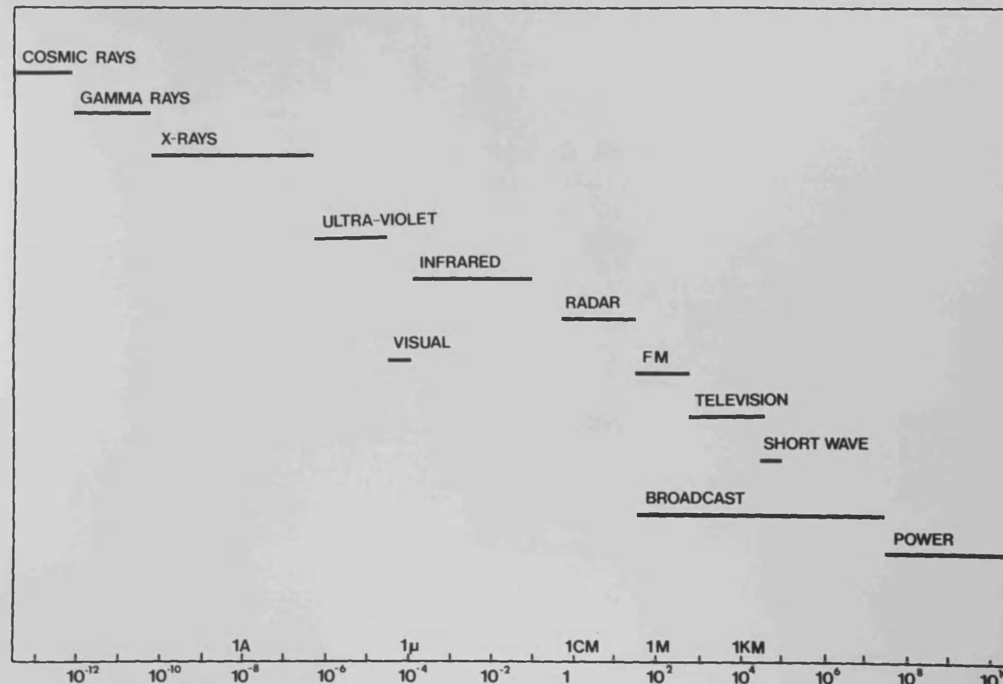
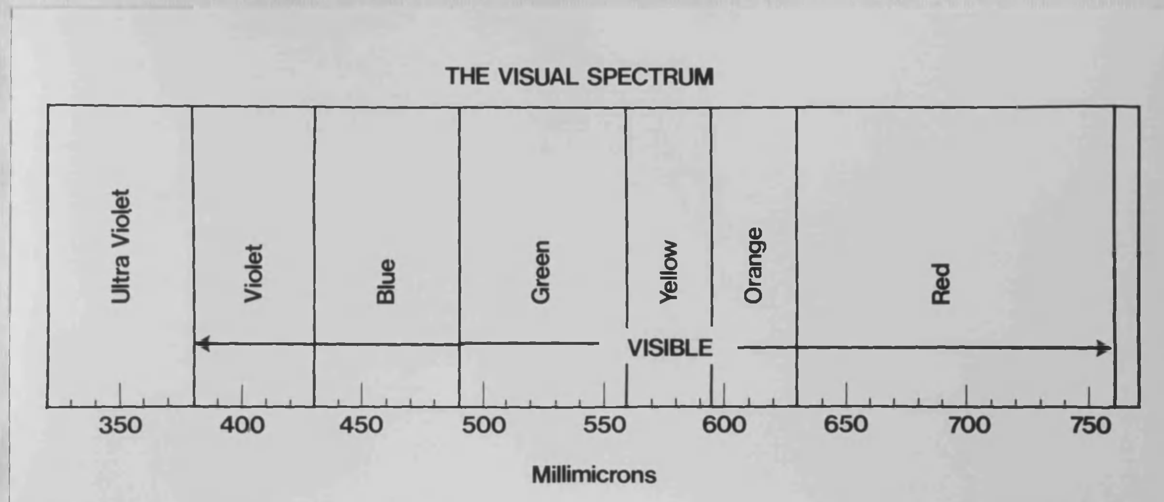
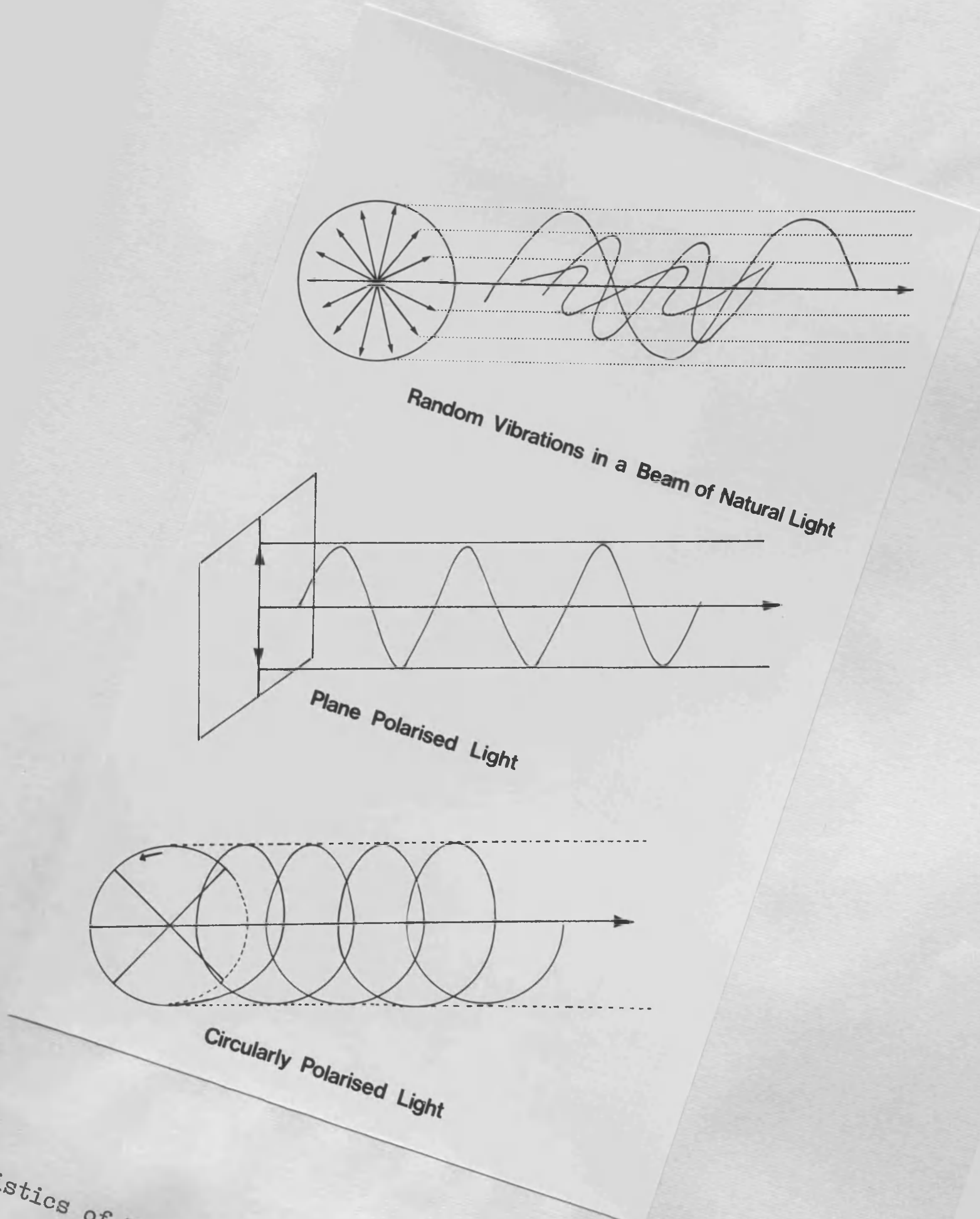


FIGURE 7.2.



THE VISUAL SPECTRUM
Ultra Violet
Violet
Blue
Green
Yellow
Orange
Red
VISIBLE
350
400
450
500
550
600
650
700
750
Millimicrons

FIGURE 7.3.



Characteristics of Light.

FIGURE 7.4.

THE PLANE POLARISCOPE

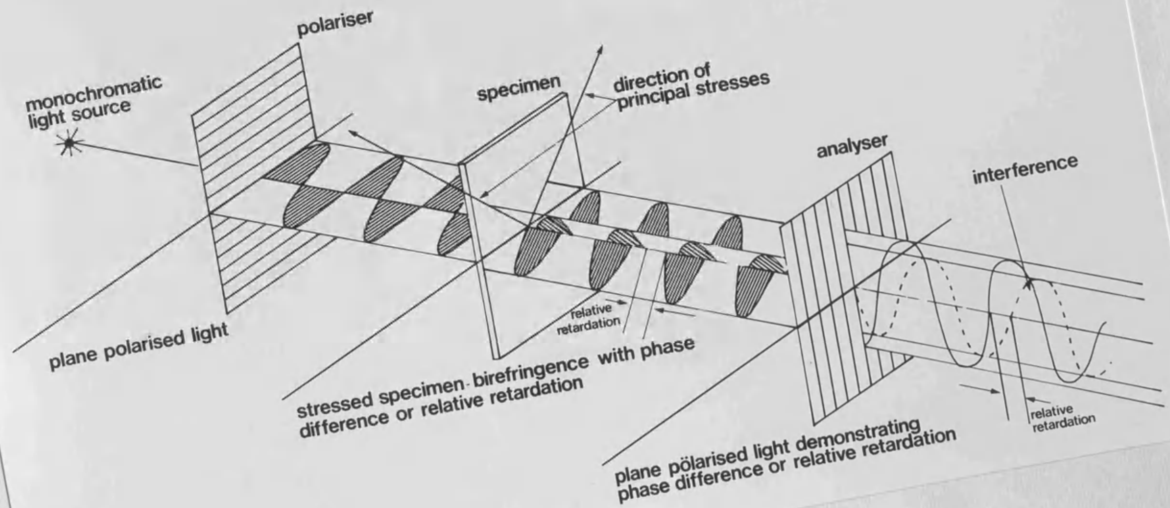


FIGURE 7.5.

