

OBSERVATIONS ON THE HUMAN MASTICATORY APPARATUS

IN ITS

DENTULOUS AND EDENTULOUS STATES

IN RESPECT TO

THE TOTAL AND FUNCTIONAL MOBILITY OF THE MANDIBLE

BY

IJAZ-UL-HAQUE

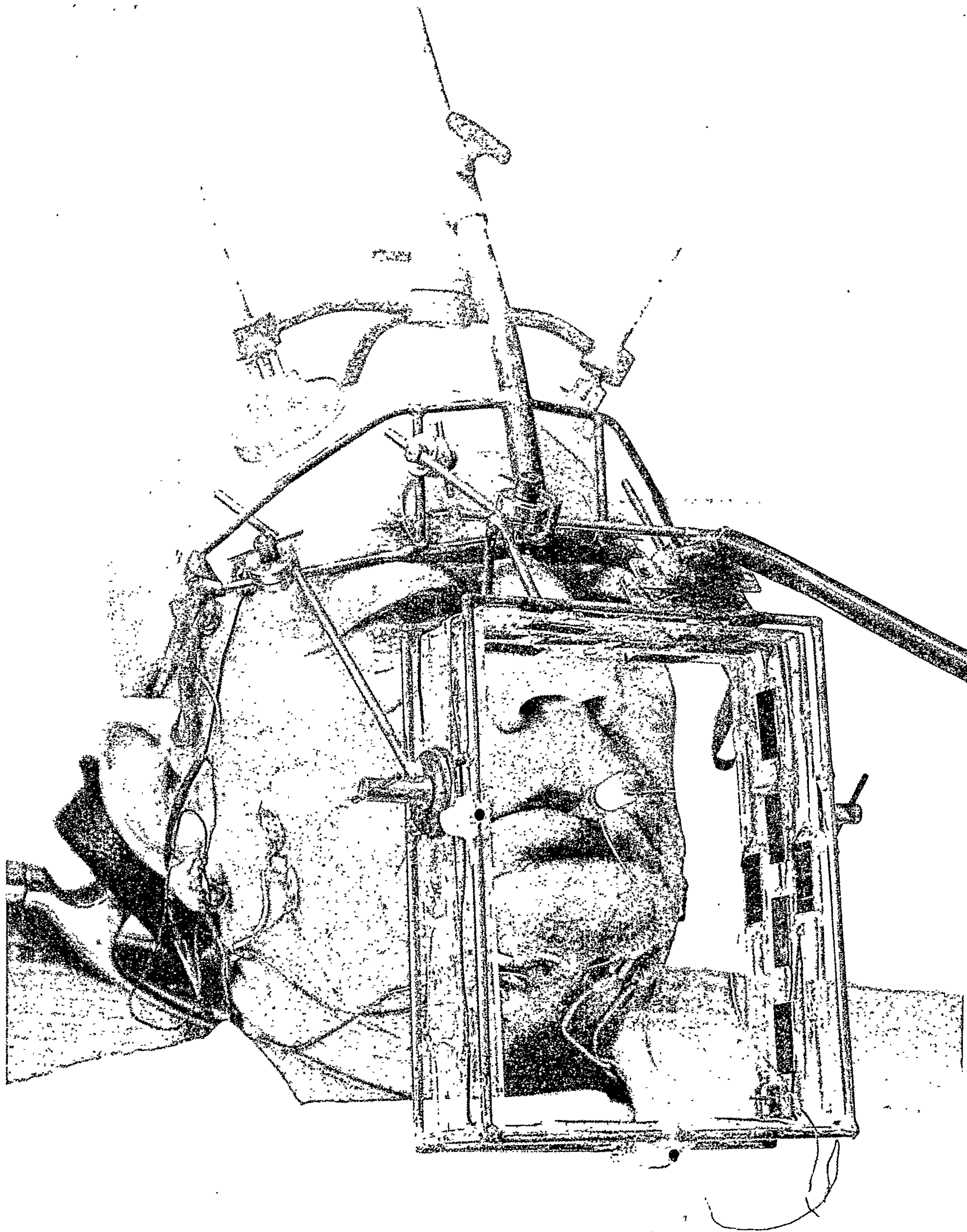
A Thesis presented to the University of Sydney

for the Degree of Doctor of Philosophy

Department of Prosthetic Dentistry

December 1972

Project Sponsored by Colombo Plan



13. Certainly We created man from the extract of a clay that had special properties.

وَلَقَدْ خَلَقْنَا الْإِنْسَانَ مِنْ سُلَالَةٍ مِّنْ طِينٍ ﴿١٣﴾

14. Then We placed him as a drop of life-germ in a secure place of confinement.

ثُمَّ جَعَلْنَاهُ نُطْفَةً فِي قَرَارٍ مَّكِينٍ ﴿١٤﴾

15. Then We gave the life-germ ability to make connections (with the place of confinement) Then We formed it into a lump of tissues. Then We defined bones in this lump of tissues. Then We draped muscles and flesh around the bones. Then We caused it to grow into another creation.

ثُمَّ خَلَقْنَا النُّطْفَةَ عَلَقَةً فَخَلَقْنَا الْعَلَقَةَ مُضْغَةً فَخَلَقْنَا الْمُضْغَةَ عِظْمًا فَكَسَوْنَا الْعِظْمَ لَحْمًا ثُمَّ أَنشَأْنَاهُ خَلْقًا آخَرَ ﴿١٥﴾

So blessed is Allah Who is the most beautiful Creator.

(The Holy Quraan Ch. XXIII, 13-15)

To my wife and colleague

FAHIMA

and children

FAAIZA, MOIZ, and FAAIZ.

CANDIDATE'S CERTIFICATE

This is to certify that the work presented in this thesis was carried out by the candidate in the Department of Prosthetic Dentistry, the University of Sydney, and has not been submitted to any other University or institution for a higher degree.

Signed:

Jayul Anwar

ACKNOWLEDGEMENTS

I am deeply indebted to Professor C.H. Graham for accepting me in the department, for helping me in the planning of this work, for his continuous guidance and supervision and extreme patience and forbearance for my insidious manner of work. Time and again he has come to my rescue in situations that generally confront research fellows in foreign lands.

Dr. B.R.D. Gillings initiated me to the subject of Mandibulography. He helped and guided me in the improvement of the equipment. I am grateful to him for the long discussions that were so helpful in containing the project and also for the language correction of the thesis.

I wish to thank Mr. Bill Alexander for being so consistently meticulous in the laboratory procedures for denture construction.

Finally I wish to pay tribute to my wife who is also my colleague in the profession, and my three children who suffered a lot, sacrificed a lot, endured a lot and never said a word of complaint. God bless them.

ABSTRACT

In one Dentulous and four Edentulous Subjects the masticatory apparatus was examined for (i) characteristics of the envelope of total movement space, (ii) characteristics of simulated chewing movements and (iii) characteristics of masticatory movements and their variations due to variations of consistencies and quantities of food bolus. The mandibular movements were recorded using the Photo-electric system of mandibulography which afforded a three-dimensional visualisation of the movements.

Both Dentulous and Edentulous Subjects indicated a preference for a particular side for masticatory performance. On the preferred side the envelope of total movement space extended further distally and reached closer to the centre of base of the skull than on the non-preferred side. This capacity for distal excursion was greater in the Edentulous Subjects than in the Dentulous Subject. This suggested a hypothesis that the posterior quadrant of the envelope of total movement space on the preferred side would offer the mandible greater stability and security and a greater mechanical advantage during masticatory performance than the non-preferred side or sections located anteriorly, and that whenever the mandible would be required to exercise greater masticatory stresses, it would perform such functions on the preferred side and in comparatively retruded positions in the envelope of total movement space, and further that this need for performance in retruded positions would be greater in Edentulous Subjects and is provided for by a further distal extension of the envelope of total movement space in the Edentulous Subjects than in the Dentulous Subject. The findings in the masticatory kinematic performance of the Dentulous and Edentulous Subjects support the above hypothesis. There is evidence that masticatory kinematic performance is influenced by the consistency and size of food bolus as well as its changing properties during a masticatory performance. The masticatory kinematic performance in a subject can be assessed as "Conservative" or "Non-Conservative" indicating the degree of confidence

the subject has in his masticatory apparatus.

The role of cuspal guidance and the envelope of movement space used during the masticatory performance of different exercises with varying consistencies and quantities of food bolus were also examined. Different functional qualities could be recognised in the different masticatory cycles. Similarly variations of movement space used during different exercises in the Dentulous and Edentulous Subjects were also observed.

The investigation also shows the versatility of the Photoelectric system of mandibulography.

TABLE OF CONTENTS. VOLUME I.

	<u>Page</u>
Acknowledgements	
Abstract	
<u>SECTION I: GENERAL INTRODUCTION</u>	1
<u>SECTION II: REVIEW OF THE LITERATURE</u>	6
<u>SOME OF THE ANATOMIC CONSIDERATIONS OF THE MASTICATORY APPARATUS</u>	
<u>APPARATUS</u>	7
1. COMPONENTS OF MASTICATORY APPARATUS	7
Temporomandibular Joints	7
Disco-Temporal Compartment	7
Disco-Condylar Compartment	8
2. POSITIONAL RELATIONSHIPS OF THE TWO COMPONENTS OF THE MASTICATORY APPARATUS	9
POSTURAL POSITION	9
TOOTH CONTACT POSITIONS	10
Ligamentous Position	11
Muscular Position	12
Tooth Position	12
BRACING POSITION	13
<u>MANDIBULAR MOVEMENTS</u>	14
CONTROLLED MOVEMENTS	14
NATURAL MOVEMENTS	14
<u>MANDIBULAR CAPACITY OF MOTION AND MOVEMENT SPACE</u>	15
Controversy of the Hinge Axis	18
<u>DIMENSIONS OF THE TOTAL MOVEMENT SPACE</u>	19
<u>CAPACITY OF MANDIBULAR MOTION AND MOVEMENT SPACE IN THE EDENTULOUS STATE</u>	19
<u>MASTICATORY MOVEMENTS</u>	20
1. SHAPE AND FORM OF THE MASTICATORY CYCLE	20
2. FUNCTIONAL PHASES OF THE MASTICATORY CYCLES	25

3.	RELATION BETWEEN FOOD AND MASTICATORY PATTERNS	26
4.	MISCELLANEOUS OBSERVATIONS	27
	<u>KINEMATIC CRITERIA FOR THE TOTAL AND FUNCTIONAL MOBILITY</u> <u>OF THE DENTULOUS MANDIBLE AS ESTABLISHED FROM AVAILABLE</u> <u>LITERATURE</u>	31
	<u>KINEMATIC CRITERIA FOR THE TOTAL MANDIBULAR MOBILITY</u>	31
1.	Criteria of Envelope of Total Movement Space in the Horizontal Plane	31
2.	Criteria of Envelope of Total Movement Space in the Sagittal Plane	32
3.	Criteria of Envelope of Total Movement Space in the Frontal Plane	33
	<u>KINEMATIC CRITERIA OF THE DENTULOUS MASTICATORY FUNCTION</u>	34
	<u>SECTION III: EXPERIMENTS, SUBJECTS, MATERIALS AND METHODS</u>	37
	EXPERIMENTS	38
	SUBJECTS	38
	MATERIALS	39
	METHODS	39
	<u>SECTION IV: MANDIBULOGRAPHY</u>	40
1.	GRAPHIC METHODS	41
2.	STILL AND CINEPHOTOGRAPHIC TECHNIQUES	42
3.	RADIOGRAPHIC AND CINEFLUOGRAPHIC METHODS	43
	<u>POSITIONAL LOCATION IN SPACE</u>	44
	<u>STUDY OF POSITIONS AND MOVEMENTS OF THE JAW</u>	44
	<u>PHOTO-ELECTRIC MANDIBULOGRAPH</u>	46
1.	The Photocell Frame	48
2.	The Head Frame	48
3.	Mandibular Light Assembly	49
4.	Remounting Guide	50
5.	Recording Devices	50
	<u>ORIENTATION, CALIBRATION AND STANDARDISATION OF THE</u> <u>PHOTOCELL FRAME</u>	52
1.	Establishment of a Central Vertical Axis of Maximal Three-Dimensional Linearity	53

	<u>Page</u>
2. Determination of the Dimensions of Space Monitored with Acceptable Linearity	55
3. Standardization of the Light - Photocell Frame Positional Relationship with the Head	58
<u>RECORDING PROCEDURE</u>	61
<u>PRE-RECORDING PREPARATION</u>	61
1. Dentulous Subject	61
2. Edentulous Subjects	62
<u>RECORDING SESSION PREPARATIONS</u>	66
1. Fixation of the Head-Frame	67
2. Fixation and Alignment of the Photocell Frame	67
3. Calibration of the Apparatus in Individual Subjects	68
<u>MANDIBULOGRAPH RECORDS</u>	69
<u>SECTION V: THE ENVELOPE OF TOTAL JAW POINT MOTION IN THE DENTULOUS AND EDENTULOUS SUBJECTS</u>	72
<u>METHOD</u>	
Method of Development of the Border Movement Paths and the Outline Form of the Envelope of Total Movement Space	75
Definition of the Objectives for the Exercises	75
<u>OBSERVATIONS OF THE ENVELOPE OF TOTAL JAW POINT MOTION IN THE DENTULOUS SUBJECT 'A'</u>	77
Key to the Figs. No. 25, 26, 27	79
<u>ASSESSMENTS</u>	79
<u>GENERAL CHARACTERISTICS OF THE TOTAL ENVELOPE OF MOTION</u>	79
1. HORIZONTAL ELEVATION	79
2. SAGITTAL ELEVATION	82
3. FRONTAL ELEVATION	84
<u>CUSPAL GUIDANCE ANGLES</u>	85
<u>THE ENVELOPE OF JAW POINT MOTION IN EDENTULOUS SUBJECTS</u>	87
1. THE HORIZONTAL ELEVATION OF THE TOTAL ENVELOPE OF MOTION IN THE EDENTULOUS SUBJECTS	88

	<u>Page</u>
2. THE SAGITTAL ELEVATION OF THE TOTAL ENVELOPE OF MOTION IN THE EDENTULOUS SUBJECTS	91
3. THE FRONTAL ELEVATION OF THE TOTAL ENVELOPE OF MOTION IN THE EDENTULOUS SUBJECTS	93
<u>DISCUSSION AND SUMMARY</u>	93
<u>SECTION VI: SIMULATED CHEWING MOVEMENTS IN DENTULOUS AND EDENTULOUS SUBJECTS</u>	98
<u>METHOD</u>	
I. POSITIONAL RELATIONSHIP OF THE OPENING AND CLOSING STROKES	100
II. ROLE PLAYED BY CUSPAL GUIDANCE	105
III. ENVELOPE OF MOVEMENT SPACE USED DURING SIMULATED CHEWING SEQUENCES	105
<u>SIMULATED CHEWING MOVEMENTS IN THE DENTULOUS SUBJECT 'A'</u>	106
I. POSITIONAL RELATIONSHIP OF THE OPENING AND CLOSING STROKES	106
1. Simulated ad lib. Chewing in the Dentulous Subject 'A'	106
2. Simulated Chewing Movements on the Right and Left Side in the Dentulous Subject 'A'	108
II. CUSPAL GUIDANCE CHARACTERISTICS IN DENTULOUS SUBJECT 'A'	112
1. Simulated ad lib. Chewing	112
2. Simulated Chewing on the Right and Left Sides	113
III. THE ENVELOPE OF SIMULATED CHEWING MOVEMENTS IN THE DENTULOUS SUBJECT 'A'	114
1. Envelope of Motion During Simulated ad lib. Chewing Movements in the Dentulous Subject 'A'	114
2. Envelope of Motion During Simulated Chewing on the Right Side in Dentulous Subject 'A'	116
3. Envelope of Motion During Simulated Chewing Movements on the Left Side in Dentulous Subject 'A'	117
<u>SUMMARY AND DISCUSSION</u>	118

	<u>Page</u>
<u>SIMULATED CHEWING MOVEMENTS IN THE EDENTULOUS SUBJECTS</u>	121
I. POSITIONAL RELATIONSHIPS OF THE OPENING AND CLOSING STROKES IN EDENTULOUS SUBJECTS B, C, D AND E	121
1. Simulated ad lib. Chewing Exercise	121
2. Simulated Chewing on the Right and Left Sides	123
II. ROLE PLAYED BY CUSPAL GUIDANCE DURING SIMULATED CHEWING MOVEMENTS IN EDENTULOUS SUBJECTS B, C, D AND E	126
III. ENVELOPE OF MOVEMENT SPACE USED DURING SIMULATED CHEWING EXERCISES IN EDENTULOUS SUBJECTS B, C, D AND E	128
<u>SUMMARY AND DISCUSSION</u>	130
<u>SECTION VII: MASTICATORY MOVEMENTS IN DENTULOUS AND EDENTULOUS SUBJECTS</u>	135
<u>METHOD OF RECORDING</u>	136
1. Confirmation of the Intercuspal Position	136
2. Placement of Food	136
3. Mastication of Food	136
4. Foods Used	137
5. Masticatory Exercises	138
<u>METHODS OF ASSESSMENT</u>	139
1. Visual Observations During Performance	139
2. Detailed Assessment of the Masticatory Cycles	139
I. POSITIONAL RELATIONSHIP OF THE OPENING AND CLOSING STROKES	140
1. Calculation of the Positional Preference Index	142
2. Interpretation of Positional Preference Index	145
II. ROLE OF CUSPAL GUIDANCE DURING MASTICATORY MOVEMENTS	147
III. ENVELOPE OF MOVEMENT SPACE USED	149
<u>OBSERVATIONS</u>	149
<u>VISUAL OBSERVATIONS DURING PERFORMANCE</u>	149
<u>DETAILED ASSESSMENT OF THE MASTICATORY CYCLES</u>	152
I. POSITIONAL RELATIONSHIPS OF THE OPENING AND CLOSING STROKES DURING MASTICATION	152

1.	Total Sample Performances in the Dentulous and Edentulous Subjects	152
2.	Variations of Positional Relationships of the Opening and Closing Strokes in Respect to the Three Phases of Mastication in the Dentulous and Edentulous Subjects	156
3.	Variations of Positional Relationships of the Opening and Closing Strokes Related to Variations of Consistency and Quantity of Food	161
4.	Positional Preference Index	161
II.	THE ROLE OF CUSPAL GUIDANCE DURING MASTICATION IN THE DENTULOUS AND EDENTULOUS SUBJECTS	164
1.	The Incidence of Cuspal Guidance	165
2.	Variations of the Incidence of Cuspal Guidance During the Three Phases of Mastication	166
3.	Types of Cuspal Guidance	166
4.	Variations of Cuspal Guidance in Respect to Variations of Food Consistencies	168
III.	ENVELOPE OF MOVEMENT SPACE USED DURING MASTICATION	172
1.	General Characteristics	172
2.	Location of the Intercuspal Position in Relation to the Envelope of Movement Space Used During ad lib. Mastication	174
	<u>SECTION VIII: GENERAL DISCUSSION</u>	176
	<u>METHODS EMPLOYED</u>	178
1.	Construction of Complete Dentures	178
2.	Photo-Electric Mandibulography	179
3.	The Points and Axes of Reference	180
4.	Recording of the Border Movement Paths and Positions	181
5.	Denture Base Movements Due to Resilience of Soft Tissues	181
	<u>ENVELOPE OF TOTAL MOVEMENT SPACE IN THE DENTULOUS AND EDENTULOUS SUBJECTS</u>	182
	<u>THE POINTS OF DIFFERENCE IN THE DENTULOUS AND EDENTULOUS ENVELOPES OF TOTAL MOVEMENT SPACE</u>	183

<u>SIMULATED CHEWING MOVEMENTS IN THE DENTULOUS AND EDENTULOUS</u> <u>SUBJECTS</u>	185
<u>MASTICATORY MOVEMENTS IN THE DENTULOUS AND EDENTULOUS SUBJECTS</u>	191
I. POSITIONAL RELATIONSHIP OF THE OPENING AND CLOSING STROKES	191
1. Points of Initiation and Termination of Simulated Chewing and Masticatory Movements	191
2. Positional Preference of Simulated Chewing Movements in the Dentulous and Edentulous Subjects	194
3. Positional Preference of Masticatory Cycles in the Envelope of Total Movement Space in the Dentulous and Edentulous Subjects	195
4. Conservative Masticatory Kinematic Performance	199
5. Non-Conservative Masticatory Kinematic Performance	200
II. ROLE OF CUSPAL GUIDANCE	202
1. Incidence of Cuspal Guidance	204
2. Location of Cuspal Guidance	204
3. Direction of Motion During Cuspal Guidance	205
4. Types of Cuspal Guidance	206
5. Functions of the Two Types of Cuspal Guidance	207
III. ENVELOPE OF MOVEMENT SPACE USED DURING MASTICATION	211
<u>SECTION IX: CONCLUSIONS</u>	215
<u>BIBLIOGRAPHY</u>	

SECTION I

GENERAL INTRODUCTION

GENERAL INTRODUCTION

Over the years, interest in the function of Mastication in humans has resulted in a vast accumulation of knowledge. Many different aspects of the function have been investigated, such as:

1. Development of the Masticatory habit. (8)
2. Neuromuscular mechanism of mastication. (26,28,29,48)
3. Brain mechanism of mastication. (26,28,29,48)
4. Sensory and proprioceptive control for mastication. (28,29,48,58)
5. Masticatory performance and efficiency. (66,67,27)
6. Mastication as related to digestion. (75)
7. Kinematics of mastication. (57,73,77,1,2,14)
8. Kinetics of mastication. (32,1,14)

Many observations in respect to these aspects and phenomena have been made in dentulous subjects and, as a generality, it has been assumed that the phenomena would be similar in edentulous subjects. Although this may be true for some of the aspects, such as basic neuromuscular physiology, the brain mechanism or the fact that the mandible moves up and down during mastication, the loss of teeth produces such basic differences between the dentulous and edentulous states of the masticatory apparatus, particularly in the mechanics involved, that complete similarity of performance characteristics in the two states is questionable.

The very fact that the teeth are absent in the edentulous state means a difference in the configuration of the two components of the masticatory apparatus. There are changes in the shape of the mandible, the condylar angles become wider, (54) there are changes in the maxillomandibular relationship, (8,65) particularly in the

vertical dimension (60,61,59,23) and there are changes in the oral space. One of the most discussed issues in the dental profession is how to re-establish the pre-extraction maxillomandibular relationship and whether or not the restored edentulous masticatory apparatus will be able to operate as efficiently as it did in the dentulous state. The fact that these problems and controversies exist indicates that there are differences in performances in the two states, and that these should be recognised and considered during the restorative procedures.

The term "Edentulous State" in itself has a very wide range of usage. Whereas generally it is used to express a complete absence of teeth from the masticatory apparatus it is also used to describe absence of teeth from a particular jaw, from a particular segment of a jaw or absence of a single tooth from an arch. There is a possibility that each of these variations of the edentulous state may, to some degree, influence the functions of the masticatory apparatus.

It is beyond the scope of a single investigation to cover all aspects of mastication as affected by the variations of the edentulous state. So, for reasons of feasibility, kinematics (i.e. the motion considered abstractly without any relation or reference to the force or mass involved, (68)) of the completely edentulous masticatory apparatus was selected for this study.*

* The thesis forms the first part of a more involved investigation in which kinetics (i.e. motion in relation to the forces responsible for it (68)) of the masticatory apparatus will be examined. Masticatory movements and EMG activity of the muscles of mastication were recorded simultaneously, with the objective of correlating one to the other. The masticatory

One method of study could be examination of the masticatory function of a group of subjects with complete dentitions at regular intervals over the years as they progress to and through, the edentulous state. The impracticability of this line of procedure is evident, but, even if this method could be followed, there would still be many individual variable factors, such as conditions of general health and disease, changing psychological and socio-economic circumstances, the sequence in which the teeth were lost, and the manner in which the dental apparatus, and the particular individual as a whole, would react to this loss. These variables would make a comparison between the states of the masticatory apparatus, in the same subject, of little significance.

So it was decided to establish criteria for the function of mastication in the dentulous state from reported literature, confirm these with the help of the equipment and methods planned for this present investigation and then compare the results with similar observations made in the edentulous subjects.

The investigation was designed to examine the following aspects related to kinematics of mandibular motion:

1. The shape and form of the total movement space in the dentulous and edentulous subjects.
2. Variations of characteristics of the masticatory cycle

movements examined in the present thesis can each be examined in respect to the muscles involved in their execution.

Example Illustrations are shown in Appendix

in the dentulous and edentulous subjects.

3. The role of cuspal guidance during mastication in the dentulous and edentulous subjects.
4. Variations of characteristics of the functional movement space used during mastication by the two types of subjects.
5. Variations of characteristics of functional movements in respect to variations of food consistencies in the dentulous and edentulous subjects.
6. Variations of functional movements during the early, middle and terminal parts of the masticatory sequence in the two types of subjects.

The investigation comprised the recording and analysing of a Photoelectric Mandibulograph ⁽¹⁷⁾ - an electronic motion analyser developed for the purpose.

SECTION II

REVIEW OF THE LITERATURE

REVIEW OF THE LITERATURE

SOME OF THE ANATOMIC CONSIDERATIONS OF THE MASTICATORY APPARATUS:

The anatomic configurations of the masticatory apparatus are quite extensively documented and available in the text books on the subject, yet some aspects and concepts relative to the present investigation need to be presented here to facilitate appreciation of the problem.

1. COMPONENTS OF THE MASTICATORY APPARATUS:

The primary masticatory apparatus consists of a fixed base, formed by the two maxillae and the base of the skull, and a movable component in the form of the mandible, the latter being suspended from the former by muscles and ligaments and related to it through the two temporomandibular joints.

Temporomandibular Joints:

Located at the extreme distal ends of the movable component, each of the two joints has two compartments. The articular disc forms the partition creating a disco-temporal or the upper compartment and a disco-condylar or the lower compartment.

(i) Disco-Temporal Compartment:

According to Sicher ⁽⁵⁴⁾, the disco-temporal, or the upper compartment of the joint, allows a translatory movement of the movable component in relation to the fixed base. The articular disc and the condyle slide down and forwards along the posterior slope and the flattening summit of the articular eminence. The movement is dependent

upon the configuration of the slope of the eminence, and may be executed symmetrically with both condyles and discs moving in the same direction or unilaterally with one disc and condyle staying in the same place and rotating around a roughly vertical axis, or moving in a direction opposite to the other. (54,38,39)

(ii) Disco-Condylar Compartment:

Again according to Sicher ⁽⁵⁴⁾, the disco-condylar, or the lower compartments of the two joints together represent a hinge joint. The axis of the hinge running approximately through the centres of the two condyles makes the hinge movements theoretically symmetrical.

It is generally accepted that a simultaneous involvement of both the compartments of the joints produces the usual normal masticatory movements. (54,38,39) Each condyle is capable of rotating around a transverse axis and, at the same time, performing a translatory forward, downward and sideways movement and, in some excursions, a limited rotation around a vertical axis. The combination of the two articulations on either side, gives the mandible a freedom of movement in all directions, ^(54,6) but in a limited space, dictated by the temporomandibular ligaments and tooth contact.

According to Posselt ⁽³⁸⁾ and Atwood ⁽⁶⁾ when the teeth are in occlusion, the condyles rest

approximately midway between the anterior and posterior limits of the fossae. This is also confirmed by radiographic examination (38,6) in living subjects. If the mandible is forced further distally manually, the space between the distal surface of the head of the condyle and the posterior limit of the articular fossa may decrease slightly. According to Posselt (38,39) further distal displacement of the condyle is prevented by the temporomandibular ligament. According to Atwood (6), this distal displacement is prevented initially by muscles, the ligaments coming to play only in extreme conditions. From this forced distal position, the mandible is incapable of performing any lateral movements.

2. POSITIONAL RELATIONSHIPS OF THE TWO COMPONENTS OF THE MASTICATORY APPARATUS:

For a proper understanding of the functional and non-functional movements of the mandible, it is essential that such positions that show a degree of constancy in occurrence and reproducibility on the borders of and within the envelope of motion should be defined and recognised. The various excursions of the mandible can then be described and compared to these basic positions. The mandible takes up many such positional relationships to the maxilla, some with, and some without contact with the opposing teeth.

POSTURAL POSITION

The position has been described by many synonyms, (e.g. Rest Position, Physiologic Rest Position, Endogenous Postural Position). It is generally considered reproducible

and is used as a position of reference.

Thompson (62) defines this as a position dependent entirely on the neuromuscular physiology. According to him, all functional movements begin and terminate in this position. He states that there is a 2-3 mm. inter-occlusal space, which, though apparent only in the vertical dimension, "exists in all planes, antero-posterior, lateral, as well as oblique."

Ballard (8), in agreement with Thompson, (62) considers this position as something built into the system. He refers to it as an endogenous posture and defines it as a position of the mandible relative to the maxilla in which all the muscles capable of acting upon it are relaxed, i.e., show no detectable electrical activity. Since the muscles are symmetrically inactive, he contends that the condyles are fully, but not forcefully, retracted. Along with many others, (39,55,10) he shares Thompson's thoughts on constancy of this posture throughout life, but also admits that short-term variables act throughout the day and make slight alterations in the postural position of the mandible.

TOOTH CONTACT POSITIONS:

When the mandible closes from the postural position, the freeway space is eliminated and the opposing teeth can come into contact in various tooth contact positions. Depending upon the functional exercise involved, the tooth contact positions differ from one another. Brill et.al. (12) describe three possibilities and have proposed specific names for these positions: (i) Ligamentous Position, (ii) Muscular Position and (iii) Tooth Position.

1. Ligamentous Position:

It is the extreme retruded border position of the mandible, such that the condyles cannot be moved further posteriorly without loss of lateral mobility. As to what structures maintain this extreme border position and prevent further distal displacement is a very controversial issue.

Atwood ⁽⁶⁾, in trying to analyse the problem, lists the various possibilities as:

- a) soft tissues posterior to the condyles,
- b) bony contact with the posterior glenoid process,
- c) ligaments,
- d) muscles.

He rules out soft tissues and bone on the grounds of convincing histologic, anatomic and radiographic evidence against them. He recognises the similarity of arguments ^(38,39,11) presented in favour of both muscles and ligaments and proposes that possibly their functions in this direction coincide with one another, or the muscles may act first, with the ligaments held in reserve as a final check in the protection of structures posterior to the mandible.