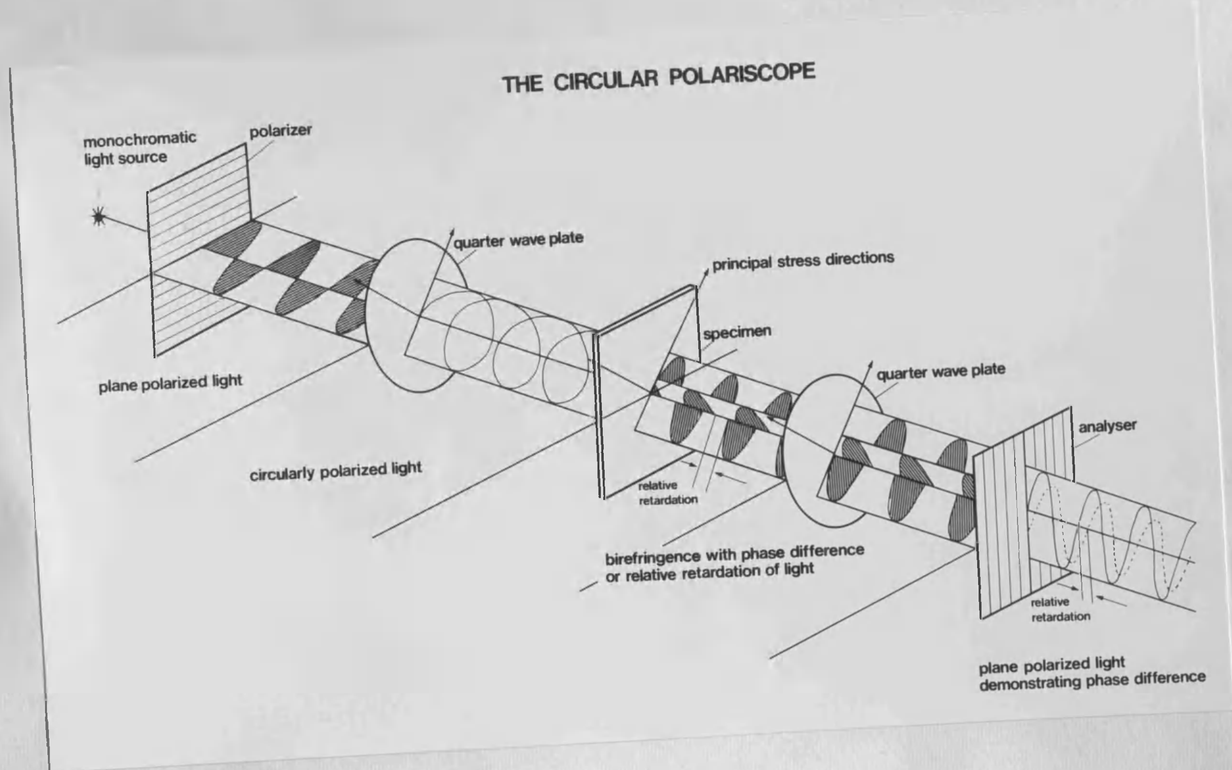
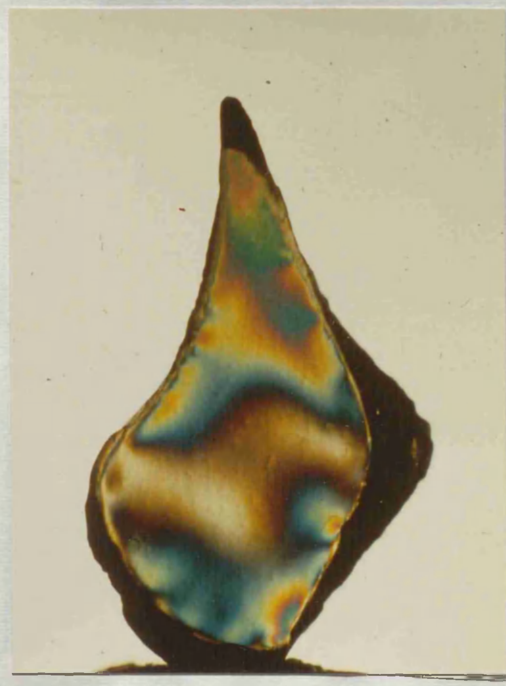

THE CIRCULAR POLARISCOPE
monochromatic light source
polarizer
quarter wave plate
principal stress directions
specimen
quarter wave plate
analyser
plane polarized light
circularly polarized light
relative retardation
birefringence with phase difference or relative retardation of light
relative retardation
plane polarized light demonstrating phase difference

FIGURE 7.6.

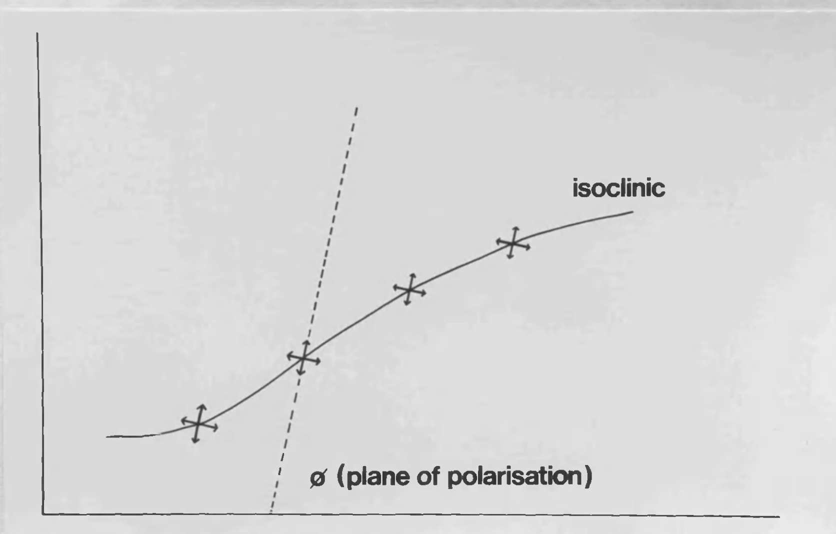


Isochromatic fringes in a section through the condylar neck of a photoelastic mandibular replica.

FIGURE 7.7.

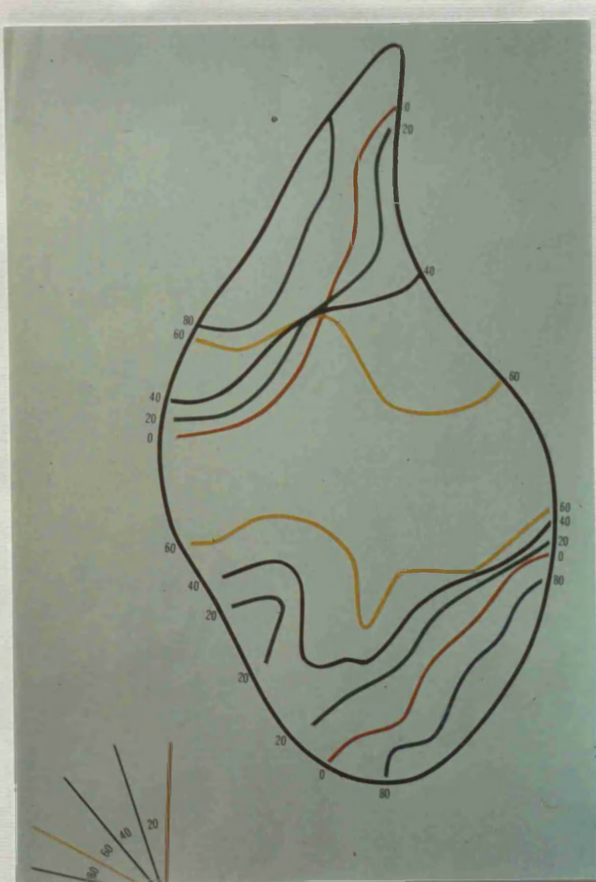
Isoclinic lines in a section through the condylar neck of a photoelastic mandibular replica.

FIGURE 7.8.



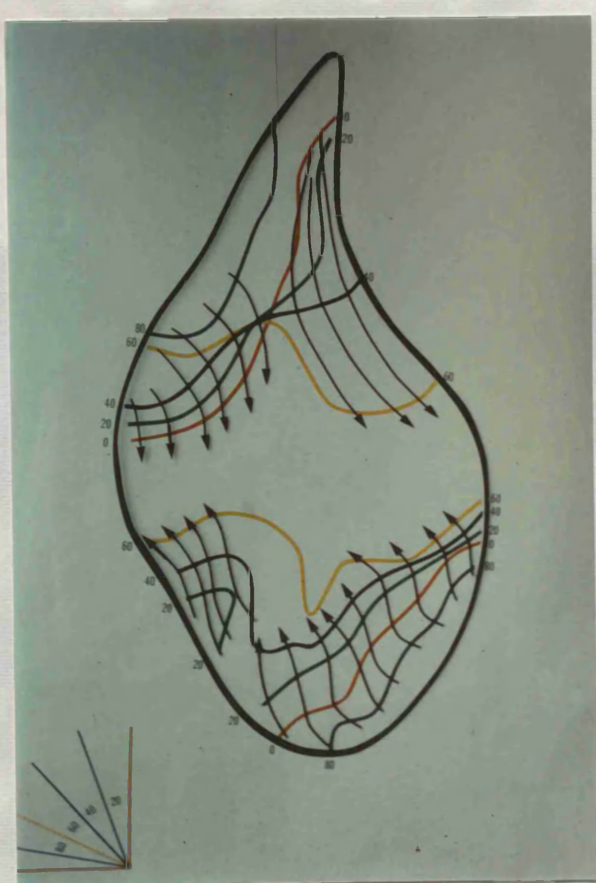
Principle Stress Direction: The small arrows represent the direction of the principle stresses on an isoclinic fringe and are aligned parallel and at right angles to the plane of polarisation.

FIGURE 7.9.



A series of isoclinic fringes on a section through the condylar neck of a photoelastic mandibular replica. Isoclinics have been drawn at intervals of 20° during rotation of polariser and analyser.

FIGURE 7.10.

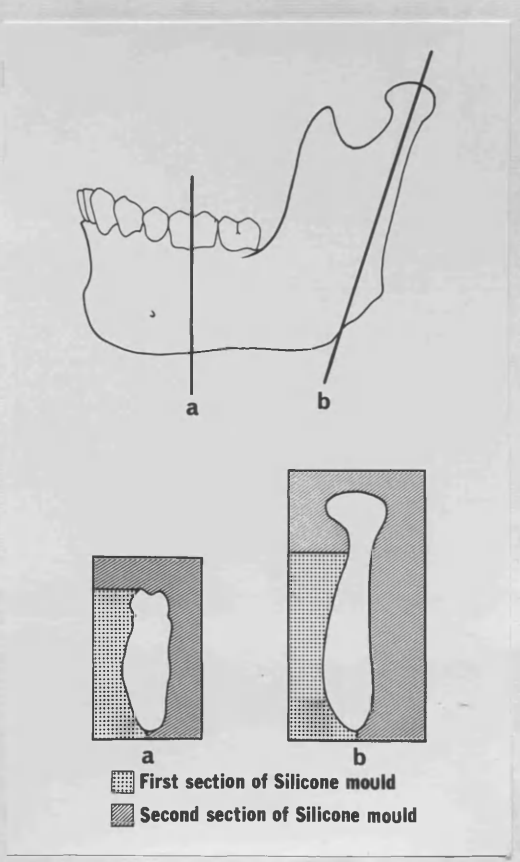


Stress trajectories tangential to the plane of polarisation superimposed upon the isoclinic fringes in a section through the condylar neck of a photoelastic mandibular replica.

FIGURE 8.1.

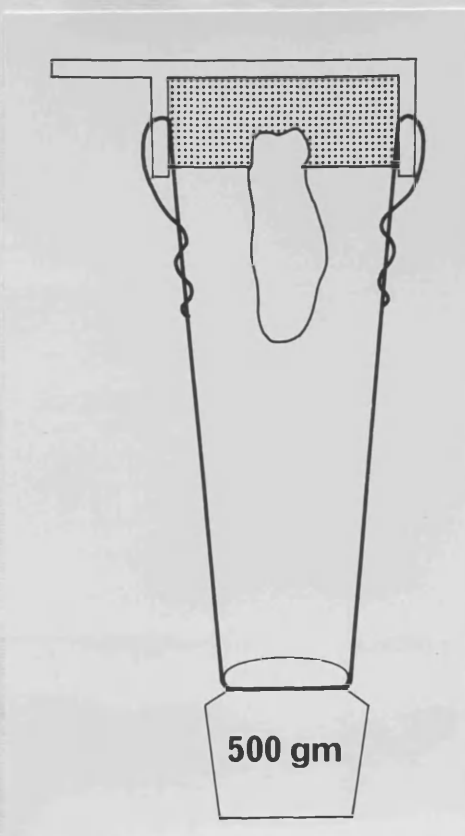
The dentate mandible and photoelastic replica.

FIGURE 8.2.



Sectional arrangement of Silicone mould.

FIGURE 8.3.



Application of occlusal load to dentate mandibular replica.

FIGURE 8.4.