The mandible may assume this position either by an active movement by the subject himself or passively through the assistance of an operator. ^(38,12,36,21)

Only during mastication, and only for a short while during the chewing of hardest foods, does the mandible go into this position. ^(12,49) According to Posselt ⁽³⁸⁾, the position is represented by the apex of the gothic arch tracing. He states "Under practical conditions, the arrow point is

generally recorded actively. Between the position thus obtained and the one achieved by means of passive arrow point tracing, differences of less than 0.1 mm. were ascertained. I think that such a difference can be considered of no practical importance." (38)

The Ligamentous position is not a neutral position, for it is maintained by a contraction of the posterior and middle fibres of the temporal muscle and the mandible must move some distance anteriorly from this position before it is possible to record minimal electromyographic activity. (39,44)

Other synonyms for this position are: centric relation, centric position, retruded position and posterior border position. It is also known as the Hinge Position, because a posterior pure hinge open and close movement can be performed, throughout which the mandible is in arrow point position. (38)

2. Muscular Position:

It is the tooth contact position of the mandible as it closes from the postural position in a habitual closing movement, (38) and is dictated by the reflex muscle pattern. (12) It is also referred to by various synonyms, (e.g. centric position and, centric relation). (49)

3. Tooth Position:

It is also known as Maximally Intercusped position, Cuspal Position and Centric occlusion position. It is a state of occlusion arrived at during a firm

closure of the jaws. The cusps and their inclines guide the mandible into final closure, so that there is maximal intercuspation. Depending upon the manner of cuspal engagement, this position may be anterior or posterior to the muscular position or may even coincide with it. According to Posselt (38), in only about 12 percent of adults does the tooth position coincide with the ligamentous position and as such, becomes a border position. In others, it may be located up to about 1.0 mm. anterior to the ligamentous position. In about 40 percent of adults, the tooth position coincides with the muscular position and, in others, it may be located anteriorly or posteriorly to the muscular position. (38,12)

In a very few subjects, all three tooth contact positions may coincide. (12)

BRACING POSITION:

Sheppard (50) has described this as a functional position. According to him, this position is dictated by the entire masticatory musculature. It is independent of the temporomandibular joint anatomy as well as of the teeth. It is possible for bracing to take place in areas of nonocclusion of the opposing teeth and even in edentulous cases without dentures. It appears to be a position of the mandible that is a resultant of a balanced isometric contraction of all the masticatory muscles. Sheppard (50) describes it as a survival mechanism by which the maxillomandibular complex braces itself to provide a stable base for other functions such as swallowing of food. It differs from the muscular position in that the latter is a function of the elevator muscles only.

MANDIBULAR MOVEMENTS

The mandibular movements can be classified as (i) Controlled and (ii) Natural.

CONTROLLED MOVEMENTS:

The term describes all movements which the jaw can perform other than when involved in actual natural function. These are:

1. Border Movements: These can be performed under instructions and are the limits of the mandible's capacity for motion.
2. Isolated Movements: These are opening, closing and lateral movements performed under instruction from specified positions of the mandible in specified directions.
3. Simulated Movements: These are empty chewing or empty swallowing movements, i.e., the element of food is missing.

NATURAL MOVEMENTS:

The term describes all movements performed by the jaw during normal function, and these movements are:

1. Masticatory Movements.
2. Movements during swallowing of food, fluids, or saliva.
3. Movements during speech and other functional involvements of the mandibulo-maxillary complex.

The scope of this present investigation will be limited to the masticatory movements.

The major difference between the controlled and natural movement is that contributed by the absence or presence of food. The function of mastication can be said to be a physiological phenomenon initiated by the food, for the food, and on the food. The function is completely under the control of sensory feed-back from extrareceptors as well as proprioceptors located in a very wide

distribution, involving many senses and sensory areas, but reacting primarily to food. (28,29,48) When the food factor is taken out, the entire feed-back system is changed. It is understandable that the consequent movements in the masticatory apparatus will be different from those performed in the presence of food.

MANDIBULAR CAPACITY OF MOTION AND MOVEMENT SPACE:

Although the interest in three-dimensional study of the mandibular movements is recent, much work has been done previously in two dimensional studies along the sagittal plane. (57,9) Generally, the movements of incision inferius have been examined and interpreted to give information about the positions of the jaw. The techniques used varied from graphical methods to photographic, cinematographic, optical, and even radiographic examinations of live subjects or postmortem preparations.

Posselt (38) described the mandibular capacity for movement three-dimensionally as movement areas along the sagittal, horizontal and frontal planes at different levels of posterior jaw opening. His observations were:

1. The border movements greatly exceed the habitual and functional mandibular movements. They differ from subject to subject, both in horizontal as well as sagittal planes,
2. In the horizontal plane:
 - a) The movement area is romboidal in shape.
 - b) The movement area is limited laterally by two acute angles, and anteriorly and posteriorly by two obtuse angles.
 - c) The size of movement area differs with different degrees of posterior bite opening, generally ending in a point at maximal opening.

- d) The sides of the posterior obtuse angle which represents the retruded lateral movements are straight or almost straight lines. This indicates a rigid restraint on these movements by the ligaments of the joints.
 - e) The sides of the anterior obtuse angle representing the paths of the protruded lateral movements are generally convex anteriorly.
 - f) The point of the distal obtuse angle represents the most retruded position the mandible can attain either passively or actively for that particular posterior bite opening.
3. In the sagittal plane:
- a) The movement area is bounded posteriorly by the retruded path of opening or closing with a restrained condyle, anteriorly by the protruded opening and closing paths and rostrally by the protrusive glide from the retruded to the most protruded position of the condyle.
 - b) The retruded opening and closing paths represent a hinge movement from the occlusal position to 19.2 ± 1.9 mm. posterior bite opening, the hinge axis being located in the condyles. After some training, this hinge movement can be performed actively by the subject himself. When the opening exceeds 25.8 ± 2.2 mm. there is a forward and downward shift of the condyle even when attempts are made to passively hold the condyle in the retracted position. This shift of the condyle produces an obtuse angle between the two parts of the retruded opening and closing path. The point of the angle represents the point where the protrusive movement of the condyle starts, thus causing a change

in the location of the axis of movement. The angle disappears when the lateral ligaments are cut, showing that the retruded border position and movement are under the guidance of ligaments. The axis of the caudal part of the retruded open and close movement path is located in the region of the site of attachment of the temporomandibular ligament.

- c) The protruded open and close path: In the maximally protruded contact position of the jaw, the condyles are not maximally protruded. The protrusion of the condyles progressively increases as the opening progresses. The condyles are maximally protracted when the mandible is at, or near, maximal opening.
- d) Protrusive glide: Due to occlusal contacts, the path of movement is irregular. It joins the four important positions of the maxillomandibular relationship, i.e.;
 - i. Retruded contact position determined by ligaments.
 - ii. Habitual contact or muscular position, determined by muscles.
 - iii. Intercuspal position determined by teeth.
 - iv. Protruded contact position determined by ligaments.

The above observations by Posselt ⁽³⁸⁾ confirm the works of Luce, ⁽⁵⁷⁾ Bennett ⁽⁹⁾ Gysi, Ficher, April et Saizar and are, in turn, generally confirmed by Schweitzer, ^(43,44) Woelfel et.al. ⁽⁶³⁾ Ingervall, ^(21,22) Atwood, ⁽⁶⁾ Knap et.al. ⁽³⁰⁾ Nemoto, ⁽³⁵⁾.

There are some points of contention which can be summarised as:

Controversy of the Hinge Axis:

Schweitzer ⁽⁴⁴⁾ confirms Posselt's observation of the presence of a hinge axis position and further claims that this position is reached during normal function and more frequently so at the beginning of a chewing sequence, rather than at the end. Similarly, Brill et.al. ⁽¹²⁾ agree with Posselt and Schweitzer and explain that, as this position is controlled by ligaments, during closing strokes that involve forces of greater magnitude, the mandible approaches the hinge axis position for greater stability.

Atwood ⁽⁶⁾ admits the possibility of a hinge axis position, but believes it to be a non-functional strained relation, where the ligaments form the last line of defence against further distal displacement of the mandible.

Knap et.al. ⁽³⁰⁾ claim that there is no evidence of the retruded pure hinge movement and that there is very little forward glide from retruded contact position to intercuspal position. They consider the retruded contact position, described by Posselt and others, as an open mouth position and believe the slide from the "retruded contact" to intercuspal position to be part of the retruded closing stroke or the posterior border movement.

Sheppard ⁽⁵¹⁾ is also of the opinion that all mandibular movements are translatory in nature and that there is no condylar hinge axis during any movement, and that if any axis exists for the open and close movements, it is somewhere in the ramus and not in the condylar heads.

Nemoto et.al. ⁽³⁵⁾ also have similar views. There is

so much controversy about this issue that it warrants further investigation.

DIMENSIONS OF THE TOTAL MOVEMENT SPACE:

Posselt (38) has assessed the average maximal opening at the inferior incisor point at 43.4 ± 4.6 mm., his figures being taken from profile radiographs.

Nemoto et.al. (35) aligned the sagittal outline form of the movement space to a horizontal parallel to Camper's plane and passing through the point representing the intercuspal position. From this horizontal they measured the perpendicular distances to the various points on the outline form representing the various positions of the inferior incisor point during the border movements. Their measurements are as under:

1. Maximal opening from the intercuspal position: 43.4 mm.
2. Posterior position of the incisor point at maximal opening in the horizontal plane in relation to the intercuspal position: 15.0 mm.
3. Length of the posterior border opening rostral to the angle (part of the retruded opening path referred to by Posselt as hinge opening) : 26.7 mm.
4. Maximal protrusion from intercuspal position: 9.2 mm.
5. Lateral border excursions: Right: 12.3 mm. Left: 14.2 mm.
6. Lateral incisal path angle (Gothic arch angle) : 120.0° .

CAPACITY OF MANDIBULAR MOTION AND MOVEMENT SPACE IN THE

EDENTULOUS STATE:

Most of the above observations refer only to the dentulous state of the Masticatory Apparatus. There is very little comparable information on the Edentulous State.

Kurth ⁽³¹⁾ attempted to investigate opening and closing movements in edentulous subjects, but the appliances used were too heavy and caused a displacement of the dentures and the base plate. He was able to examine the gothic arch tracings and reported their similarity to those obtained in the dentulous state. Posselt's ⁽³⁸⁾ examination of one edentulous postmortem preparation was quite incidental, he also suggests that the movement areas are similar to those in the living dentulous subjects.

Although the object of this present investigation is to examine the masticatory function in the edentulous state, it was considered necessary to examine the capacity of mandibular motion and determine characteristics of the envelope of total movement space in the edentulous subjects, to enable a comparison to be made with the space used during mastication.

MASTICATORY MOVEMENTS

Various aspects of masticatory movement have been examined, though generally, only in the dentulous subjects. The available relevant literature is presented under the following headings:

1. Shape and form of the masticatory cycle.
2. Functional phases of the masticatory cycles.
3. Relation between food and masticatory movements.
4. Miscellaneous observations.

1. SHAPE AND FORM OF THE MASTICATORY CYCLE:

Generally, the movements of a point located between the lower central incisors during mastication have been monitored and interpreted as masticatory movements but other points, such as mental protuberance, ^(18,4) heads of the condyles, ⁽¹⁹⁾ posterior occlusal surfaces and the side of the face ⁽⁴²⁾

have also been used.

Hildebrand (20) examined the masticatory movements of the teeth at the incisor point. In the frontal view, he compared the movements to the median plane and in the sagittal view, to an arbitrary curve representing a hinge movement of the mandible with the axis located at the highest point on the radiographic profile of the condyle. His observations can be tabulated as under:

Frontal Plane:

- (i) The opening stroke starts with a gliding movement between the teeth.
- (ii) Reaches maximal opening at about one third the distance of the total maximal mouth opening.
- (iii) The mandible then moves obliquely to the preferred side during the closing stroke, shows further lateral deviation on the preferred side, and
- (iv) Reaches the "occlusal position" after occlusal gliding.

Sagittal Plane:

- (i) Both the opening and closing strokes pass anteriorly to the hinge movement curve.
- (ii) The closing stroke has no definite positional relationship to the opening stroke, one may pass anteriorly or posteriorly to the other.
- (iii) The closing stroke terminates after slight gliding.

Hildebrand (20) observed that there is no difference in the shape and form between the crushing and grinding strokes.

Schweitzer (43,44) examined the masticatory cycles at the incisal point and made the following observations:

- (i) In the sagittal view, when chewing food, the opening stroke was usually posterior to the closing stroke at the start of a sequence, but as the mastication progressed, this relationship became indefinite.
- (ii) There is evidence of rubbing together of teeth both in mediolateral as well as anteroposterior directions.
- (iii) The maximally open position of the masticatory cycles may be pointed or rounded.
- (iv) The posterior "borderline" or hinge closure path is not reached during functional chewing.
- (v) Often, the individual chewing cycles end below the level of the intercuspal position, indicating presence of food between the teeth.
- (vi) The chewing cycle in the sagittal plane is much smaller than the extreme envelope of movement.
- (vii) The individual chewing cycles become smaller as the food is broken up. The amplitude increases with the movements of the tongue which, at intervals, gathers up food and reloads the occlusal surfaces; subsequently the cycles become smaller again.
- (viii) In the frontal view, observations similar to the sagittal view were made.

Ahlgren ⁽¹⁾ observed the masticatory movements at the incisal point in school age children. His observations are as below:

- (i) Pattern of masticatory movements: There were considerable inter- and intra-individual variations yet there were recognisable characteristics for each individual subject and for each side of mastication.
- (ii) The masticatory cycles could be grouped into

seven types:

- Type I. Opening phase in the median plane and an ipsilateral closing phase.
- Type II. Open phase going to the contralateral ending on the ipsi-lateral side and a closing phase on the ipsi-lateral side, lateral to the opening phase.
- Type III. Opening phase with a direct ipsi-lateral movement and a closing phase lateral to the opening phase. There may be crossing of the paths of movement.
- Type IV. Opening and closing phases along the median plane (chopping masticatory stroke)
- Type V. Opening phase ipsilateral and closing phase medial to the opening phase. Crossing of paths of movement may occur.
- Type VI. Opening phase on the contra-lateral side and closing phase medial to the opening phase. Crossing of paths of movement may occur.
- Type VII. Opening and closing phases without any consistent patterns. There may be crossing of paths of movement.

- (iii) The movement patterns changed with different foods in most subjects.
- (iv) The average opening and abduction of the mandible from intercuspal position were 19.1 mm. and 5.3 mm. respectively.
- (v) Tooth contacts during masticatory movements:
During gum chewing, tooth contacts occurred in 95

percent of all chewing cycles. In some subjects, there were no tooth contacts at all, while in others, contacts occurred in every cycle. The contacts took place in the intercuspal position.

In carrot-chewing, tooth contacts occurred in 84 percent of all chewing cycles. In some subjects, there were contacts in every cycle, while in others, the contacts occurred in up to 40 percent of cycles. The contacts took place in the intercuspal position.

Closing gliding contacts occurred in 62 percent of cycles during gum-chewing, and in 54 percent of cycles during carrot-chewing. Opening gliding contacts occurred in 74 percent of total cycles during gum-chewing, and 49 percent of cycles in carrot-chewing.