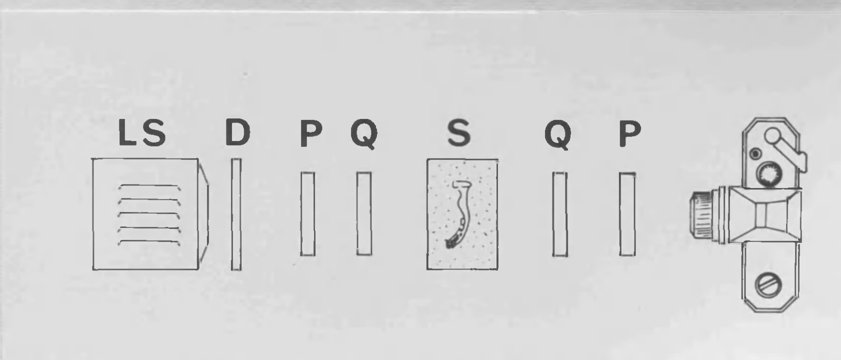


Diagram of the arrangement of the polariscope for examination of hemi-mandibular specimens.

L.S. Light Source
D. Diffuser
P. Polarising Lens
Q. Quarter Wave Plate
S. Specimen in microscope immersion oil

FIGURE 8.5.

Location of sections through mandibular body and ramus.

FIGURE 8.6.

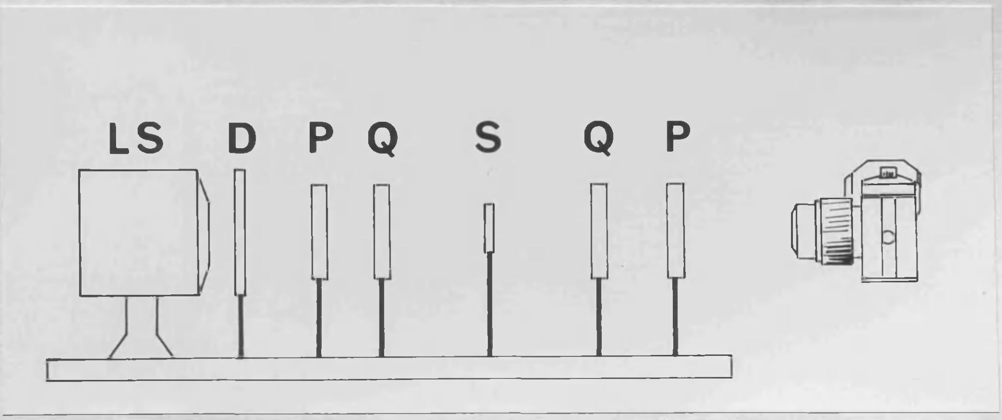


Diagram of the arrangement of the polariscope for examination of sections through the mandibular body and ramus.

L.S.	Light Source	P.	Polarising Lens	S.	Specimen
D.	Diffuser	Q.	Quarter Wave Plate		

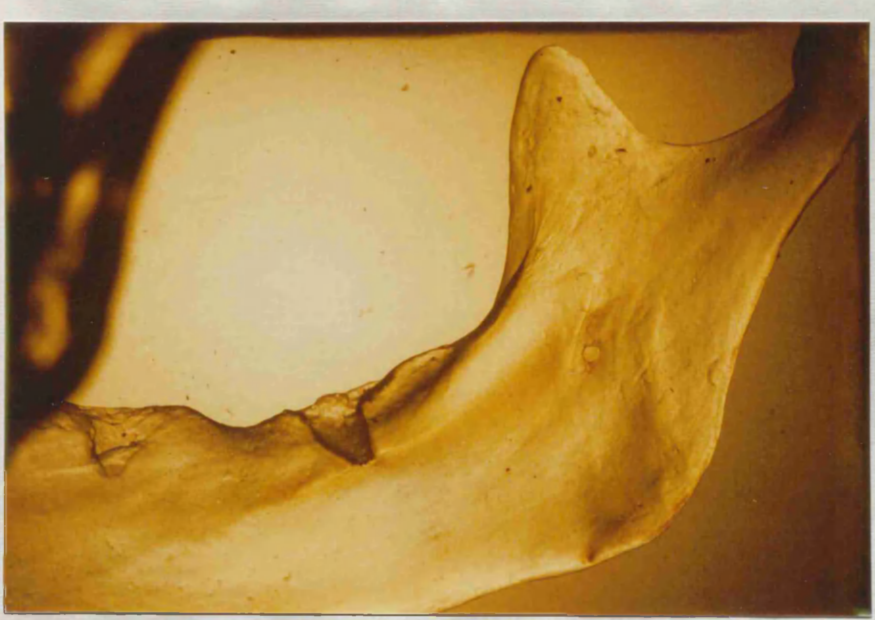
FIGURE 9.1.

The edentulous mandible.

FIGURE 9.2.

Photoelastic replica of the edentulous mandible.

FIGURE 9.3.

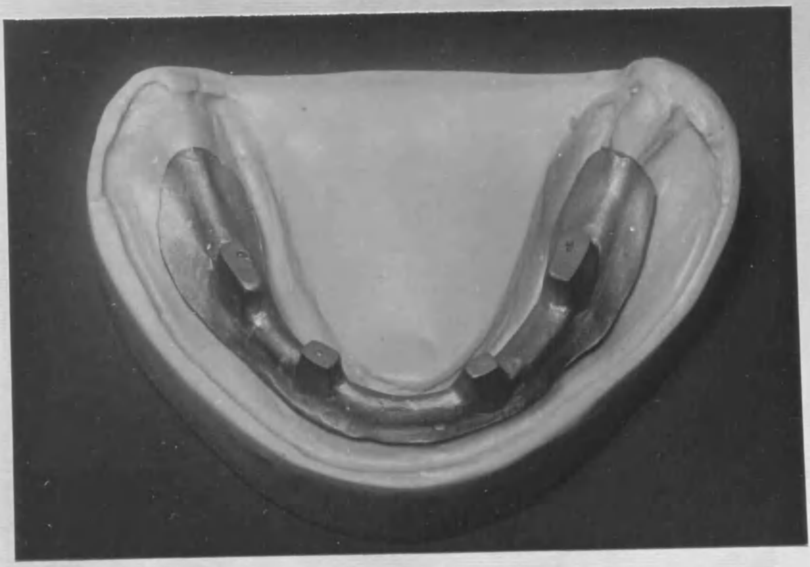


Stress-free replica of the edentulous mandible viewed in polarised light.

FIGURE 9.4.

Fully extended mandibular complete denture base.

FIGURE 9.5.

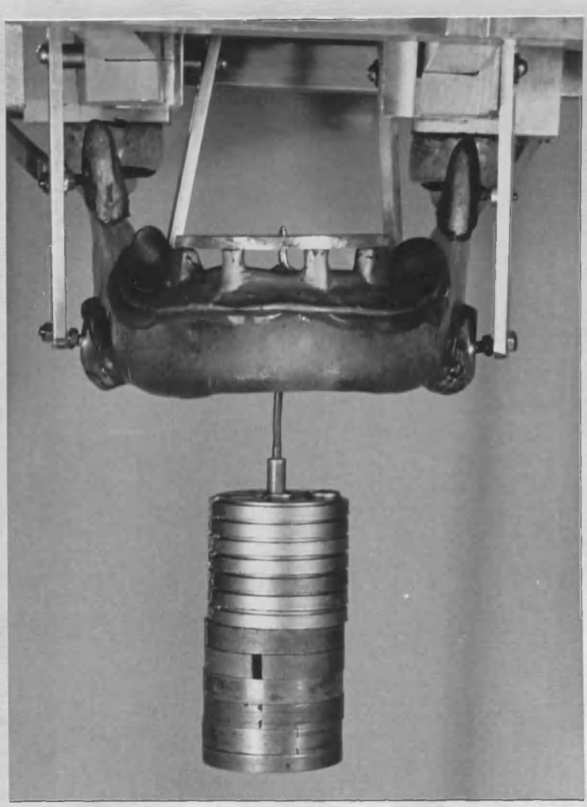


Underextended mandibular complete denture base.

FIGURE 9.6.

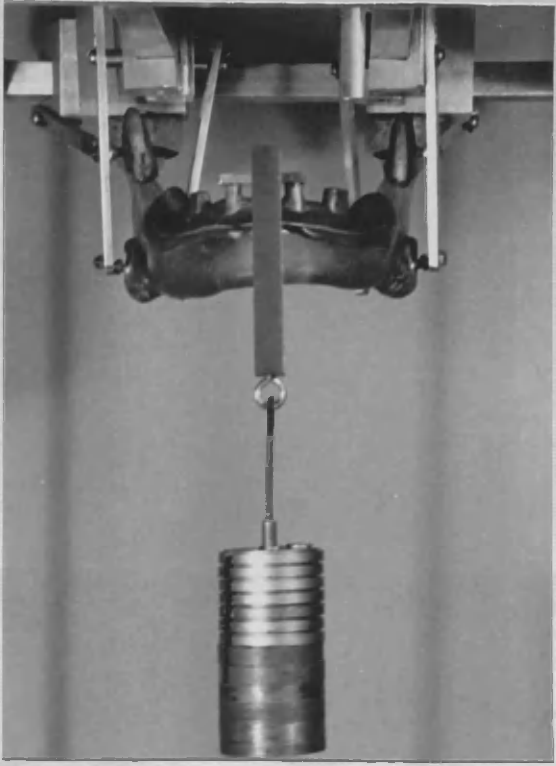
Mandibular subperiosteal implant framework.

FIGURE 9.7.



500 gm load applied over all four posts on the fully extended denture base.

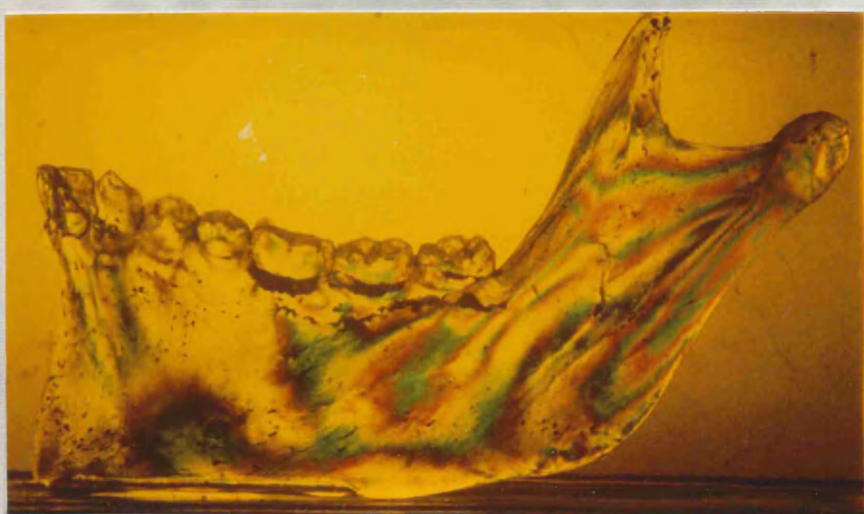
FIGURE 9.8.



500 gm load applied to the two canine posts on the fully extended denture base.

FIGURE 10.1.

A

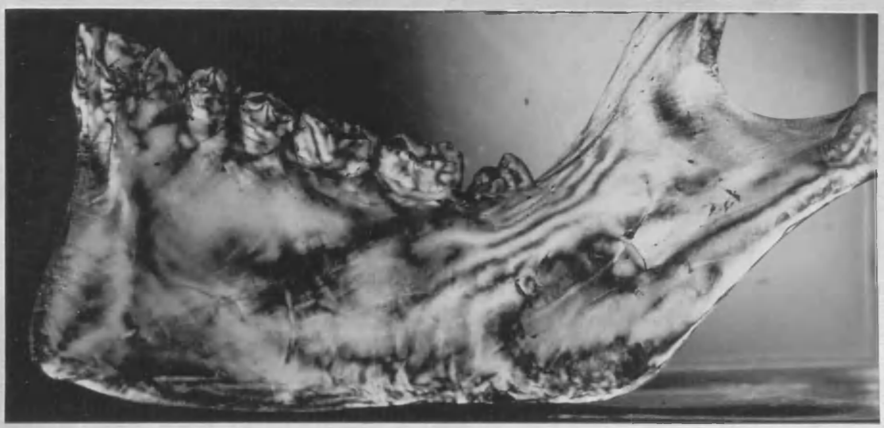


B

Dentate Mandible Specimen 1.

A. Left side, medial aspect, monochromatic light.
B. Left side, lateral aspect, white light.

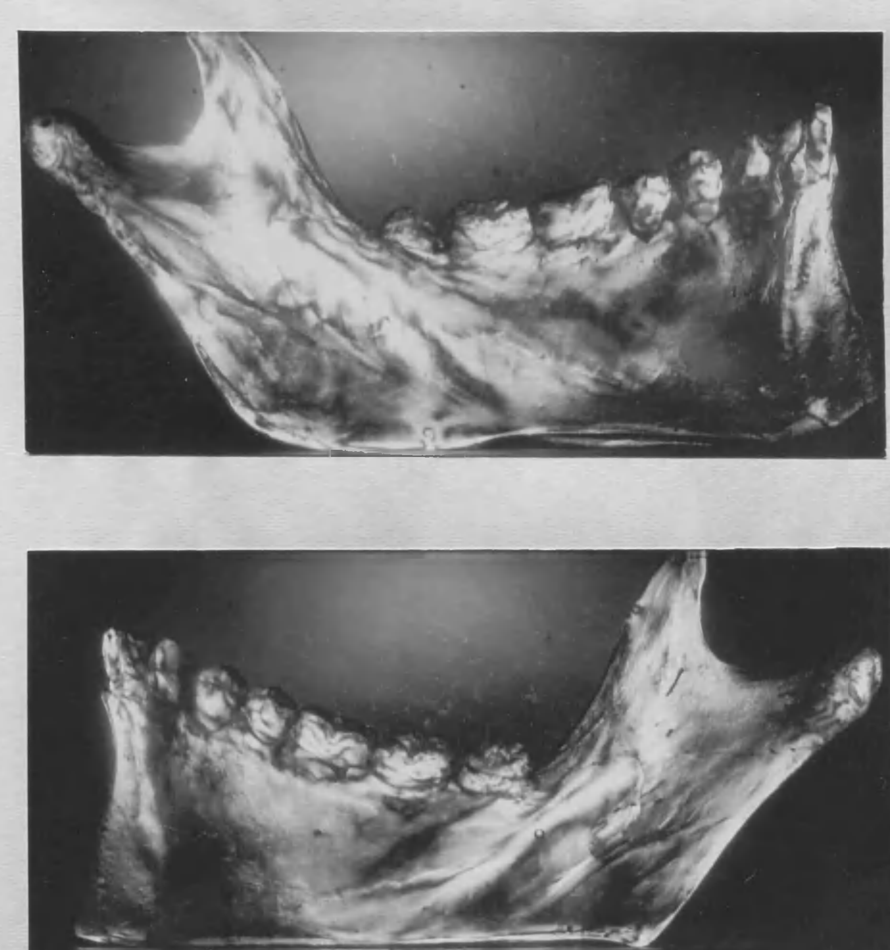
FIGURE 10.2.



Dentate Mandible Specimen 2.

Right side, medial aspect.

FIGURE 10.3.



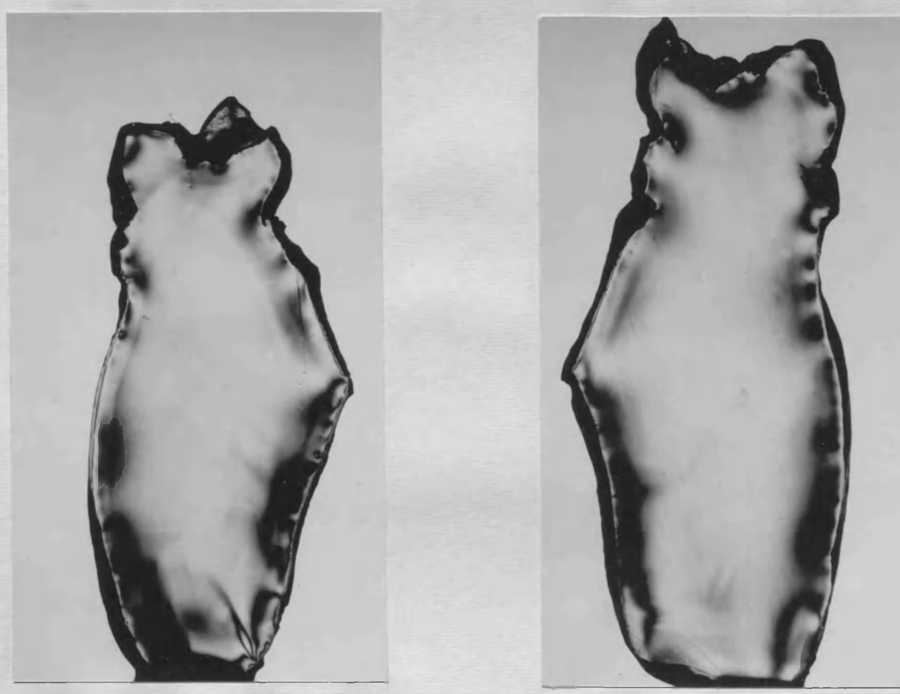
A

B

Dentate Mandible Specimen 3.

A. Right side, lateral aspect.
B. Left side, lateral aspect.

FIGURE 10.4.



A B

Dentate Mandible Specimen 1.

Sections through first molar region.

A. Right Side B. Left Side.

FIGURE 10.5.

A

B

Dentate Mandible Specimen 2.

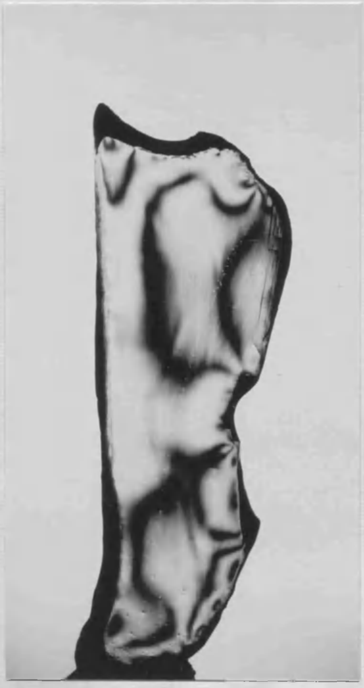
Sections through premolar region.

A. Right Side. B. Left Side.

FIGURE 10.6.

Dentate Mandible Specimen 3.
Section through central incisor region.

FIGURE 10.7.

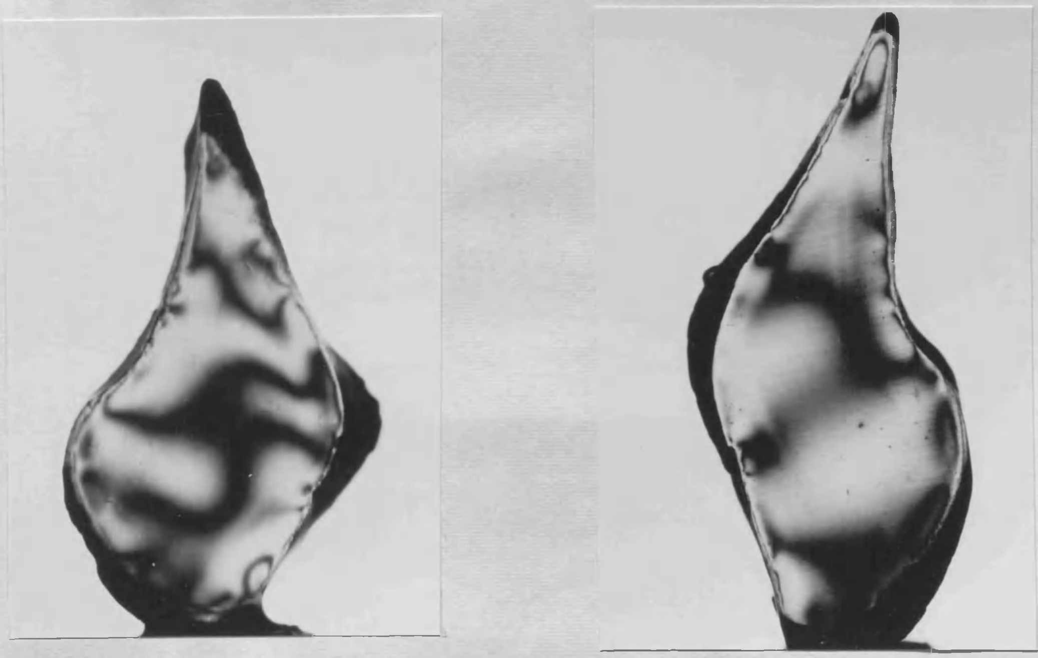


A

B

Dentate Mandible Specimen 3.
Sections through angle of mandible.
A. Right Side B. Left Side.

FIGURE 10.8.



A B

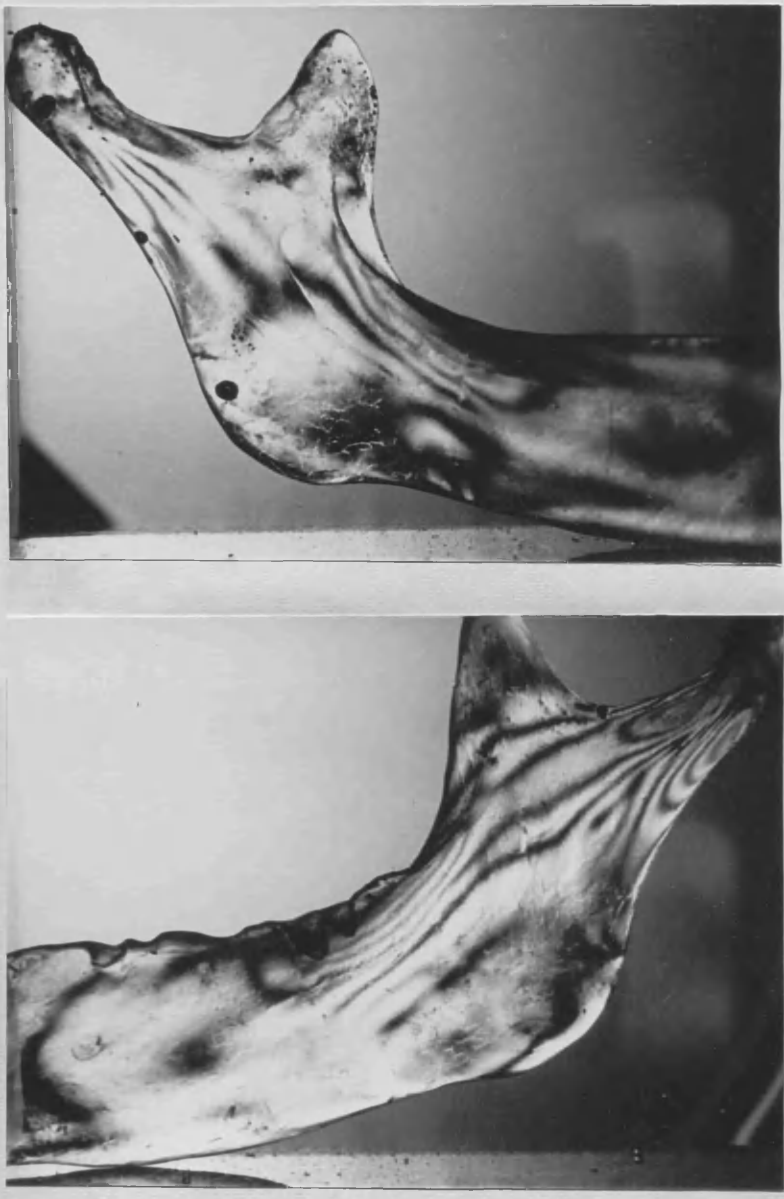
Dentate Mandible Specimen 3.