Gibbs et.al. ⁽¹⁶⁾ observed mastication at the incisal point and also at the condyles. Their observations were:

- (i) The terminal functional movements on the food side are generally from the direction of the food side towards the opposite side.
- (ii) The terminal position of the central incisors shows good repeatability during closure in subjects with normal occlusion. The central incisors return to the same position.
- (iii) Many of the closing paths are lateral to the medial opening paths.
- (iv) Irregular, self crossing motions are typical for subjects with malocclusion. The closing positions in such subjects are not as repeatable.

- (v) Many closing strokes pass distally to the opening strokes.
- (vi) The paths of motion of the central incisors during mastication are dependent more on the individual subject than the food being chewed.

2. FUNCTIONAL PHASES OF THE MASTICATORY CYCLES:

Murphy ⁽³³⁾ made cinematographic observations of masticatory performance by an Australian Aboriginal girl. She was selected because her masticatory habits were considered not yet influenced by the restraint of society and etiquette and possibly even the food consumed was also not refined. Murphy ⁽³³⁾ divided the masticatory cycle into various phases and described their characteristics as follows:

1. Preparatory Phase:

The mandible deviates to the non-food side and descends. The descent is slow initially, but accelerates rapidly. There is a change in the direction of descent towards the food side. The descent is just enough to grasp the food. There is no "free ascent" prior to contact with the food.

2. Contact with the Food Bolus:

As the resistance of food is encountered, the jaw slows down, and may even come to a halt.

3. Crushing Phase:

The mandible accelerates in its ascent. Deviation towards the food-side continues and reaches its maximum. Without pause, there is a change of direction and the jaw moves towards the median

plane. The mandible slows down as the food resistance increases. The crushing phase ends some distance from the intercuspal position.

4. Tooth Contact Phase:

This point is indicated by a slight change in the direction of motion which is constant in its occurrence.

5. The Grinding Phase:

The recording point moves upwards and medially along a constant slope leading into centric occlusion.

6. Centric Occlusion Phase:

The recording point stops at the centric occlusion before commencing the next cycle.

3. RELATION BETWEEN FOOD AND MASTICATORY PATTERNS:

Brill et.al. ⁽¹²⁾ in their review "Mandibular Positions and Mandibular Movements" associate the patterns of masticatory movements with the physical characteristics of food. They classify the foods into three categories:

1. Liquid or Semi-Solid Foods: such as soups and custards. These are manipulated by tongue and hard palate and do not require much physical masticatory effort.
2. Solid Foods: that require heavy masticatory force such as raw fruits, vegetables, fibrous meats and hard breads.
3. Solid Foods: that flow and are comminuted by light masticatory force only.

Brill et.al. ⁽¹²⁾ divide a masticatory performance into

four stages:

- | | |
|-------------------------|------------------------------|
| (i) Incision, | (iii) Finer comminution, and |
| (ii) Power comminution, | (iv) Swallowing. |

(As this investigation is not involved in Incision and Swallowing, these stages are not included in this review.)

- (ii) Power comminution: The food is transferred to the molar area by the tongue and as such, it is located very close to the region of insertion of the elevator muscles; at the same time, there is a retraction of the mandible to the ligamentous position. Both these factors place the mandible in a position of greatest mechanical advantage, particularly if the temporomandibular joint is considered to be the fulcrum of jaw movement. Thus, the mandible is in a position to exercise greater stresses on the food without any traumatic effects upon the masticatory apparatus.
- (iii) Finer Comminution: In this third stage, the food particles are spread over a wider area reaching on to the premolars. The stroke at this time becomes more vertical and may not have a lateral component. There is a straight opening movement, then a deviation to the working side, followed by closure along an oblique path, directed a short distance lateral to the intercuspal position, while, on the balancing side, the condyle is placed anteriorly and slightly medially.

4. MISCELLANEOUS OBSERVATIONS:

Atkinson, ⁽⁴⁾ observed masticatory movements in patients after parts of the mandible had been resected. He indicates

that there is a loss of precise control of mandibular movements which can be attributed to disturbance of the proprioceptive mechanism on the affected side.

Niell, (34) points out that with advancing age changes in the alimentary mucosa result in impairment of digestion and absorption and make restoration of efficient mastication desirable.

Yurkstas and Emerson, (66) indicate that loss of masticatory efficiency in the edentulous subjects is not compensated by an increase in the number of masticatory strokes.

Shepherd, (52) and Atkinson and Shepherd, (7) observed variations in the masticatory patterns related to (i) the age of the subjects, (ii) type of dentition, whether natural or artificial, (iii) the personality of the subject, (iv) variations of form of the teeth, and (v) variations of consistency of food.

They observed that (i), the older subjects show a lesser total movement of the mandible. They consider this feature analogous to the older persons not lifting the feet so far when walking. (ii) Subjects with steep cusps and deep overbites display chopping or straight open close type of cycle. When the natural or artificial dentures allow a freedom of lateral movement, this is employed and shows up in the form of a small intercuspal glide. They claim a similarity between masticatory pattern before and after loss of teeth and replacement by dentures.

Sheppard (51) observed that masticatory movements tended

to be irregular and showed frequent antero-posterior and postero-anterior shifts.

Sheppard and Sheppard (53), discussing the persistence of masticatory movement patterns in edentulous subjects, indicate that there exists the possibility of a muscle memory or neuromuscular habit executing the customary cyclic masticatory movements, even in the absence of any functional need for such performance.

Wood (65) considers the recording of the maxillo-mandibular relation as one of the most indefinite procedures in the construction of dentures and states:

"A solid centric occlusion on delivery day could become a dental disappointment several weeks later".

He distinguishes the maxillomandibular relations as being either functional or non-functional and complains that the usual procedures for recording the relationship are non-functional. He advocates the use of a training denture in which adjustment and modifications of occlusal relationship can be accomplished while the subject is using the dentures. He does not define whether the failure of dentures is due to an anterior location or a forced retruded location of the recorded maxillomandibular occlusal relations.

Jankelson et.al. (25) made the following observations about mastication and masticatory cycles:

- (i) "A lateral movement of varying range often was evident at the terminal position of the stroke". They are doubtful whether this movement represents shearing action between cusps or is a shift in direction,

preparatory to the next opening stroke.

- (ii) Tooth contact during mastication is non-functional, due to the presence of food between the teeth at all times and only acts as a warning to terminate the stroke.
- (iii) The act of chewing is influenced by the constantly changing consistency, shape and size of the food (bolus), by its taste and even by the state of subject's emotions.

Woelfel et.al. (64) observed that the shape of the chewing cycles does not become more orbital, nor do they diminish in size as the bolus is reduced.

Ai and Ishiwara (3) observed that lateral gliding was seen in 60 percent of the cycles and that the inclinations of cusps appeared to have an influence on masticatory movements.

Schweitzer (44) observed that muscular effort is required to maintain the mandible in its border positions, both anteriorly as well as posteriorly.

Silverman (56) "The resultant biting point has been noted at the apex of the needle point tracing in some patients, anterior to the apex in others, and also posterior to the apex". He contends that further anterior location of the "biting point" is more common in subjects who have been edentulous for some time and have not been using dentures.

Campbell (13) indicates that where capsular ligaments are torn and weakened, there is bound to be resiliency in the joint and the condyle can move into distal positions.

He contends that this can happen in edentulous subjects.

KINEMATIC CRITERIA FOR THE TOTAL AND FUNCTIONAL MOBILITY OF THE
DENTULOUS MANDIBLE AS ESTABLISHED FROM AVAILABLE LITERATURE

The literature related to mandibular mobility has already been quoted in the preceding section. The movements of a point referred to as "Incision Inferior" or the "Jaw Point" and located on the median plane, between the mesio-incisal angles of the lower central incisors, rather than movements of the mandible, have generally been examined. The various features of the total and functional mandibular mobility, as manifested through the movements of the Jaw Point, are tabulated hereunder as Kinematic criteria for the Dentulous masticatory apparatus.

KINEMATIC CRITERIA FOR THE TOTAL MANDIBULAR MOBILITY:

The envelope of total mandibular motion is a three dimensional space which can be described in relation to three planes, i.e., the horizontal, sagittal and frontal planes. (12)

1. Criteria of Envelope of Total Movement Space in the
Horizontal Plane:

- i. The movement area at a particular vertical dimension is rhomboidal in shape. It is limited laterally by two acute angles and anteriorly and posteriorly by two obtuse angles. (38)
- ii. The posterior obtuse angle at the intercuspatated position measures, on an average, 120 degrees and is the gothic arch angle indicating the most retruded position and the border lateral excursions of the jaw point. (35) The lateral

and anterior angles have not been subjected to much investigation.

- iii. The size of the horizontal movement area differs with different degrees of posterior bite opening. It ends in a point at maximal opening. (38,39) The movement area at the level of the intercusped maxillomandibular relationship forms the superior boundary of the Total Movement Space. (38,39).
- iv. The average maximal protrusion from the intercuspal position has been measured as 9.2 mm. (35) The average lateral excursion has been measured as 12.2 mm. on the right side, and 14.2 mm. on the left side.
- v. It is controversial whether the intercuspal position is essentially a border position (30,35,51) or just incidentally so. (38,12)
- vi. It is controversial again, whether the ligamentous position, muscular position and the intercuspal positions, as defined by Brill et.al. (12) are three definite functional tooth contact stations, which may or may not coincide with one another or that the intercuspal position is the most retruded functional tooth contact station, contacts posterior to intercuspal position being considered as non-functional and at a greater vertical dimension than the intercuspal position. This latter school of thought also considers that all other functional tooth contacts occur anterior to the intercuspal position. (30,35)

2. Criteria of Envelope of Total Movement Space in the Sagittal Plane:

- i. It is bounded posteriorly by the retruded path

of opening or closing movement with a restrained condyle, anteriorly by the most protruded opening and closing path, and rostrally by the protrusive glide from the retruded to the most protruded position while occlusal contact is maintained.

- ii. It is controversial whether at any stage during function a pure hinge movement of the mandible with the axis located transversely through the heads of the two condyles takes place. (38,39,12) It is claimed that the initial 19.2 mm. of the retruded opening and closing path is a pure hinge movement with the axis located in the two condyles. When the movement exceeds 25.8 mm., protrusive shift of the condyles becomes an essential feature of the opening movement. (38,39,12) A contrary concept is that mandibular movement at all stages is translatory and a protrusive shift of the condyles is an essential feature of the opening movement, even at the commencement of the opening, and if any axis can be located for the retruded open and close movement, it is in the region of the ramus, rather than in the condylar heads. (51)
- iii. Average maximal opening from the intercuspal position has been measured as 43.4 ± 4.6 mm. (38,35) It is believed that maximal opening in its terminal part is a hinge movement.

3. Criteria of Envelope of Total Movement Space in the Frontal Plane:

It is shaped like a shield, the pointed centre of the upper border representing the intercuspal position. The concave sides of the upper border are formed by the contours of the cusps of the teeth gliding against

one another. The maximally open position also ends in a point. (43)

KINEMATIC CRITERIA OF THE DENTULOUS MASTICATORY FUNCTION:

1. Pattern of Masticatory Movements:

There are considerable inter- and intra-individual variations, yet there are recognisable characteristics for each individual subject and for each side of mastication. (1)

2. Pattern of Masticatory Stroke is Related to:

- (i) Physical characteristics of the bolus. (12,33,52,7,5)
- (ii) The stage of mastication of bolus. (12,33)
- (iii) Age of the subject. (52,7,3)
- (iv) Nature of dentition and type of occlusion. (52,7,5)
- (v) Personality and social status of the subject. (52,7,5)

3. Masticatory Stroke has been Described in Six Functional Phases:

- (i) Preparatory phase: Lasting 35.3 percent of total stroke time.
- (ii) Contact with food: This phase lasts for 11.8 percent of total stroke time after the initiation of the closing phase.
- (iii) Crushing phase: Lasts for 33.8 percent of total stroke time after contact with food has been made.
- (iv) Tooth contact phase: There is no loss of time during this phase. The mandible merely changes direction of movement.
- (v) Grinding phase: Lasts for 11.8 percent of total stroke time after tooth contact.

- (vi) Central occlusion phase: Lasts for 5.9 percent of total stroke time after the grinding phase.

The details of these phases have been described earlier (33) and are for an Australian Aboriginal subject. The total time for each cycle was measured from the initiation of one opening stroke to that of the next and was 1.45 sec. (33) Others have measured lesser time periods and have considered the total masticatory stroke as from the initiation of the opening stroke till the termination of the closing stroke. They have not taken into account the centric occlusion phase. (Timings of the masticatory cycle are not included in this investigation)

4. The Envelope of Masticatory Movements:

- (a) In all the three planes, i.e. horizontal, sagittal and frontal, the envelope of masticatory movement is much smaller than the total movement space. (43,44)
- (b) In the sagittal plane:
- i. The cycle becomes progressively narrower and smaller as mastication progresses and the food becomes more fluid. (37) The movements also become smoother. (52,7,5)
 - ii. The opening stroke is usually posterior to the closing stroke, particularly at the start of a chewing sequence. As the mastication progresses, this feature becomes indefinite. (43,44)
 - iii. The posterior border, or hinge closure path is not reached during mastication. (43,44)
- (c) In the frontal plane:
- i. The movement patterns can be grouped into seven types (1) (described earlier)

- ii. Gliding occlusal contacts occur in most of the chewing strokes and take place in all directions. (43,44,53,7,5)
- iii. The jaw may be guided to the intercuspal position or may reach it directly.
- iv. The individual cycle may end below the level of the intercuspal position, indicating presence of food between teeth.

SECTION III

EXPERIMENTS, SUBJECTS, MATERIALS AND METHODS

EXPERIMENTS, SUBJECTS, MATERIALS AND METHODS

EXPERIMENTS:

As the objective of this investigation is to establish kinematic criteria for the Masticatory functions in the Edentulous state of the Masticatory apparatus and their comparison to those of the Dentulous state, the following three experiments were carried out:

1. Recording and assessment of the total Envelope of Jaw Point Motion in the Dentulous and Edentulous subjects.
2. Recording and assessment of the Simulated Masticatory Movements in the Dentulous and Edentulous subjects.
3. Recording and assessment of the Masticatory Movements in the Dentulous and Edentulous subjects.

The details of each of these experiments will be discussed under the sections devoted to them.

SUBJECTS:

One dentulous and four edentulous subjects were used in the investigation.

Age was the primary factor considered in the selection of the subjects. As indicated earlier, the function of mastication is influenced by many variable factors that can be operative at any period of life. To minimize the confusion resulting from these variable factors, dentulous and edentulous subjects were

selected from the extreme age limits of the two states of the masticatory apparatus. The dentulous subject was an eighteen year old male with complete dentition, showing good intercuspatation, minimal occlusal attrition and no signs and symptoms of temporomandibular joint disturbances.

The edentulous subjects belonged to the sixty to sixty five years age group, with more than ten years of complete denture experience. With the exception of subject 'C', who had stopped using the lower denture five years ago after some repairs to the denture, the edentulous subjects had been using both of their previous upper and lower complete dentures for a period of more than five years. All the edentulous subjects presented oral conditions which promised good retention for artificial dentures. Subject 'D' had "bulbous" lower alveolar ridges, the crest being covered by comparatively thick and non-displaceable mucoperiostium. The soft tissue undercuts promised maximal mechanical retention, but poorer stress bearing qualities.

All the dentulous and edentulous subjects were in good condition of health and physique.

MATERIALS:

Peanuts, beefsteak and hard sugar drops were used to examine the masticatory movements and will be discussed in detail in the section on masticatory movements.

METHODS:

The method of investigation will be referred to as "Mandibulography" and the equipment used, as a "Mandibulograph." The method of its use is described in the Section II.

SECTION IV

MANDIBULOGRAPHY

MANDIBULOGRAPHY

Recordings of the mandible's capacity for movement and the patterns of functional movements have been made in post-mortem preparations and also in living subjects.

Various techniques and media have been used, which can be grouped as:

1. Graphic methods.
2. Photographic and cinemetographic methods.
3. Radiographic and cinefluorographic methods.

1. GRAPHIC METHODS:

Although nearly every investigator has designed his own recording apparatus, the basic feature of any graphic method being that a tracing device is fixed to the mandible. This device either directly records mandibular movements on suitably aligned cards or recording paper, or provides the force to drive a motion analyser, which, in turn, records the movements. (18) The tracing device is usually attached to a point on the lower incisors, although other points (mental protuberance, (18) heads of the condyles (19) and sides of the face) have also been used. Similar techniques have been employed by Langer (38) Posselt (38) Hickey (19) Griffen (18) and many others. (16,31,70)

Bennett (9) used the graphic method but substituted lights on a rigid frame anchored to the lower teeth for the tracing device. He aligned the lights to the position of the heads of the condyles and used a lens system to project images of the lights, thereby

magnifying the movements of the light many times.

Nemoto et.al. (35) modified the technique so that the mandible, during excursion, activated an electronic motion analyser into three dimensional movements and displayed them on oscilloscope screens. These displays were then photographed and recorded. In this procedure, the head had to be immobilized.

Such graphic recording techniques have inherent disadvantages, e.g.:

(a) Neuromuscular mechanisms relate masticatory movements to the head movements in normal function. If, during chewing, the head is not restrained, its movement will be superimposed on the records of the functional movements and the purity of the records will be lost. If the head movements are eliminated by external fixation of the head to a head-rest, or simply by conscious control by the subject himself, (which is not within the scope of every individual) the functional movements may not resemble those of an unrestrained subject.

(b) The motion analysers operated mechanically by mandibular movements exercise a restraint upon the natural movements. There is a possibility that such restrained movements may differ from normal unrestrained functional movements.

2. STILL AND CINEPHOTOGRAPHIC TECHNIQUES:

These have been used by Shanahan (45), Atkinson and Shepherd, (5) Murphy, (33) and Ahlgren (1). Small light sources, or brightly coloured beads are attached

as markers to the maxilla and mandible along the median sagittal plane and photographed during function. From the individual frames of a cinephotographic sequence, the positions of the maxillary and mandibular markers are plotted on graph paper. Taking the position of the maxillary marker as a point on the base line, the successive positions of the mandibular markers can be plotted to trace out the path of movements. The technique eliminates errors due to head movements. With a camera speed of 24 frames per second, a movement lasting one second (the average duration of a masticatory stroke) requires analysis of 24 photographs and provides information about the movement in one plane only. For a three-dimensional appreciation, either two additional cameras are required, or, alternatively, the images of the lights must be photographed through mirrors arranged to obtain views of the lights from other directions. Such an arrangement may introduce distortion of the light positions, as recorded on the film.

3. RADIOGRAPHIC AND CINEFLUOROGRAPHIC METHODS:

In these techniques, the variations in the positions of either anatomical landmarks or suitably located radio-opaque markers are compared with the positions of static landmarks or radio-opaque markers. The techniques expose the subjects to ionising radiation and cannot be employed in extensive studies on a given subject, because of the possibility of radiation hazards. These cephalometric techniques require fixation of the head with the attendant possibility of modification of movement patterns as discussed previously. The works of Posselt ⁽³⁸⁾ and Jankelson, Hoffman and Hendron ⁽²⁵⁾ are examples where

this technique has been used.

In this present investigation, an electronic technique has been used for three-dimensional recording and analysis of mandibular movements. The equipment used consists of a motion analyser utilizing the photoelectric properties of specially prepared silicon wafers. The technique has thus been termed photo-electric mandibulography. The following principles are utilized in the construction and operation of the device.

POSITIONAL LOCATION IN SPACE:

Space is generally described as having three dimensions, length (or height), breadth and depth. Location of a point in space can be designated by three linear coordinates, usually referred to as X, Y and Z representing the relations of the point to the three dimensions of space. When an object has to be located in space, the three linear coordinates of a minimum of three points located at various levels and at some distance from one another, will provide the desired information about the position of the object. The total number of coordinates relative to the three points can be reduced to a minimum of six, because some of the nine coordinates carry redundant information. ⁽¹⁷⁾ (Figures No. 1, 2 and 3)

STUDY OF POSITIONS AND MOVEMENTS OF THE JAW:

There are two feasible approaches: (i) The mandibular position and movements can be examined by following the mandible as a whole. The spatial coordinates for a minimum of three points located far apart would have to be monitored, such an approach being difficult because of the complexities of monitoring, recording and interpretation involved, (ii) a simpler alternative would be to monitor the spatial coordinates of a suitably located

single point on the jaw, which considerably reduces the complexity of the recording equipment, and can still provide considerable jaw point movement information.

The concepts advanced by Posselt, ⁽³⁸⁾ Schweitzer, ⁽⁴³⁾ Shepherd, ⁽⁵¹⁾ and others, indicate that the movements of the mandible can be described as a combination of rotation and translation. Regardless of where the axis of rotation of the mandible may be, the movement of the jaw point when it occurs will necessarily be the result of movement of the jaw, but not vice versa. There may be a movement of the jaw, yet the selected jaw point may be stationary or even moving in the opposite direction.

Thus, the position or movement of a point on the jaw may not be a certain indication of the position or excursion of the mandible itself. Fortunately, the parameters of the mandibular motion are so definite in position and so limited in space, ^(38,39,40,41) that even though examination of the positions or movements of a single jaw point, located along the median plane, may not indicate the exact position of the jaw at any time, it will provide considerable information about jaw movement during the function of mastication.

PHOTO-ELECTRIC MANDIBULOGRAPH

The equipment was originally described by Gillings (17). The principal feature of the apparatus is the use of siliconed photo-electric cells. When exposed to light, a potential difference is created between the two sides of the siliconed cells, which can be measured as electric output displayed on an oscilloscope screen and recorded by suitable means.

The electrical output is proportional to the intensity of light falling on the photocell face, the latter being inversely proportional to the square of the distance between the light source and the photocell face. The electrical output from the photocell is also related to the distance between the light source and the photocell face. If the intensity of light, or the distance between the photocell face and the light source is changed, the output also changes.

The photo-electric cells are said to be "matched" when they show similar output on exposure to the same intensity of light at the same distance. The photocells can be grouped together in series and two such groups are said to be matched when the individual photocells in one group are matched to the opposite member in serial order in the other group.

The original apparatus and its principle of operation are shown in Fig. Nos. 3, 4 and 5.

In the case of mandibular movements, the three directions of motion can be referred to as (i) up-down (ii) right-left, and (iii) anterior-posterior. In the mandibulograph, each direction is detected by its appropriate set of two groups of matched photocells. These sets are arranged on the "photocell frame".

The photocells sensing the up-down movements are arranged on the upper and lower sides of the frame. Those recording the right-left component of motion, are arranged on the right and left sides of the frame. The arrangement of photocells for recording the anterior-posterior direction of motion presented problems, in that the photocells, if arranged in accordance with the principles employed for the detection of up-down and left-right movements, that is, facing the direction of motion at right angles, would interfere with movements of the light source. In the original apparatus, these photocells were fixed to two strips attached to the upper half of the frame on the anterior and posterior aspects facing slightly downwards and towards the light source. Although this arrangement allowed ample up-down movement of the light, the location of photocells encroached upon the zone of maximum linearity as monitored by the photocell frame. The anterior-posterior dimension recordings also had a very short range of linearity.

Different arrangements of the photocells were tried out. It was found that if the two photocell groups monitoring the motion in anterior-posterior direction were arranged in the form of two rectangles, one anteriorly and the other posteriorly, the anterior-posterior movements could be monitored with much greater accuracy and over a much greater range. (Fig. 6). This particular arrangement also provided better access to the face and the mouth. A new photocell frame embodying these improvements was constructed.

The mandibulograph has five essential components:

1. The photocell frame (Fig. No. 7)
2. The head frame (Fig. No. 8)
3. The mandibular light (Fig. Nos. 9,10)
4. The remounting guide (Fig. No. 11A)
5. The recording devices (Fig. No. 12)

1. The Photocell Frame: (Fig. No. 7)

It is a $5\frac{1}{2}$ " x $4\frac{1}{2}$ " rectangular frame made from light weight stainless steel tubing. The photocells, 28 in number, are cemented on a thin acrylic rectangular frame, fitting into the stainless steel frame. Two sets, each consisting of eight photocells, were used to monitor the up-down and right-left movements, and a set of twelve photocells was used to record the anterior-posterior movements. The frame weighed 138 gms.

2. The Head Frame: consists of four parts:

(i) The fronto-nasal shield. (Fig. No. 11B)

(ii) The anterior bow. (Fig. No. 8a)

(iii) The parietal support. (Fig. No. 8b)

(iv) The occipital cap. (Fig. No. 8c)

(i) Fronto-nasal Shield: (Fig. No. 11B) This is an acrylic plate covering at least 4" square area of the forehead and extends on to the bridge and sides of the nose. An individual shield was made for each subject from a cast of the fronto-nasal part of the face. The shield provided anterior support for the apparatus in edentulous subjects. (Fig. No. 17)

(ii) Anterior Bow: (Fig. No. 8a) This has a reinforced rigid construction. It gains support on the fronto-nasal shield in the region of the bridge of the nose and through universal joints, it provides a three point suspension to the photocell frame. The bow is connected to the parietal support through an adjustable vertical component and to the occipital cap with elastics.

(iii) Parietal Support: (Fig. No. 8b) This provides a

three point support on the top of the head for the anterior bow and the photocell frame, thus preventing it from slipping down on the bridge of the nose. The junction between the vertical component of the anterior bow and the parietal support has a universal joint by which the connection between the two parts can be made rigid.

- (iv) The Occipital Cap: (Fig. No. 8c) This is made from clear acrylic. It is 4" in diameter, is lined with foam rubber and fits the occipital part of the head. It is connected to the bow by elastics and holds the apparatus in position in front of the mouth.

3. Mandibular Light Assembly: Fig. No. 10. This is the only moving part in the entire equipment and has the following components:

- (a) Light Globe. A Philips 6v, 3w frosted festoon globe with an axial filament is used. One of the terminals to the globe is located in the globe holder and the other clips onto the free end of the globe through a coil spring (Fig. 10A).
- (b) Globe Holder. Fig. 10B. It is an acrylic holder with a brass tube on its end, which slips onto the entire length of the light rod coming in contact with the labial surfaces of the lower teeth. The holder maintains a constant distance of 45 mm. between the centre of the globe and the labial surface of the teeth.
- (c) The Light Rod. Fig. 10C. This is anchored to the labial surface of the lower natural or artificial teeth and carries the globe holder. It is aligned

in relation to the face so that it extends anteriorly along the median plane, and is also parallel to the horizontal of the face, which is indicated clinically by a line joining the ala of the nose to the tragus of the ear.

In the dentulous subject, the light assembly is cemented to the labial surface of the lower anterior teeth using Eastman 910 resin as suggested by Gillings. ⁽¹⁷⁾ The essential features of the mandibular light are that:

- (i) It extends labially from the median plane.
- (ii) It is parallel to the horizontal of the head (Camper's plane)
- (iii) The distance between the centre of the filament and the labial surface of the lower natural or artificial teeth is kept constant for all test subjects.
- (iv) The complete mandibular light assembly weighed only 8.0 gm. in the case of dentulous subject and 6.0 gm. in the edentulous subjects. It did not cause any readily apparent dislodgement of the dentures or interference to the functional movements.

4. Remounting Guide: Fig. No. 11A. The guide is used to mount the photocell frame in similar relationship to the head and face in all the subjects, and is described in detail later. (Fig. No. 18)

5. Recording Devices: Fig. No. 12. The output from the three sets of photocells is fed into three D.C. push-pull amplifiers on a Sanborn four track recorder which

uses heat-sensitive paper and can be operated at selected speeds, ranging between 0.5 mm/second and 50 mm/second. The recordings were generally made at a speed of 25 mm/second. One second timing marks can be made on the margin of the paper with an extra pen. This pen also can be controlled by an over-riding control push button as an event marker or to identify places in a record.

For a simultaneous display of mandibular excursions, output of the photocells was also connected to a dual beam storage oscilloscope displaying jaw point movements in any two of the frontal, sagittal and horizontal views. The storage mode of the oscilloscope may be used when it is desired to examine single or multiple chewing stroke displays or photograph them using polaroid ^(R) film. Both the paper recordings and polaroid photographs were studied in this investigation.

ORIENTATION, CALIBRATION AND STANDARDISATION OF THE
PHOTOCELL FRAME:

The photocell frame is merely a convenient carrier for three separate monitoring devices. The individual photocell sets give information about the position or movements of the light in relation to these sets individually. Thus, repetitive jaw point movement patterns will produce identical movements of the light, yet these may be displayed or recorded differently in successive experiments unless the photocell frame bears the same relation to the light for each experiment and the same amplifier gain settings are used on the recording devices.

For the device to be an effective tool for studying jaw movements, it should record movement patterns which are in effect, the exact reproduction of mandibular or incisor point movements, as they are demonstrated by the subject. Because the condylar end of the mandible has less freedom of motion than the incisal end, opening and closing movements of the mandible generally produce convex paths or arcs at the incisor point. Provided the centres of these arcs lie to the condyle side of the incisor point, the movements of the incisor point will be magnified when these are monitored from points located anterior to the incisor point. Because the centre of the light globe is situated 45 mm. anterior to the labial surfaces of the teeth, any arc movements as described above will be magnified, the magnification being proportional to the difference between the two radii, i.e., distances from the axis of motion to the incisor point and the centre of the light globe. It would require complicated calculation to convert mandibular light movements into actual jaw point movements.

Thus, for a valid comparison of the recordings from

various subjects, it was necessary to standardize the procedures and to calibrate the recorded movements according to fixed standards.

To achieve these objectives, the following tests were performed:

1. Establishment of a central vertical axis of maximal three dimensional linearity in the photocell frame.
2. Determination of the dimensions and location of the space within the photocell frame, which is monitored with acceptable linearity.
3. Standardization of the light - photocell positional relationship with the base of the skull.

1. Establishment of a Central Vertical Axis of Maximal Three-Dimensional Linearity: Fig. No. 13

The photocell frame was secured in a vertical position in an adjustable stand. The light rod was fixed to the stage of a travelling microscope capable of reproducing movements in measured distances along the three axes. The microscope and the photocell frame were then aligned so that the light could be moved freely within the perimeters of the photocell frame in the up-down, right-left and anterior-posterior directions.

The outputs from the photocell frame were fed into a dual beam oscilloscope recording in the X-Y, X_1 -Y mode without time base. By suitable arrangements of inputs, the oscilloscope could display any of the three views of the movement space: The result of up-down and right-left outputs displayed the frontal view. The

result of anterior-posterior and right-left outputs displayed the horizontal view and the result of up-down and anterior-posterior outputs displayed the sagittal view. Thus, any two views of the movements of the light globe along the X, Y and Z axes in space could be displayed simultaneously on the oscilloscope.