Sections through neck of mandible.

A. Right Side B. Left Side.

Sections supported on posterior border and viewed from inferior aspect.

FIGURE 11.1.



A

B

Edentulous Mandible Specimen 1.

A. Left side, medial aspect.
B. Right side, medial aspect.

FIGURE 11.2.

A

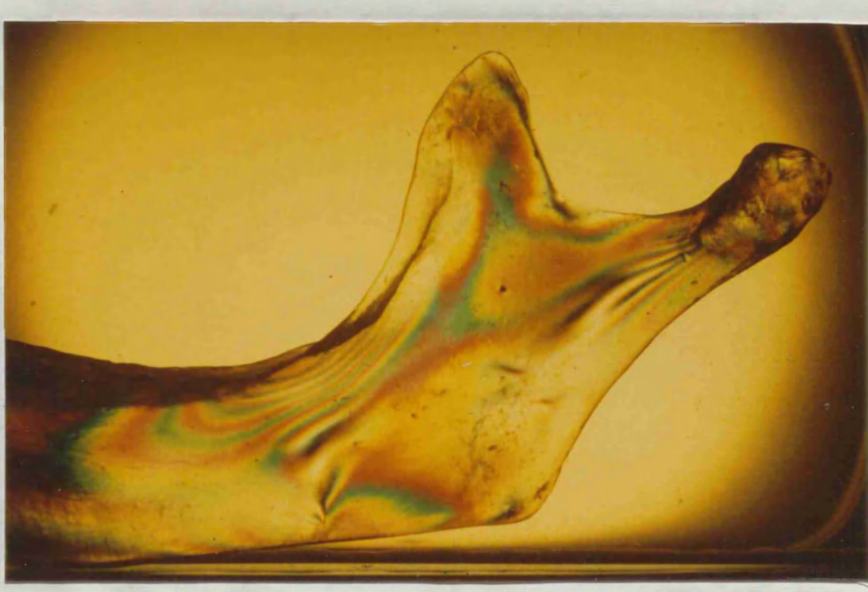
B

Edentulous Mandible Specimen 2.

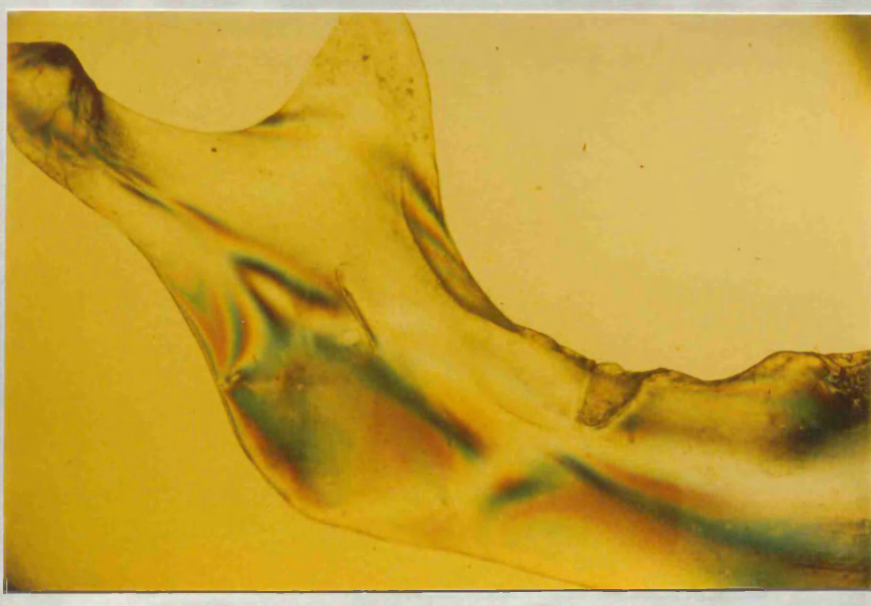
Left side, medial aspect.

A. Monochromatic light.
B. White light.

FIGURE 11.3.



A



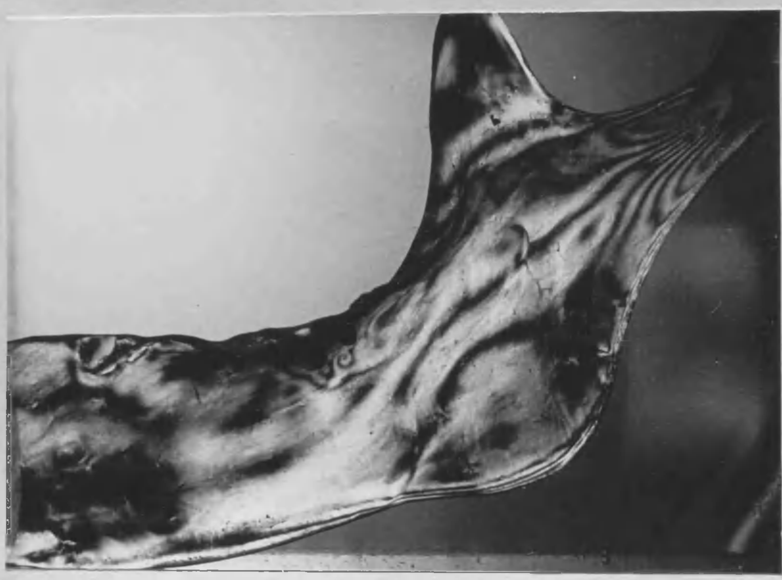
B

Edentulous Mandible Specimen 3.

A. Left side, lateral aspect.
B. Right side, lateral aspect.

FIGURE 11.4.

A

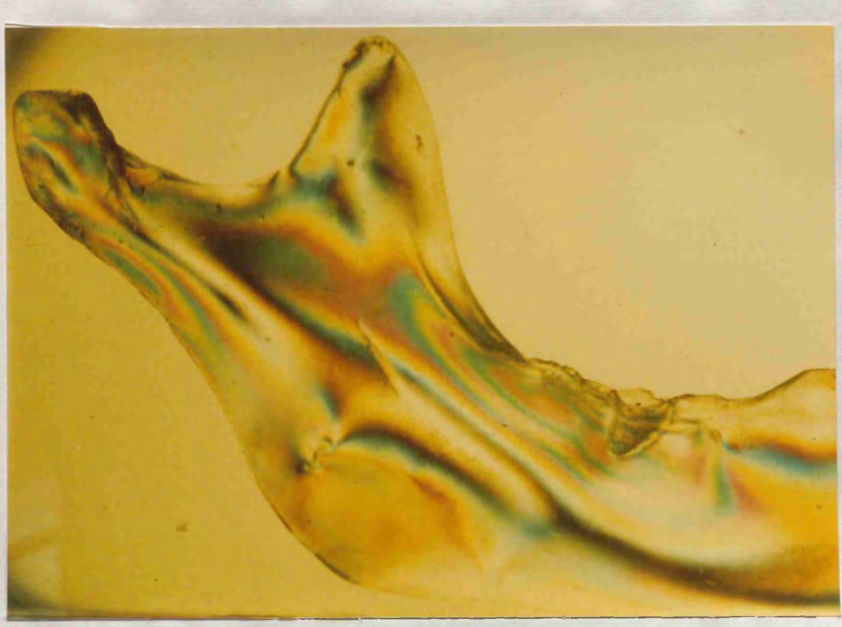


B

Edentulous Mandible Specimen 4.

A. Right side, lateral aspect.
B. Right side, medial aspect.

FIGURE 11.5.



A

B

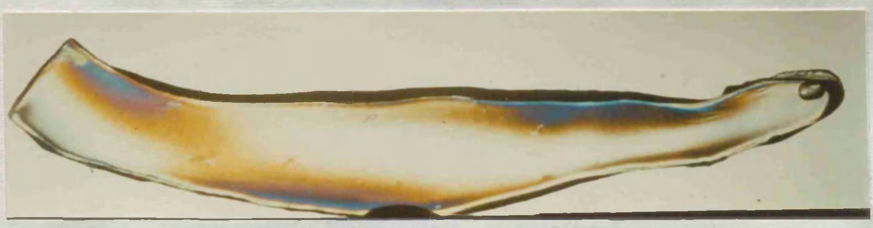
Edentulous Mandible Specimen 5.

A. Right side, lateral aspect.
B. Left side of mandibular body, medial aspect.

FIGURE 11.6.

Edentulous Mandible Specimen 1.
Section through right molar region.

FIGURE 11.7.



Edentulous Mandible Specimen 1.

Longitudinal section - inferior border.

Specimen supported on lateral surface and viewed from superior aspect.

FIGURE 11.8.

Edentulous Mandible Specimen 2.
Section through incisor region.

FIGURE 11.9.

A B

Edentulous Mandible Specimen 3.
Sections through premolar region.
A. Right side B. Left Side.

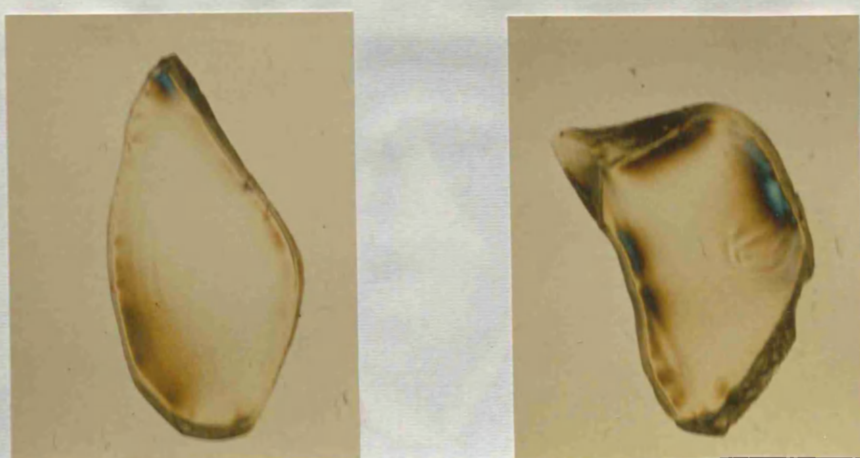
FIGURE 11.10.

Edentulous Mandible Specimen 4.
Section through right premolar region.

FIGURE 11.11.

Edentulous Mandible Specimen 5.
Section through right molar region.

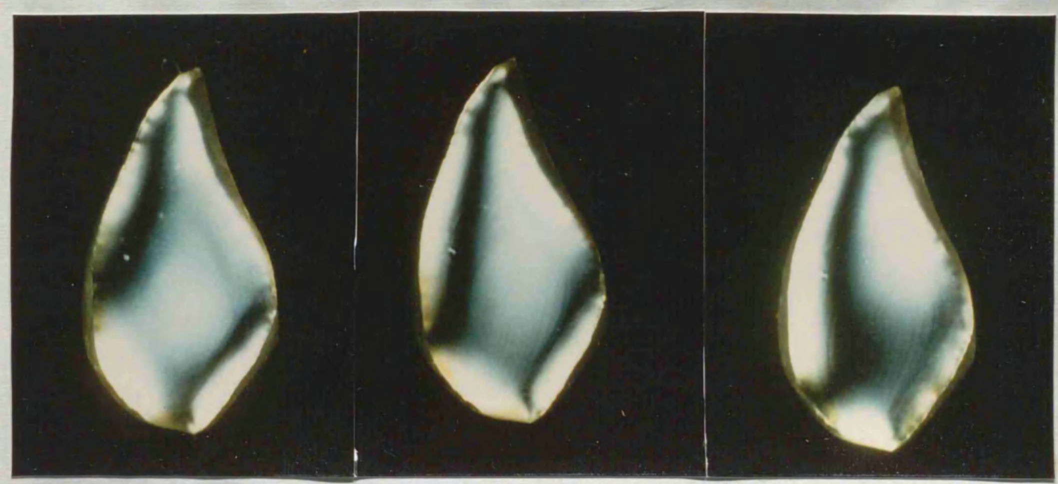
FIGURE 11.12.