The light was arbitrarily located in the middle of the frame, equidistant from the opposing groups of photocells. The gains on the three amplifiers were adjusted so that a 1 cm. movement of light, in any direction, up-down, right-left, or antero-posterior, was displayed as a 1 cm. displacement of the tracing spots on the oscilloscope screen in the respective directions.

Because of the unavoidable discrepancies in matching the opposing groups of photocells, the geometric axes of the photocell frame did not conform with axes monitored by the photocells and displayed on the oscilloscope screen. The alignment of the photocell frame to the light source on the microscope was rectified by turning the frame in a clock-wise or anti-clockwise motion around the X, Y or Z axes, till the up-down movement, as traced by the tracing spots on the oscilloscope became parallel to the vertical axis of the grid on the oscilloscope screen, and likewise, the right-left movements and the anterior-posterior movements became parallel to the respective axes on the oscilloscope screen. By repeated up-down scanning of the space within the photocell frame, a central vertical axis of maximal linearity was located within the frame. When the light source moved up-down along

this axis, the tracing in both the frontal, as well as the sagittal views, followed a vertical course. The central vertical axis was linear only in direction. It lost linearity in dimension progressively, as the light approached the upper or lower ends of the photocell frame.

2. Determination of the Dimensions of Space Monitored with Acceptable Linearity:

The space within the confines of the photocell frame was scanned by moving the light source along three frontal and three sagittal planes. Fig. No. 14 is a diagrammatic representation of the space examined and the location of the six planes scanned. The three frontal planes were located: (1) One centimeter posterior to the central vertical axis; (2) passing through the central vertical axis; and (3) one centimeter anterior to the central vertical axis. For each of the frontal planes, the light source was moved laterally in 0.5 cm. steps through a distance of 2 cm. on either side of the central position and through a vertical distance of 5 cm. The position of the tracing spot on the oscilloscope through all the steps was recorded photographically by repeated exposure on the same film.

The three sagittal planes were located: (4) one centimetre to the right of the central vertical axis, (5) along the central vertical axis; and (6) one centimeter to the left of the central vertical axis. Similar to the frontal planes, the light source was moved through a distance of 2 cm. anteriorly and 2 cm. posteriorly to the central vertical axis in 0.5 cm. steps and a vertical distance of 5 cm. Again, the tracing

on the oscilloscope screen during the scanning was recorded photographically.

Fig. No. 15 represents the oscilloscope display of the positions of the tracing spot on the six planes compared to a 1 cm. grid.

Fig. No. 16 represents the percentage loss of linearity in the reproduction of the movements of the light by the photocell frame along the X, Y and Z axes on the two frontal and sagittal grids passing through the central vertical axis. (Figs. No. 14, 15, 16 Grids No. 2 and 5) The loss of linearity was calculated by measuring the distance travelled by the light on the microscope stage and the distance travelled by the tracing spot on the oscilloscope screen. The percentage loss or gain in the distance was interpreted as loss of linearity.

The loss of linearity was examined in the total dimensions of the grids, i.e., 4 cm. right to left, 5 cm. vertical and 4 cm. anterior-posterior and also in limited dimensions of 2 cm. right-left, 2 cm. vertical and 2 cm. anterior-posterior.

In grid No. 2, the total upper border right-left movement path a-b showed a 1.9 percent loss of linearity. The lower total right-left movement path c-d showed a loss of linearity to the extent of 3.9 percent. In the limited zone, the upper border right-left movement path (a'-b') one cm. on either side of the central axis (A-A') showed a loss of linearity to the extent of 1.9 percent, while at the level of 2 cm. below the upper border along the path c'-d', the loss of linearity reached up to 5.8 percent. The

distance measured by the oscilloscope was greater than actually travelled by the light on the microscope stage. This resulted in a barrel distortion effect on the grid pattern. The loss of linearity in the total up-down excursion along the central vertical axis A-Á was to the extent of 5.5 percent, but in the upper part, 2 cm. from the point A to the point B, the loss of linearity was as little as 1.9 percent. In the lateral extremities of the grid, 2 cm. from the central axis on the right side, along the path a-c and on the left side along the path b-d, the percentage loss of linearity was much greater, 14.1 percent and 15.7 percent respectively, but at a distance of 1 cm. from the central axis along á-ć and b-d, the loss of linearity was much more acceptable, i.e., 3.9 percent and 1.9 percent respectively.

In the sagittal grid No. 5 (Figs. No. 14, 15, 16), the upper limit of the total antero-posterior movement 2 cm. anterior and 2 cm. posterior to the central vertical axis along e-f showed a loss of linearity to the extent of 9.8 percent, but in the middle zone along the path é-f, one cm. on either side of the central vertical axis, the excursions were reproduced on the oscilloscope screen with complete linearity. The same degree of accuracy of reproduction of the dimensions was observed along the path g-h and g-h, 2 cm. and 5 cm. from the upper border of the grid respectively. The up-down component of the sagittal grid showed a 5.5 percent loss of linearity in the total movement, along A-B, the loss of linearity was as little as 1.9 percent. The loss of linearity at the anterior and posterior extremities of the grid along the paths f-h and e-g was measured as 30.7 percent and 18.1 percent

respectively, while, along the paths $f-h$ and $e-g$ 1 cm. anterior and posterior to the central axis respectively, it was measured as 13.7 percent and 5.8 percent. Thus, the sagittal grid also displayed the barrel distortion along its periphery.

Fortunately, the average simulated and functional movements of the jaw point remain well within the confines of the middle zone of the two grids. It is evident that, if point 'A' (Fig. No. 16) located on the central vertical axis be accepted as the starting point and during the recording of jaw point movements made to coincide with the intercuspal position, the excursions of the jaw point in their most important phase, i.e., the initiation and termination, can be monitored very accurately in three dimensions. The ultimate loss of linearity along the X, Y and Z axes liable to affect the functional movements of the jaw point during the translation through the photocell frame would be 1.9 percent, 1.9 percent and zero, respectively. Thus the equipment can be accepted as a means for accurate three-dimensional recording of the jaw point movements. The exactness of the recordings along the Z axis makes the mandibulograph most suitable for studying the antero-posterior positions and excursions of the jaw point. In the subsequent procedures, distances will be measured and described in relation to this 'zero point'.

3. Standardization of the Light - Photocell Frame Positional Relationship With the Head:

When the light source was assembled on the travelling microscope, as described above, the tracings on the oscilloscope screen showed only the positions of the light in relation to the central vertical axis of the zone

of acceptable linearity in the photocell frame. These gave no information about the movements of the light in relation to the base of the microscope, unless the positional relationship that existed between the base of the microscope and the central vertical axis of the photo-electric sensitivity field of the photocell frame was known.

The same restriction applies to the monitoring of mandibular movements. Unless a definite, easily obtainable and easily recognisable positional relationship is established between the central vertical axis of the field of the photocell frame and the base of the skull, the tracings will give no reproducible information about the movements of the jaw. This requirement becomes most vital when the jaw movements for different test subjects are to be compared. The requirement could be fulfilled by establishing:

- (a) Standardization of the light source and photocell frame relationship.
- (b) Standardization of the light source and mandibular relationship.
- (c) Standardization of the photocell frame and base of the skull relationship.

(a) Standardization of the Light Source and Photocell Frame Relationship:

Using the travelling microscope as described above, the central vertical axis and the perimeters of the space monitored with acceptable linearity were determined. The light source was located on the central vertical axis as close to the upper limits of the zone of acceptable linearity as possible. The inter-relation of the position

of the light, the alignment of the photocell frame and the base of the microscope was immobilized with clamps. The light holder was then removed from the light rod and a remounting guide assembled on it. The remounting guide (Fig. No. 11A) consists of three parallel rods, soldered at the end of a tube that fits snugly on to the light rod and is also parallel to the rods. The ends of the rods of the remounting guide fit into three sleeves parallel to one another and located on the sides and bottom of the photocell frame (Fig. No. 7g, 18). Using this guide, the photocell frame could be aligned in exact relationship to the light for each successive experiment.

(b) Standardization of the Light Source - Mandible Relationship:

This has already been described, under the description of the Mandibular light assembly.

(c) Standardization of the Photocell Frame - Base of the Skull Relationships:

To record the movements of the jaw in relation to the frontal, horizontal and sagittal planes of the head, the central vertical axis of the zone of acceptable linearity of the frame had to be aligned to the face such that, when the jaw was in the intercuspal position, the centre of the light globe occupied the selected starting or zero position in the photocell frame and the central vertical axis aligned with the median plane at right angle to the horizontal plane. The location of the light rod on the natural teeth or the dentures in the intercuspal position formed the key to this three-way relationship.

When the light rod was in the proper position in the lower

dentures, or on the anterior surfaces of the lower anterior teeth, and the subject closed the teeth in the intercuspal position, the photocell frame with the remounting guide in position could be aligned to the face by slipping the tube of the remounting guide on to the light rod now the position of the frame was secured by tightening the universal joints between the photocell frame and the head-frame. The remounting guide could then be withdrawn anteriorly and replaced by the light globe without disturbing the position of the photocell frame.

RECORDING PROCEDURE

Recording procedure involved preparation of the subject in two stages:

- I. Pre-recording preparation
- II. Recording session preparation.

PRE-RECORDING PREPARATION:

1. Dentulous Subject:

(a) Construction of Calibrating Plates: From the upper and lower casts, two cold curing acrylic resin plates, covering the palatal and lingual surfaces were constructed. The plates extended up to the maximum convexities of the respective surfaces of the teeth, and were retained in position only by friction, no other means of retention being necessary. A central bearing device was attached to these plates. The tracing table was fixed to the upper and central bearing screw to the lower plates.

From a cast of the forehead, and nose area of the face, a fronto-nasal shield was constructed, also in cold curing

acrylic resin.

2. Edentulous Subjects:

(a) Construction of Dentures: The usual procedures were adopted except that special efforts were made to record, confirm and reproduce in the dentures the most retruded, horizontal relation of the mandible to the maxilla that could be achieved by the subject himself. The measures adopted were:

- (i) Maxillo-mandibular relationship recorded by the intra-oral central bearing gothic arch tracing method. According to Posselt ⁽³⁸⁾, the apex of the tracing represents the desired maxillo-mandibular relationship.
- (ii) The upper denture was processed and finished first. The lower denture was then retried against the finished upper denture. If indicated, another gothic arch tracing record was made - the upper denture carrying the tracing table against the lower acrylic resin baseplate with the central bearing screw that was used for the first tracing. The upper denture was remounted on the articulator with the new recording, and the articulation of the lower teeth readjusted. The denture was again tried in the mouth for verification of the maxillo-mandibular relationship and then processed.
- (iii) The lower denture, kept on the model, was remounted on the articulator. Any occlusal discrepancies due to processing etc. were rectified and the denture finished, polished and tried in the mouth. Acrylic teeth were used to simplify the occlusal adjustment and subsequent polishing of the ground tooth surfaces.

The dentures were issued to the subject and were adjusted as or when necessary, until these were comfortable to the subject's satisfaction.

The subjects wore the dentures for from 2-8 weeks. The termination of this conditioning period was determined by:

- (i) The subject's expression of complete comfort and satisfaction with the dentures in regard to mastication of food, speech and aesthetics.
- (ii) Absence of any clinical signs, such as inflamed or congested areas on the denture foundation or periphery.
- (iii) Complete absence of any clinical evidence of shifting or sliding of dentures in the antero-posterior or other horizontal directions, when the jaw closed from rest position to intercuspal position. Some degrees of vertical displacement due to compression of the mucoperiostium was noticed, but was accepted as inevitable. Where indicated, a third central bearing record was taken and the articulation of the dentures readjusted on an articulator.

(b) The Fronto-Nasal Shield: was constructed for each of the edentulous subjects.

(c) Preparation of Dentures for Recording:

This involved:

- (i) Attachment of the mandibular light rod.
- (ii) Attachment of calibrating central bearing device.

(i) Attachment of the Mandibular Light Rod:

1¼" long brass tubing which fitted accurately into the

sleeve of the mandibular light holder was attached to the lower denture in the median plane and parallel to Camper's plane. The light rod did not interfere with the opposing teeth. The location of the light rod on the denture was carried out in the mouth. Cold curing acrylic resin was used for the attachment of the light rod to the denture (Figs. No. 9, 10)

(ii) Attachment of the Calibrating Central Bearing Device:

As has been described earlier, the photocell frame gave information about the position and movements of a point 45 mm. anterior to the incisal point. The determination of the actual position or movements of the jaw point involved complication calculations. This difficulty was overcome by adjusting the gain on the amplifiers for individual subjects so that the distances recorded by the amplifiers were equal to the distances travelled not by the light globe but by the jaw point in the particular subjects. This necessitated arrangements by which the jaw could be moved through measured distances, while the gains on the amplifiers were being adjusted. A conventional central bearing device was used for the purpose and the following technique was adopted:

The dentures were placed on the articulator. In the palatal space of the upper denture, a stainless steel tracing table was fitted about $\frac{1}{4}$ " deep into the space and away from the occlusal surfaces of the teeth, yet parallel to them. The palatal surface of the denture was lightly lubricated. Some low fusing composition was built up on the under surface of the tracing table, which was then pressed in to the

palatal space of the denture. After chilling, the composition block with the tracing table on it could be removed from the denture, cleansed of the lubricant, replaced in position and tacked with sticky wax.

(Figs. No. 9a, 9c, 11C)

In the lower denture the central bearing screw was attached (Fig. No. 9c). The three supporting legs of the screw were so bent and shaped that one rested on the lingual side of the lower central incisors along the median plane and the other two - one on each side - on such surface or interproximal spaces that offered positive support to the device against displacement by vertical forces.

The surface of the denture was lubricated and small beads of cold curing acrylic resin were placed on the three spots designated for the three legs of the central bearing screw. The legs were seated into the beads and the acrylic allowed to harden. When in position, the screw device did not interfere with occlusion. The screw device was then removed from the denture, finished and polished. It was replaced on the denture and tacked with sticky wax.

Calibrating Gothic Arch Tracings: The two dentures with the central bearing devices attached were now inserted in the mouth. The height of the central bearing screw was so adjusted that when in the mouth, the incisal edges of the upper and lower central incisors just barely cleared one another. At this vertical height, a film of blue inlay wax was applied to the tracing table, and the subject was asked to perform protrusive

and lateral sliding movements and trace out a gothic arch. Keeping the apex of the tracing as centre and using a sharp ended pair of dividers, an arc of 0.5 cm. radius was marked between the two sides of the tracing. On this arc, three points were located, one at the intersection of the arc and a line bisecting the angle of the tracing, and the other two, one on each side, at the point of intersection of the arc and the sides of the tracing. On these points, three well defined pits were made in the stainless steel tracing table with a No. 1 round burr. (Fig. No. 11c) When the upper and lower dentures were placed in the mouth, the subject could hold the retruded position of the jaw himself and come back to it easily after excursions. With a little practice, he could recognise the location of the three depressions and could engage the point of the central bearing screw into any of these when asked to do so. Thus, the subject was able to move his jaw a measured distance in lateral border or protrusive directions and hold it there, and again come back to it while the gains on the amplifiers were being adjusted.

An exactly similar procedure was followed for the dentulous subject. The palatal and lingual plates bearing the central bearing device were used.