A B

Edentulous Mandible Specimen 3.
Sections through neck of mandible.
A. Right side B. Left side.

FIGURE 11.13.

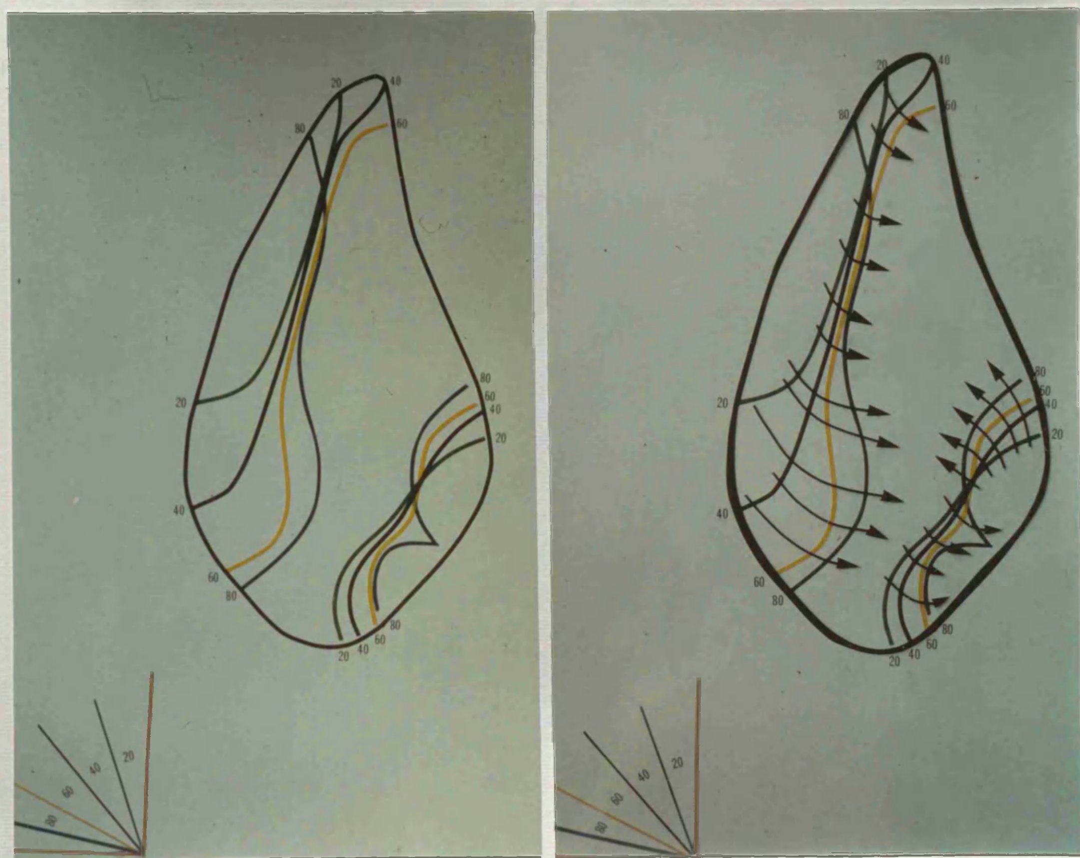


A B C

Edentulous Mandible Specimen 5.

Section through neck of mandible, right side.
Isoclinic fringes at (A) 20°, (B) 40° and (C) 60° rotation of polariser and analyser.

FIGURE 11.14.



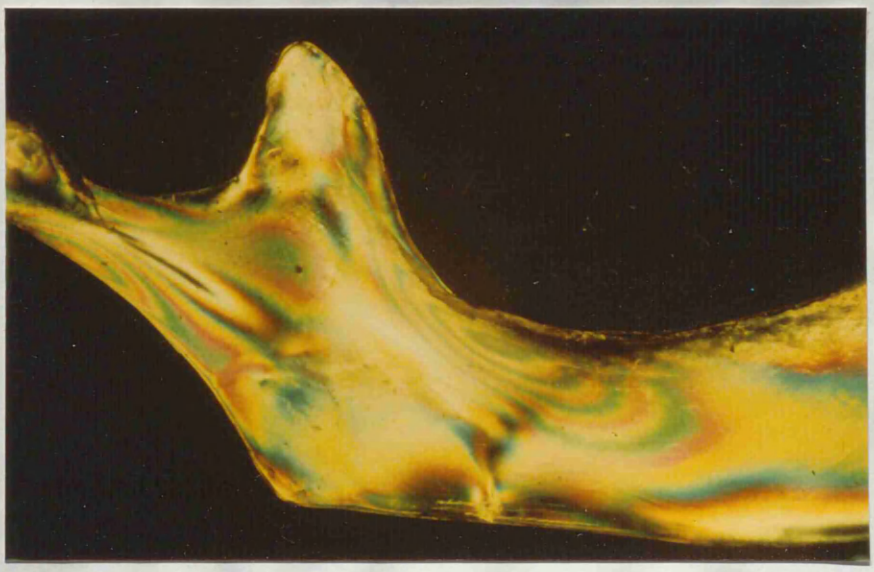
A B

Edentulous Mandible Specimen 5.

Section through neck of mandible, right side.

A. Series of isoclinic fringes drawn at intervals of 20°.
B. Stress trajectories tangential to the plane of polarisation, superimposed upon the isoclinic fringes.

FIGURE 12.1.

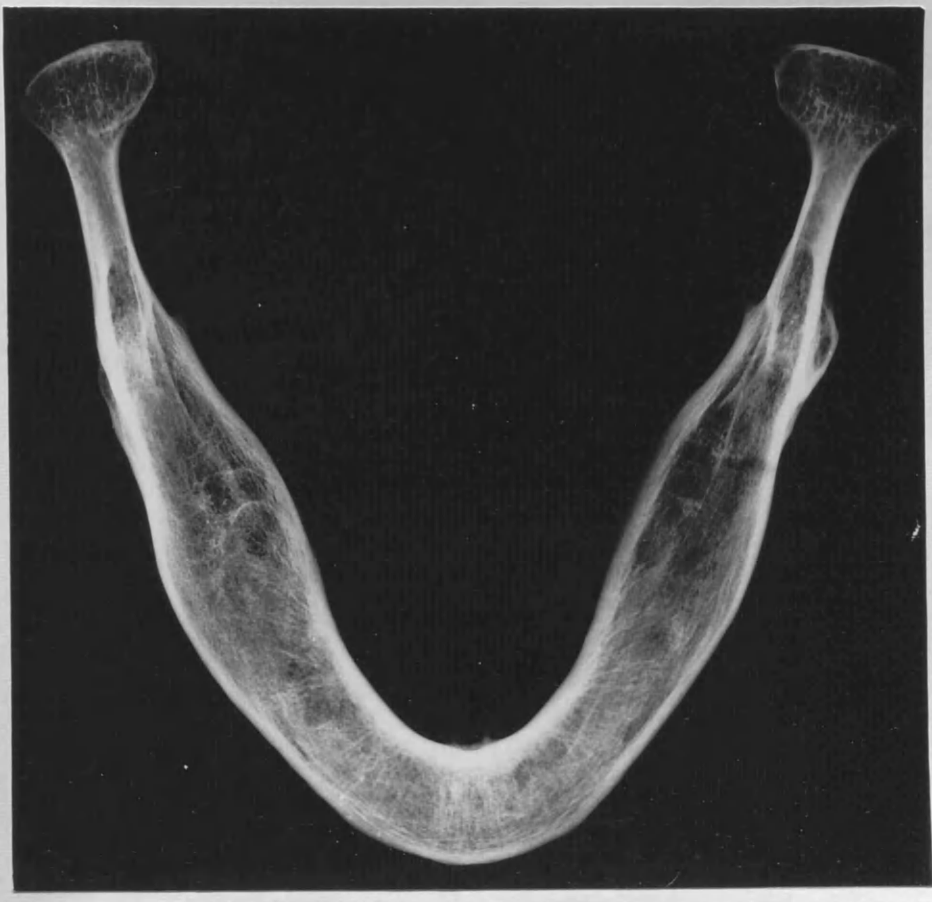


Stress patterns in the edentulous mandibular replica viewed against dark ground illumination.

FIGURE 12.2.

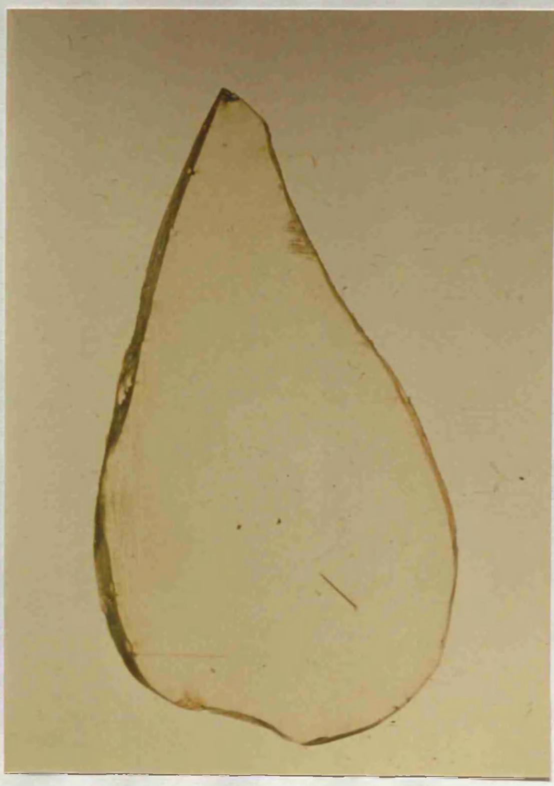
Diagramatic representation of a section through the molar region of the edentulous mandible, illustrating the thickness of the compact cortical bone.

FIGURE 12.3.