RECORDING SESSION PREPARATIONS:

This involved the following steps:

1. Fixation of the head-frame.
2. Fixation and alignment of the photocell frame.

3. Calibration of the apparatus for the individual subject.

1. Fixation of the Head-Frame:

The fronto-nasal shield was tried in position on the nose. Being made of clear acrylic, any areas of over compression or pinching under the shield could be easily detected and relieved. (Fig. No. 17) When it was comfortable, the head-frame was placed in position. It was supported anteriorly on the fronto-nasal shield and superiorly by the parietal stops on the sides of the top of the skull. It was held in position by the elastics joining it to the occipital cap. Care was taken to ensure that the parietal supports took their due share of the load and prevented a downward sliding of the frame on the bridge of the nose. The parietal supports also helped to keep the two sides of the head-frame horizontal.

2. Fixation and Alignment of the Photocell Frame:

The procedure was simpler for the edentulous subjects. The upper and lower complete dentures (the lower denture with the mandibular light rod attached as described earlier) were inserted in the mouth and seated in position. The subject held the jaws together with the denture in the intercuspal position. The remounting guide was attached to the photocell frame. The tube of the guide was slipped in position on the mandibular light rod, the extensions of the photocell frame were engaged into the universal joints on the head-frame and secured. The remounting guide could be now withdrawn and replaced by the light globe. (Figs. No. 18, 19)

In the dentulous subject, the technique had to be modified as the attachment of the mandibular light rod with the

910 monomer was not strong enough to take the weight of the frame during the alignment procedure, so the tube of the remounting guide was aligned parallel to the light rod in the sagittal and horizontal planes and the extensions of the photocell frame secured into the universal joints.

Stability: The apparatus remained stable in position during average normal activity. During sudden vigorous head movements, independent swinging of the photocell frame was observed and all such excursions or movements were avoided.

3. Calibration of the Apparatus in Individual Subjects:

The necessity for this operative has been discussed previously. In the dentulous subject the palatal and lingual plates with the specially prepared calibrating gothic arch tracings were seated in the mouth. Similarly, in the edentulous subjects, the upper and lower dentures carried the central bearing device with the gothic arch traced and prepared. Calibration was carried out in three directions, lateral, anterior-posterior and up-down. The following procedure was used in both the dentulous as well as the edentulous subjects:

Calibration of the Lateral Movement Records:

The subject was asked to move the jaw laterally and engage the lateral pit on the particular side while the shift of the writing pen on the recorder was observed. As the jaw point moved 0.5 cm. laterally to engage the lateral pit, the relevant amplifier gain was so adjusted that the pen of the right-left channel showed a 0.5 cm. deflection. As the system is symmetrical, adjustment of the gain was

necessary only on one side. The adjustment was verified and recorded. (Fig. No. 20A)

Calibration of the anterior-posterior movement records

was carried out by asking the subject to open the mouth and close on a cylinder 1 cm. in diameter located between the upper and lower central incisors. The central bearing screw was adjusted so that the upper and lower central incisors just cleared one another, thus, interposition of a 1 cm. cylinder between their edges represented a 1 cm. downward displacement of the incisal point, and the extent of overbite did not influence the adjustment in any way. The up-down calibration was also recorded. (Fig. No. 20C) The calibration assured that the apparatus recorded the movements with maximal accuracy in dimension and direction. The mandibular movements were recorded generally at a paper speed of 25 mm. per second.

MANDIBULOGRAPH RECORDS:

(Fig. No. 21) shows a mandibulograph recording of an "open wide and close" excursion of the jaw point in an edentulous subject. The base line on the three channels of the record represents the position of the mandibular light in the intercuspal relation of the jaws. Channel No. 1 represents the vertical or the X axis component of the open-close movement and channel No. 2 and No. 3 represent the right-left or Y axis and anterior-posterior or Z axis components respectively. The timing marks are recorded on the lower margin of the paper and indicate a paper speed of 25 mm. per second.

For a three-dimensional visualization of the excursions of the jaw point during various exercises, the three views of the excursions were constructed along the frontal, sagittal and horizontal

planes as inter-relations of X-Y, X-Z and Y-Z co-ordinates respectively. (Fig. No. 21)

From the up-down tracing on channel No. 1, points were selected, 0.5 mm. to 5 mm. apart - closer when greater accuracy and detail was required, as near the intercuspal position, and farther apart when only the general direction was the object of study, e.g. near the maximally open position. The distances of these individual points from the base line on channel No. 1 was measured and represented the X axis co-ordinates for the particular points. The Y and Z axis co-ordinates of these points were measured from the tracings on channels No. 2 and 3 respectively. As the three dimensions of position and motion of the jaw point were recorded simultaneously on the same 1 mm. graph recording paper, the position of the points selected on the up-down record could be easily located on the right-left and anterior-posterior records by tracing along the vertical lines of the graph and reading the location of the points of intersection of the vertical graph lines and the movement tracings in relation to the base lines on channels No. 2 and 3.

For the reading of records, a 4 X magnifier was used. This allowed a visual reading with a low error of 1 mm. \pm and was considered acceptable.

To develop the frontal view of the excursion, the intercuspal position was located on a graph paper as a point of intersection between the 'X' and 'Y' axes at right angles to one another. The positions of the points selected on the up-down tracing relative to the intercuspal position was then plotted on the graph paper using the 'X' and 'Y' co-ordinates in relation to the plotted intercuspal position. When all the points selected for one excursion were plotted, these were interconnected using french curves. A minimum of three points were aligned with the appropriate

curve form and connected. The resulting outline formed the frontal view of the excursion.

The sagittal and horizontal views were developed in a similar manner as the relations of X-Z and Y-Z co-ordinates respectively.

To obtain a magnified view of the jaw point movements, the distances were plotted on a 1/10" graph paper, using a scale of 1" = 5 mm.

Fig. No. 22 is a graphic illustration of X, Y and Z axes and a masticatory cycle in relation to the subject's face as recorded by the mandibulograph.

SECTION V

THE ENVELOPE OF TOTAL JAW POINT MOTION

IN THE

DENTULOUS AND EDENTULOUS SUBJECTS

THE ENVELOPE OF TOTAL JAW POINT MOTION
IN THE
DENTULOUS AND EDENTULOUS SUBJECTS

METHOD:

It was considered that if the envelope of total jaw point motion could be looked at from three directions, i.e., (i) from above, (ii) from the side, and (iii) from the front, it would show up as three elevations of the space, i.e. horizontal elevation, sagittal elevation and the frontal elevation. Each of these elevations would be a two-dimensional representation of the extreme positions the jaw point could reach along the particular dimensions. Thus, the horizontal elevation would represent extreme border positions in the antero-posterior and lateral directions along the horizontal plane, the sagittal elevation would represent border positions in the antero-posterior and up-down directions along the sagittal plane, and the frontal elevation would show limits of mobility in the right-left and up-down directions along the frontal plane.

For mutual correlation of the three elevations of the envelope of total jaw point motion, it was necessary to adopt a common reference point, so that the three dimensions of space could be measured from this point. The reference point also had to be a position which the jaw point could reach with maximal consistency and ease. The position of the jaw point when the teeth were in contact in the intercuspal position was adopted as this reference point.

To record the extreme limits of mobility in the three dimensions the following set of exercises was planned:

1. Slight open-close and clench (O/C, C1). The objective being to verify the recurrence of contact in the intercuspal position.

2. Sliding contact protrusive, followed by retrusion, assisted by manual posterior traction (S.C.P. Post. Tract. Return). This recorded the occlusal border movement path and the most protruded and the most retruded jaw point positions.
3. Open-Close movement during manual posterior traction (Post Tract. O/C) This recorded the most retruded border movement path.
4. Sliding contact protrusive, open-close, sliding contact retrusive (S.C.P. O/C return). This determined the anterior border movement path, and also confirmed the most protruded jaw point position.
5. Sliding contact Right (S.C.R.) and sliding contact Left (S.C.L.). These exercises recorded the lateral border movement path at the occlusal end of the envelope of motion on the right and left sides.
6. Sliding contact Right, open-close, return (S.C.R., O/C, return) and Sliding contact Left, open/close, return (S.C.L., O/C, return) the objective being recording of lateral border movement paths.

The dentulous subject expressed discomfort in the performance of such exercises as S.C.R., O/C, return and S.C.L., O/C return. Likewise, the edentulous subjects, either due to displacement of the dentures during extreme border movements or possible impairment of the voluntary control associated with age were also unable to perform all the exercises successfully. So the boundaries of these exercises were mutually overlapped, e.g., sliding contact protrusive was complimented by posterior traction applied during

the return movement. The excursion provided information about the intercuspal position, the maximally protruded position, the path of the protrusive stroke and the maximally retruded position. Information about the maximally protruded position and the path of the protrusive stroke could also be obtained from the exercise S.C.P., O/C, return and information about the maximally retruded position could also be gathered from the exercise (O/C during Post. Tract.). Thus, it was possible to gather three dimensional information about the border positions and the paths of motion in one dentulous and three edentulous subjects.

Method of Development of the Border Movement Paths and the Outline form of the Envelope of Total Movement Space:

Following the procedure described under "Mandibulography", (Section IV) the three elevations of the movement paths, i.e. the horizontal, the sagittal, and the frontal were developed for each cycle of each exercise. It was found that repeat performances of the same exercise even in the young dentulous subject differed from each other and did not always follow the border pathways either completely or in part (Fig. No. 23). Outside assistance during the excursion evoked muscular resistance and did not always assure border movements. So it was decided to define the specific objectives for each exercise and look for them in the drawings of the repeat performances of each exercise and select such cycles or parts of cycles as came closest to the objectives.

Definition of the Objectives for the Exercises:

1. Sliding Contact Protrusive: The exercise was intended to find a path that ran closest to the Z axis, both vertically as well as horizontally and reached farthest anteriorly.
2. Sliding Contacts Right and Left: The exercise was intended

to determine the posterolateral boundaries of the occlusal end of the envelope of the movement space. So the excursions would have to be closest to the Y axis vertically, related farthest posteriorly to it in the horizontal plane and reaching most laterally.

3. Open/Close Exercise During Posterior Traction: The objective was to locate a path closest to the X axis laterally, yet farthest from it posteriorly and reaching the maximally open position vertically.

4. Sliding Contact Protrusive, Open/Close, Return: The objective of the exercise was defined as location of an Open/Close path most anterior to the X axis, yet closest to it laterally and reaching maximal opening.

5. Sliding Contact Right or Left, Open/Close, Return: The objective was to determine an Open/Close path located most lateral to but reaching closest to the Y axis at its upper end and maximal opening at its lower end.

To develop the outline form of the three elevations of the border movement path, the three sets of axes X-Y, X-Z and Y-Z were drawn out on tracing paper. The axes were aligned to the axes of the respective drawings of the repeat performance of the exercise and such points or sections as most closely fitted the definition of the objectives of the particular exercise were traced out on the tracing paper. The trace was aligned to all the repeat performances of the exercise one after the other and modified until the drawing of the movement cycle was complete. The drawing thus formed was considered as a border movement path.

To form the drawing of the envelope of total movement space, the respective elevations of the border movements were aligned to one another with the help of the X, Y and Z axes and the composite picture of the horizontal, sagittal and frontal elevations of the total envelope of motion developed.

From the drawings, the following assessments were made:

1. General characteristics of the envelope of total jaw point motion.
2. Characteristics of the three elevations of the envelope of total jaw point motion in the dentulous subject.
3. Characteristics of the three elevations of the total envelope of motion in the edentulous subjects.
4. Comparison of characteristics of the envelope of total jaw point motion in the dentulous and the edentulous subjects.
5. Evaluation of the cuspal guidance angles.
6. Relationship between the envelope of total jaw point motion and the simulated and functional movements.

OBSERVATIONS OF THE ENVELOPE OF TOTAL JAW POINT MOTION IN THE DENTULOUS
SUBJECT 'A'

From the mandibulograph records of the guided movements, three two-dimensional drawings representing the horizontal, sagittal and the frontal elevations were drawn out for each cycle of all the exercises. Applying the criteria for selection, the cycles displayed in Fig. No. 24 were adopted to represent the boundaries and border excursions of the envelope of total jaw point motion.

1. The Superior or the Occlusal Boundary: The 'S.C.P.' exercise cycle No. G 1/4 ('a' Fig. No. 24) was selected and only the

protrusive stroke which was the closest to the Z axis laterally as well as vertically was adopted.

2. The Superior Posterior Lateral Border on the Right Side was adopted from S.C.R. Exercise, cycle No. G 2/6 ('b' Fig. No. 24). It was the most retruded excursion involving minimal vertical displacement of the jaw point. Only the out-going part of the cycle was used. The return path passed anteriorly at a greater vertical distance from the zero point.

3. Superior Posterior Lateral Border on the Left Side: The out-going part of S.C.L. excursion No. G 3/3 ('c' Fig. No. 24) was selected, the reason for selection being the same as for the right side.

4. The Posterior Vertical Boundary: The 'O/C, Post. Tract.' exercise cycle No. G 4/1 ('d' Fig. No. 24) was used as it was the most retruded excursion involving minimal lateral deviations.

5. The Anterior Boundary: The closing stroke of the (S.C.P, O/C, Return) exercise cycle No. G. 6/1 ('e' Fig. No. 24) was used. The closing stroke was most protruded and closest to the medium plane.

The three elevations of the total envelope of motion were developed by superimposing the zero points and the respective axes, i.e. Y and Z for the horizontal elevation, X and Z for the sagittal elevation and X and Y for the frontal elevation of the above sections of exercises. The horizontal, the sagittal and the frontal elevations of the total envelope of jaw point motion in the dentulous subject examined are represented in the Figs. No. 25, 26, 27.

Key to the Figs. No. 25, 26, 27

I.C.P.	Intercuspal position
M.R.P.	Maximally retruded position
M.P.P.	Maximally protruded position
M.O.P.	Maximally open position
M.L.P.R.	Maximal lateral position right side
M.L.P.L.	Maximal lateral position left side

- a.á. The occlusal and the remote halves of the posterior border movement path.
- b. The anterior border movement path.
- c. The protrusive movement path.
- d & e Right and left posterior superior lateral border movement paths respectively.
- f & g Arbitrarily drawn out anterior superior right and left borders of the envelope of motion.
- i & h Lateral open and close movement paths were adopted from functional movements.

ASSESSMENTS:

GENERAL CHARACTERISTICS OF THE TOTAL ENVELOPE OF MOTION:

1. HORIZONTAL ELEVATION: Fig. No. 25.
 - (a) As suggested by Posselt (38,39) the total movement space presented a rhomboidal cross-section, the dimensions of which differed at different degrees of mouth opening. At maximal open position, M.O.P., the envelope of motion ended in a point.

The rhombus described by the jaw point motion with maintained tooth contact formed the occlusal boundary of the total movement space.

In the subject examined, the maximal lateral position to which the jaw point could move during a sliding contact lateral excursion was located on the right side at a distance of 10.2 mm. and on the left side a distance of 13 mm. from the median sagittal plane.

From the intercuspal position, I.C.P., the maximal protrusive position, M.P.P., reached during a sliding contact protrusive excursion (S.C.P.) was 5.5 mm. anteriorly and 1.2 mm. to the right of the Z axis.

- (b) The intercuspal position, I.C.P., was not the most retruded position on the occlusal boundary of the pyramidal movement space. The jaw point could be shifted .5 mm. distal to the intercuspal position by the application of manual posterior traction during excursions.