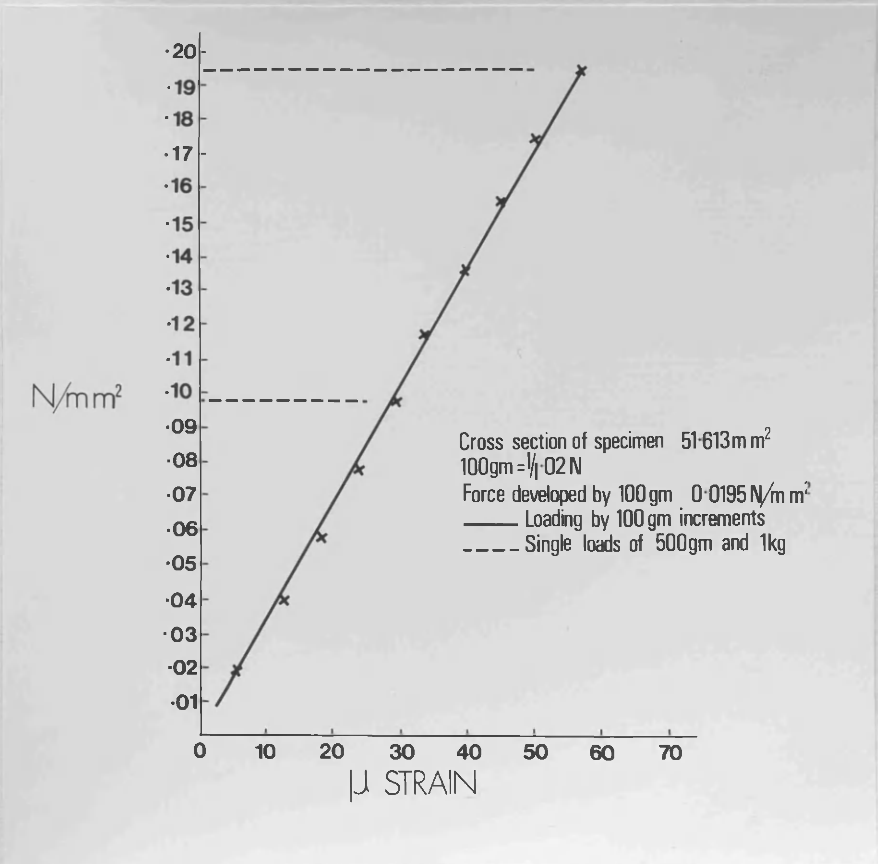
Occlusal radiograph of the edentulous mandible.

FIGURE 12.4.



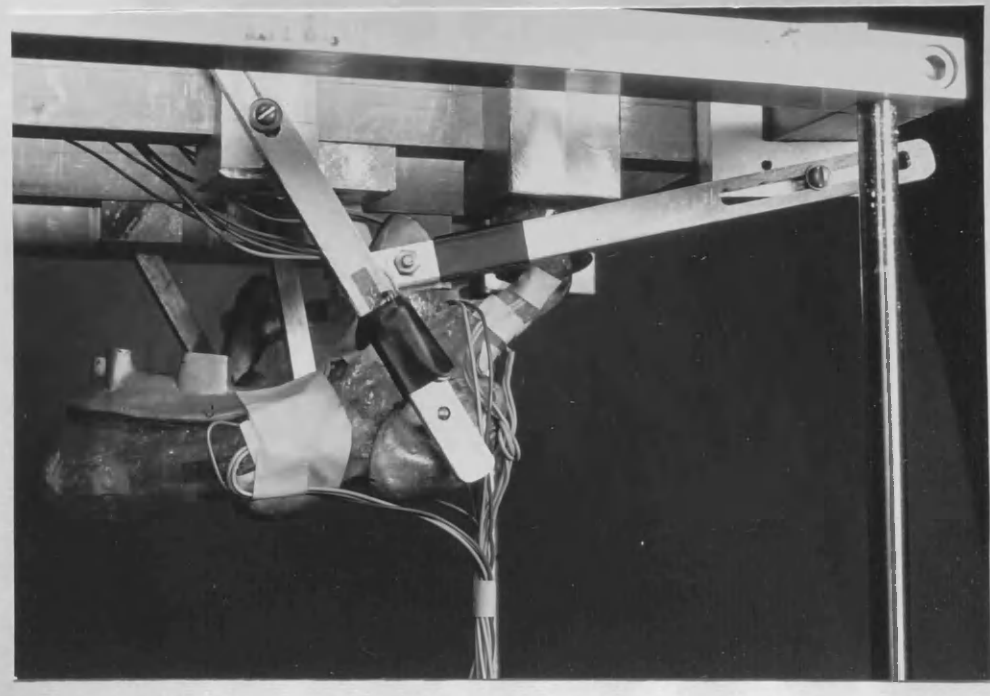
Section through the incisor region of a stress-free replica of the edentulous mandible, demonstrating that no stresses were generated by the sectioning and polishing procedures.

FIGURE 13.1.



Graph of Stress/Strain for the model material.

FIGURE 13.2.



Strain gauged mandibular replica in supporting frame.

FIGURE 13.3.

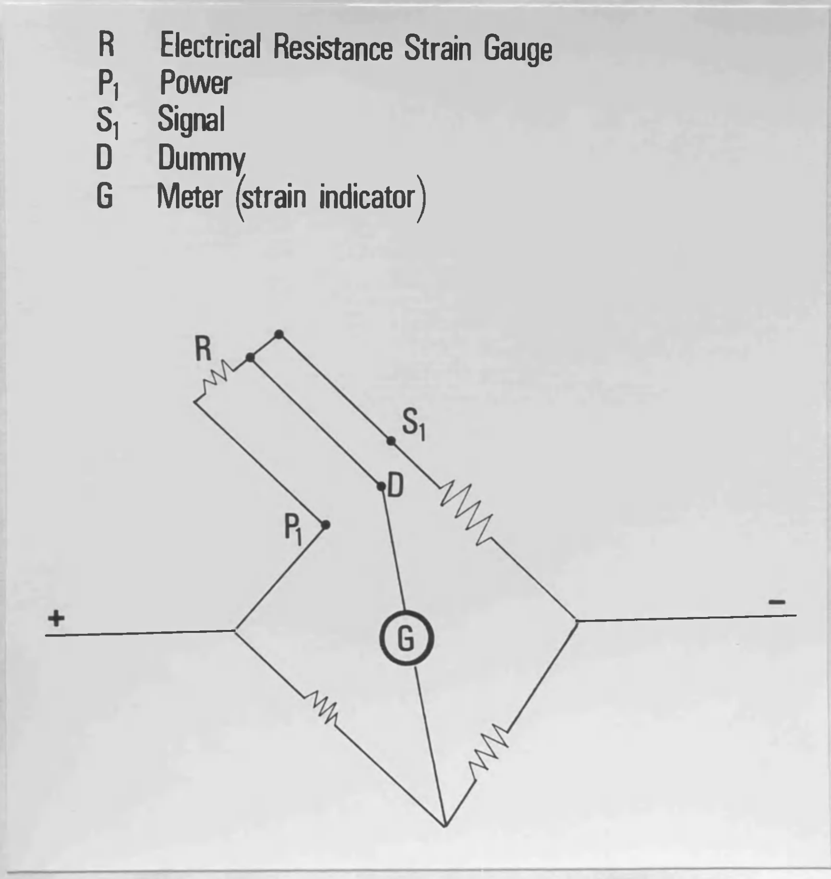
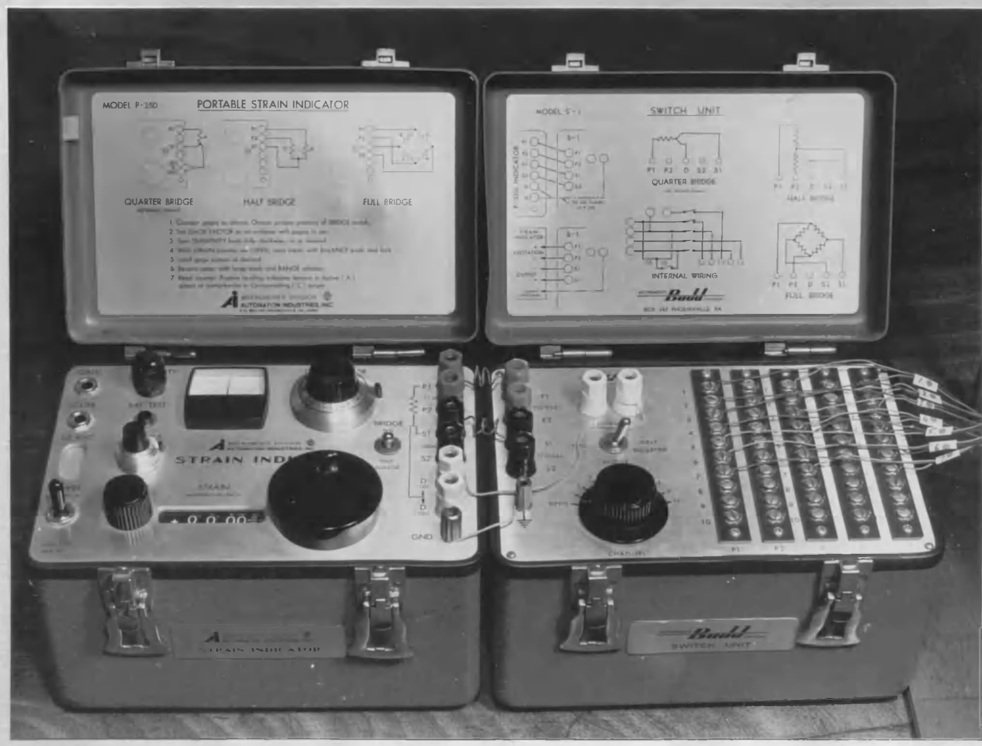


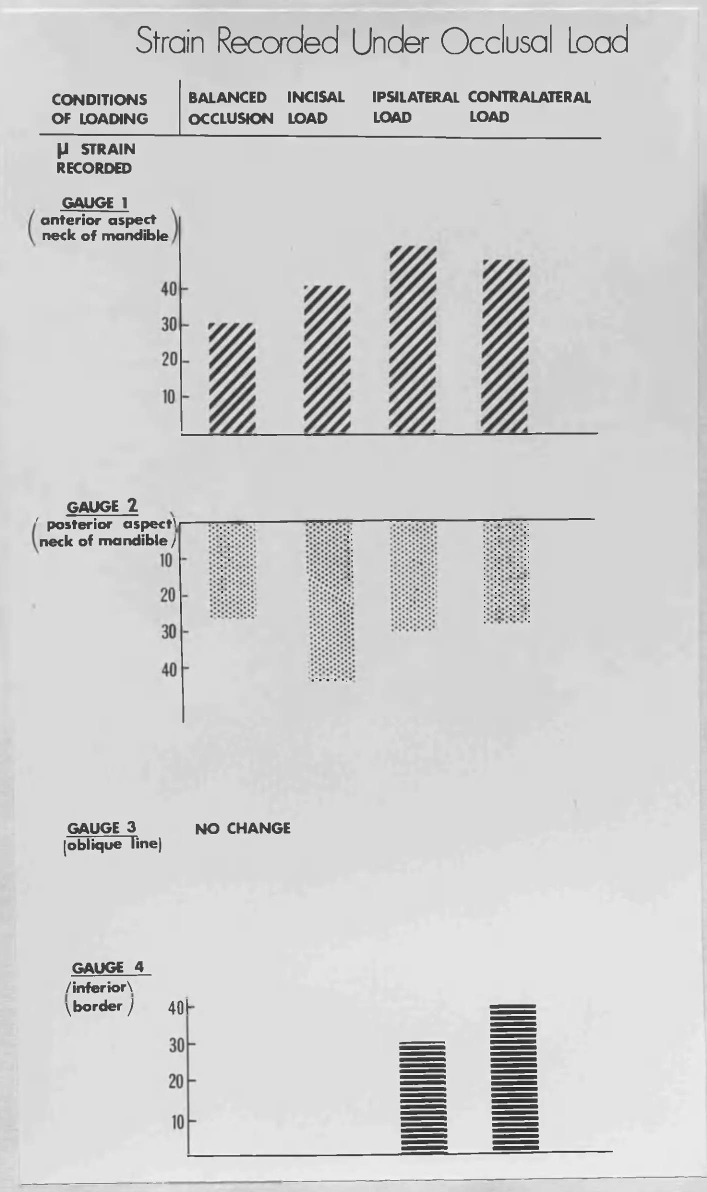
Diagram of the Wheatstone Bridge System.

FIGURE 13.4.



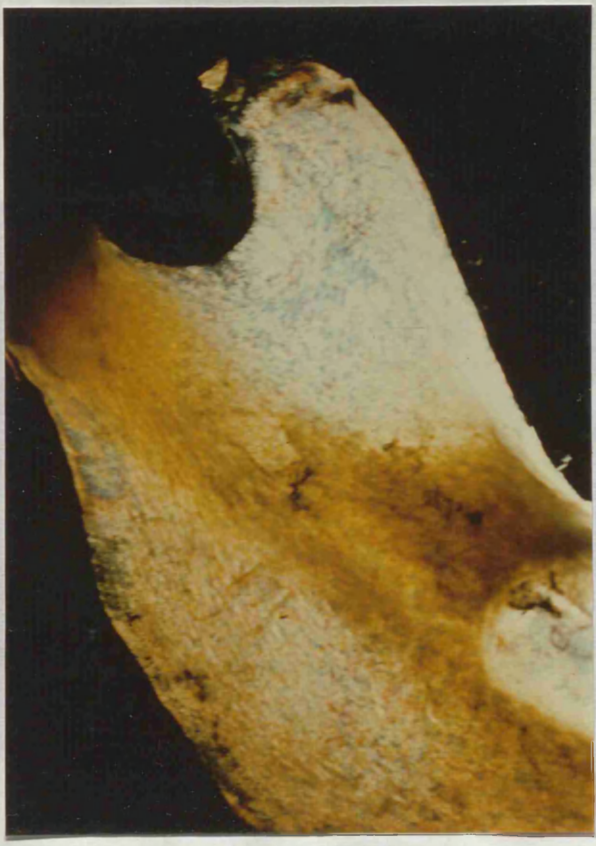
Switch unit and strain indicator.

FIGURE 13.5.



Results of Strain Gauge Study.

FIGURE 14.1.



Ramus of decalcified baboon mandible, cleared, immersed in methyl salycilate and viewed in polarised light.

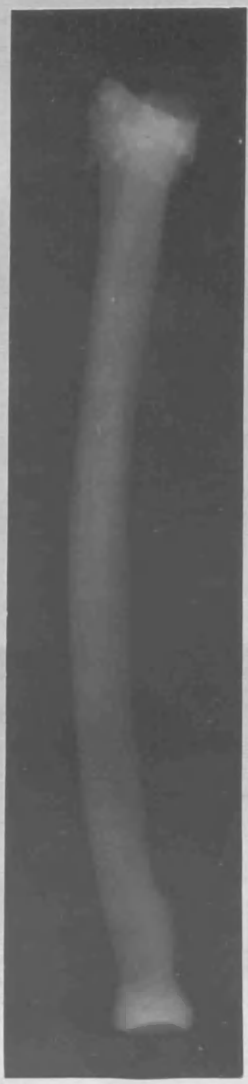
FIGURE 14.2.

Baboon radius positioned on loading frame.

FIGURE 14.3.

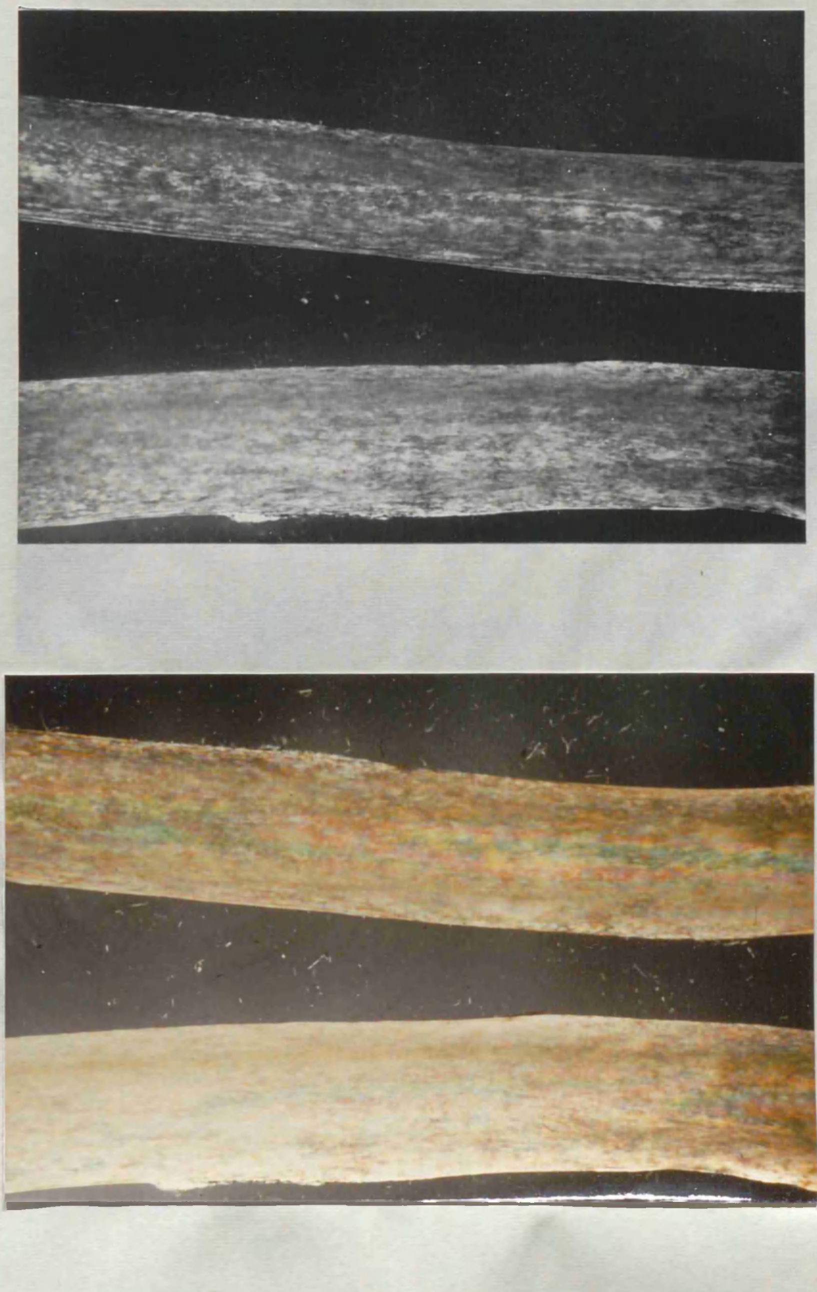
Radiograph of baboon radius prior to decalcification.

FIGURE 14.4.



Radiograph of decalcified baboon radius.

FIGURE 14.5.



A T C

B T C

Decalcified baboon radii.

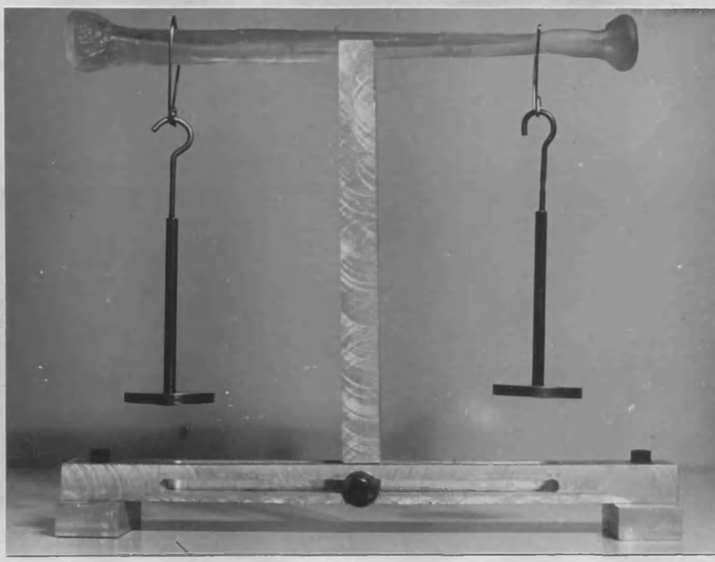
A. Monochromatic light
B. White light

T. Test Specimen
C. Control

FIGURE 14.6.

Stress free photoelastic replica of baboon radius.

FIGURE 14.7.

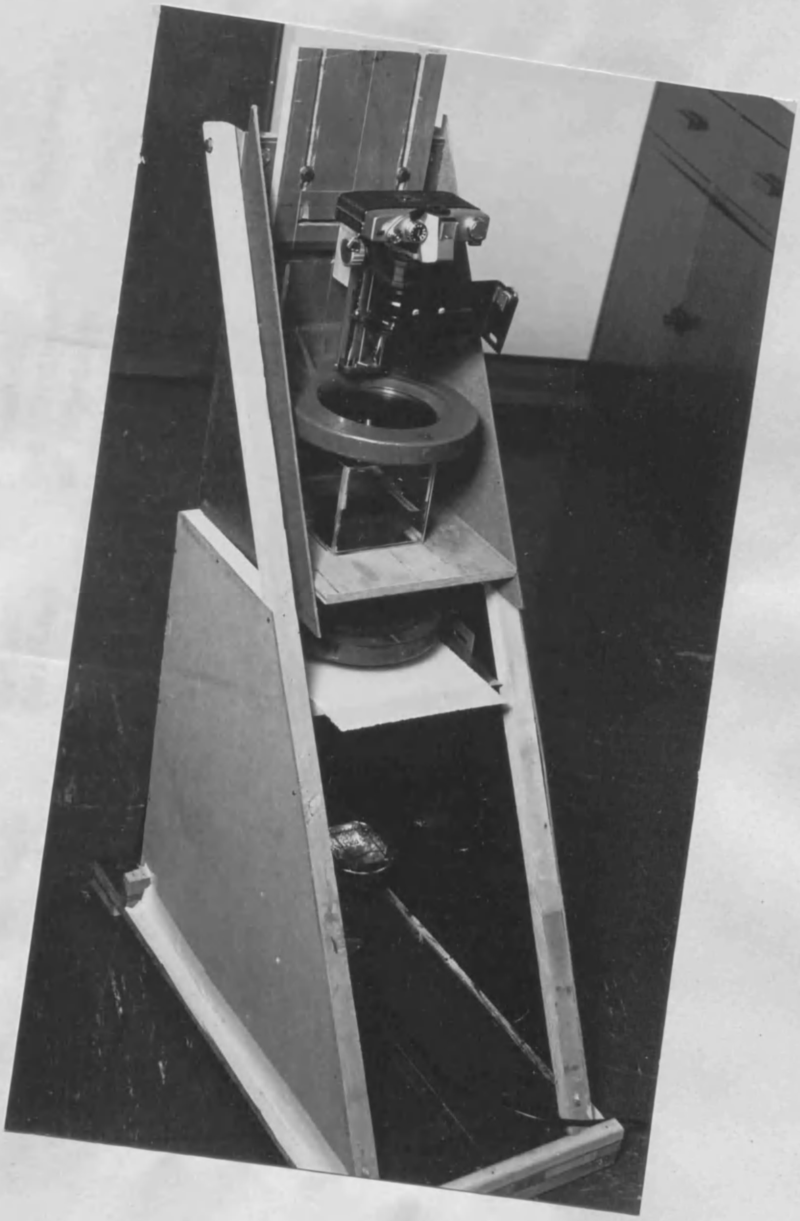


Replica of baboon radius on loading frame prior to stress freezing.

FIGURE 14.8.

Stresses generated in replica of baboon radius.

FIGURE A.1.



The polariscope.

TABLE B.1.

<u>Properties</u>

		Modulus of Elasticity (GN/m^2)	Tensile Strength (MN/m^2)	Stress Optical Constant (N/mm fringe)	Thermal Coefficient of Expansion (/°C)	Poisson's Ratio	Index of Refraction
PLM-4	20°C	2.93	62	1.07	70×10^{-6}	0.36	1.60
	135°C	0.02	2	0.039			
CT 200	20°C	3.0	70	1	$60\text{–}65 \times 10^{-6}$	0.35–0.38	1.59
	135°C	0.015	22	0.025			

Comparison of the physical properties of the model materials.