This maximally retruded position, M.R.P., was located directly on the Z axis and was a definite point position, i.e., there was no lateral deviation seen at this point. Unlike the I.C.P., which appeared to be a range and not a point position, i.e., the jaw point could move along the Y axis some distance to the right and left of the zero point or the I.C.P., without any vertical displacement of the jaw, before the jaw point approached the M.R.P. the freedom of lateral movement was lost. This is best illustrated in the Table No. 1, which shows the relative mandibulograph readings of the three components of motion in the terminal parts of four "O/C Post. Tract" cycles.

The R/L component became zero while the teeth were still some distance apart.

(c) Again, as suggested by Posselt (38,39) the occlusal border movement area was bounded anteriorly and posteriorly by two obtuse angles and laterally by two acute angles.

(i) The anterior obtuse angle: It measured 145° degrees. The angle itself appears to be of no great importance, but the point of the angle coincided with the maximally protruded position, M.P.P., which was consistently recorded with the three spatial coordinates as O/C = 4.0 mm., R/L = 1.2 mm, R., and A/P = 5.0 mm. A (Fig. No. 23). The protrusive exercises were performed without any external assistance. The consistent recurrence of this position suggests that it is a position of balance between the right and left side muscle components during protrusion. The matter was not investigated any further.

(ii) The posterior obtuse angle was measured at the maximally retruded position by extending the lateral movement paths posterior to the Y axis by straight lines that followed the general direction of the lateral movement paths into maximally retruded position. (Fig. No. 25) The angle measured 164 degrees. The flatness of the angle is due to the fact that it was not traced on a horizontal plane, instead the jaw point was constantly dropping vertically due to cuspal guidance. The same angle in the frontal view measures 120° . (Fig. No. 27).

(iii) The right lateral acute angle measured 35° and

the left 28° . This difference was due to the right lateral border movement path being closer to the Y axis than the left. The left lateral border movement path formed an angle of 11° with the Y axis and the line joining the maximally protruded position to the I.C.P. also formed an angle of 11° with the Z axis. Thus the entire envelope of motion appeared rotated on the vertical axis towards the right side which was the subject's preferred side for mastication. (Fig. No. 25)

- (d) The occlusal border movement rhombus was not a flat surface so its exact area could not be assessed from the mandibulograph records. It was divided into two triangular forms by the protrusive movement path. The right triangle showed a surface coverage of 30.25 sq.mm. and the left 40.00 sq.mm. The total area being 70.25 sq.mm.

2. SAGITTAL ELEVATION: (Fig. No. 26) The sagittal profile of the total movement space also resembled the form suggested by Posselt (38,39).

- (a) The Posterior Boundary of the total envelope of motion was formed by the O/C movement path (a a) during manual posterior traction on the chin. The jaw point shifted .5 mm. posteriorly from the I.C. Position to the M.R. Position but remained on the Z axis. The O/C movements were initiated from, and terminated into, this position. As is evident from the Table No. 1. (Appendix II, Vol. II), the lateral component of motion became zero before the jaw point reached the Z axis or occlusal contact position.

For a distance of 16 mm. from the M.R. Position, the posterior border open/close movement path followed a straight course downwards and posteriorly, forming an angle of 75° with the Z axis. Beyond 16 mm. mark, the posterior border movement path showed a protrusive component giving it the arched form 'a' ending up into maximal open position 31.2 mm. from the intercuspal position, and 10.5 mm. posteriorly to the X axis.

- (b) The Occlusal Boundary was formed by the protrusive sliding contact excursion 'c'. From the I.C., Position the jaw point dropped through a distance of 4.7 mm. to provide incisal clearance and then lifted up again to reach the M.P. Position 5.0 mm. anterior to the intercuspal position and 4 mm. from the Z axis.
- (c) The Anterior Boundary The open/close path from M.P. Position formed the anterior boundary of the total envelope. It commenced almost vertically, parallel to the X axis, indicating a further protrusive shift of the mandible. The path then gradually sloped in a downward and distal direction, becoming almost horizontal at the M.O. Position.

There appeared to be some distortion of the recording in maximally open position, due to the mandibular light reaching sections of the photocell frame that gave a lesser degree of linearity to the recordings.

3. FRONTAL ELEVATION: Fig. No. 27

- (a) As reported by Schweitzer, ⁽⁴³⁾ the frontal elevation of the envelope of motion was shield-like in shape. The I.C. Position forms the highest point in the envelope. All border movements ended in this position. The left lateral excursions reached the Y axis 0.7 mm. from the zero point, while the right excursions, 0.2 mm. to the right of the zero point. Thus, although there was a definite point intercuspal position located at the zero point which formed the starting and finishing point of the excursions, there was a free space on either side of this position and the jaw point reached the intercuspal position without any further closing due to cuspal guidance.
- (b) The anterior and posterior border open/close paths did not coincide with the X axis or the median plane. The anterior border open/close path 'b' started from the M.P. Position located 4 mm. below and 1.2 mm. to the right of the I.C. Position. The path crossed the median sagittal plane at 17 mm. from the I.C. Position and ended up in M.O. Position 1.5 mm. to the left and 32 mm. from the intercuspal position.
- The posterior border movement path 'a a' started from the intercuspal position progressively shifting to the left side, it reached the M.O. Position 1.5 mm. to the left and 32 mm. from the intercuspal position.
- (c) The lateral border open/close movement paths were adopted from functional exercises. It is very likely

that the actual lateral borders may be located some distance still farther away from the X axis. The capacity for lateral motion increased as the mouth opened, it was maximal at about the middle of the open/close path then decreased progressively and was lost as the jaw point reached the M.O. Position.

The frontal border outline form covered an area of 670 sq. mm.

CUSPAL GUIDANCE ANGLES:

To assess the part played by the cusps during functional movements, cuspal guidance angles were measured. The lateral and protrusive excursion exercises were performed with maintained tooth contact, so it was considered that the initial 0.5 mm. vertical displacement of the jaw point must necessarily be due to cuspal guidance in both the protrusive as well as lateral excursions. Tangents were drawn at the 0.5 mm. level on the respective paths. The angles formed by the tangents on lateral movement paths to the Y axis were measured as lateral cuspal guidance angles and those formed by the tangents on protrusive movement paths to the Z axis were measured as protrusive guidance angles. Table No. 2 represents the angle readings on three sets of four excursions in each direction.

The variation in the cuspal guidance angle readings in similar movements were due to slight variations of the three components of motion during these excursions. The right or left excursion involved varying degrees of protrusion and similarly protrusive excursion involved varying degrees of lateral components. This caused cuspal inclines to come together in different combinations and so each time the jaw point was displaced to different levels.

Thus the lateral and protrusive cuspal guidance angles were not the product of any particular incline planes, instead these were produced by cuspal inclines coming together in a particular manner. To determine the presence, or absence, of cuspal guidance, the maximal angle reading of 54° which occurred during the protrusive excursion was taken as a guide. It was considered that, if the cuspal guidance angle was 54° or less, it would positively indicate cuspal guidance and if the angle was greater than 54° it would mean lack of cuspal guidance.

THE ENVELOPE OF TOTAL JAW POINT MOTION
IN EDENTULOUS SUBJECTS

Similar to the procedure followed for the dentulous subject, three elevations of the total envelope of motion were developed for the three edentulous subjects. (Figs. No. 29, 32, 34).

Before considering the assessments, it has to be remembered that the dentures for the edentulous subjects were made using a central bearing device for the registration of the maxillo-mandibular relationship, the objective being registration of the most retruded, unstrained relationship, and special efforts were made for the accurate incorporation of this relationship in the finished dentures. In other words, the dentures were constructed so that the teeth occluded in a position consistent with the apex of the gothic arch tracings, which according to Posselt (38,39) is the "most retruded maxillo-mandibular relationship." During mandibulography, the accuracy of this intercuspal position was verified by asking the subject to open slightly and then close and clench during a swallowing act. Fig. No. 28 shows the drawings of the terminal parts of the closing strokes of the above exercise in the three edentulous subjects. The mandibulograph readings are shown in Table No. 3. The closing strokes commenced from different degrees of right, left and antero-posterior deviations, but the jaw point approached the intercuspal position directly along the X axis, both laterally as well as antero-posteriorly. The right-left component reached zero position much earlier than the antero-posterior component. In each of the three subjects, the intercuspal position was reached without any cuspal guidance, indicating that the intercuspal position assumed by the upper and lower dentures coincided with the retruded maxillo-mandibular relationship, as recorded by the gothic arch tracing and according to the definition by Posselt. (38,39)

1. THE HORIZONTAL ELEVATION OF THE TOTAL ENVELOPE
OF MOTION IN THE EDENTULOUS SUBJECTS

(Fig. No. 29.)

Posterior Border:

The edentulous outline forms differ from the dentulous subject (Fig. No. 25) in the shape of the posterior border. In the dentulous subject, the posterior border lateral excursion with maintained occlusal contact remained anterior to the Y axis and terminated in the intercuspal position. During posterior traction, the jaw point moved to the maximally retruded position 0.5 mm. posterior to the intercuspal position only along the Z axis. In all the three edentulous subjects, the retruded lateral excursions with maintained occlusal contact passed posterior to the Y axis and terminated in maximally retruded positions, located directly on the Z axis posterior to the intercuspal position (apex of the gothic arch tracing). In two subjects, this maximally retruded position was located 0.7 mm. posterior to the intercuspal position and in the third subject, 0.5 mm. posterior.

The posterior lateral excursions on the right side in all the three subjects approached the M.R.P. from a postero-lateral direction. On the left side in two subjects, the posterior lateral excursion approached the M.R.P. from a postero-lateral direction, while in one subject (subject 'c' Fig. No. 29) the left posterior lateral excursion passed posterior to the Y axis very close to the zero position and approached the M.R.P. from an antero-lateral direction. The postero-lateral approach of the lateral excursions to the M.R.P. gives the posterior boundary of the envelope of motion a cleft appearance, the M.R.P. being located at the apex of the cleft. This is best illustrated in subject 'D' Fig. No. 29.

The lateral excursions on the right side pass much further posteriorly to the Y axis than on the left side. The mandibulograph readings of the most posterior points on the right and left side in the lateral posterior superior border excursions in the three edentulous subjects and one dentulous subject, are shown in Table No. 4.

Schweitzer (43,44) observed that the distal location of the jaw point in the open mouth position was due to the fact that the jaw point movement was, after all, a type of hinge movement. Regardless of where the exact location of the hinge may be, the anterior part of the jaw having a greater freedom of movement than the condylar part, would be expected to move in a downward and backward direction during any excursion involving a retracted opening of the mouth. The phenomenon presented here is different from the observations by Schweitzer, in that the capacity for distal displacement of the jaw point at the occlusal level of the total envelope of motion during the posterior border lateral excursions was more on the right side than on the left. In other words, the envelope of motion extended further posteriorly on the right side than on the left side. The phenomenon as seen in the dentulous subject, was much more pronounced in the edentulous subjects.

Maximal Lateral Positions: (M.L.P.R. and M.L.P.L.)

The maximal lateral position to which the jaw point could move during a border-sliding-contact-lateral excursion, was located closer to the intercuspal position on the right side than on the left side. Table No. 5 shows the distances the M.L.P.R. and M.L.P.L. were located from the intercuspal position in the subjects tested.

Maximally Protruded Position:

The sliding contact protrusive path generally remained very close to the Z axis vertically as well as laterally. In two edentulous subjects, the maximally protruded position was directly along the Z axis, and in one, it deviated 0.5 mm. to the right. Table No. 6 shows the actual location of the M.P.P. in relation to the I.C.P. in the four subjects.

Lateral Acute Angles:

Similar to the dentulous subject, the lateral acute angles were measured by joining the maximal lateral positions to the maximally retruded points on the respective lateral border excursions (Fig. No. 30). The measurements of the angles compared with the measurements for the dentulous subject are shown in Table No. 7. Similar to the dentulous subject, the occlusal border movement envelope appeared to be rotated around a vertical axis towards the right side, which, as indicated earlier, was the "preferred side" in all the subjects.

In the dentulous as well as edentulous subjects, the right lateral angles were greater than the left lateral angle, because the right lateral angle movement paths were located further posteriorly than the left lateral movement path. Both the right and left lateral angles were greater in the edentulous subjects than in the dentulous subject because border lateral excursions in the edentulous subjects followed a much further posterior course than in the dentulous subject.

The areas covered by the horizontal elevation of the occlusal border outline forms were measured in sq. mm. by counting up the squares on graph paper and are shown in Table No. 8, in comparison with the area in the dentulous subject.

The area covered by the horizontal elevation of the occlusal boundary of the total envelope of motion is much smaller in the edentulous subjects than in the dentulous subject and has a more symmetrical distribution on the right and left sides. (Table No. 8)

2. THE SAGITTAL ELEVATION OF THE TOTAL ENVELOPE
OF MOTION IN THE EDENTULOUS SUBJECTS

(Fig. No. 32)

A complete envelope could not be recorded because of shifting of the lower dentures in extreme open mouth positions. The subjects were asked to bring the teeth together firmly, swallow and then perform the exercises involving opening of the mouth. As the jaw closed from the open position, the subject was again asked to bring the teeth together and swallow before the next opening of the mouth. In the mandibulograph records, the point of dislodgement of the dentures from the foundation could be easily detected as a closing movement, (Fig. No. 31). For the drawings of the sagittal outline forms, only records of the opening strokes were used, with the exception of subject 'D', where the alveolar ridges were bulbous and the dentures were not easily displaced, so that a recording of actual opening and closing movement of the jaw point was possible.

The sagittal outline form of the total envelope of motion in the edentulous subjects differed from that in the dentulous subject in the form of the posterior open/close border path. At the occlusal level the jaw point shifted 0.7 mm. posterior to the intercuspal position in two subjects and 0.5 mm. posterior in one subject (Table No. 9).

Unlike the dentulous subject, the strained maximally retruded position in the edentulous subjects allowed a certain degree of freedom of lateral movement. Table No. 10 shows some of the mandibulograph readings for the terminal parts of the closing strokes. The maximally retruded position was reached from a disto-lateral and inferior direction,

Whereas in the dentulous subject the maximally retruded open/close movement path is interrupted in the middle by an obtuse angle (Fig. No. 26) in the edentulous subjects no such angle was observed (Fig. No. 32).

For sliding contact protrusive, (a cusp-guided excursion,) the protrusive cuspal guidance angles were measured as the angles formed by tangents to the movement path when the jaw point was at 0.5 mm. vertical distance from the Z axis. Fig. No. 33 and Table No. 12 show the protrusive cuspal guidance angles in the three edentulous subjects.

The maximal cuspal guidance angles were used to establish presence or absence of cuspal guidance during function. Angles less than the maximal angle were considered to indicate definite cuspal guidance and angles greater than the maximal angle were accepted as indicating absence of cuspal guidance during the particular movement.

The maximally open positions were not considered because of displacement of the dentures.

3. FRONTAL ELEVATION OF THE TOTAL ENVELOPE OF MOTION
IN THE EDENTULOUS SUBJECTS

(Fig. No. 34)

The frontal elevation of the total envelope of motion in the edentulous subjects was very similar to that in the dentulous subject. In only one edentulous subject could the lateral border open and close movements be executed i.e. subject 'D' (Fig. No. 34). The outline form was shield-like, similar to the dentulous outline form. The maximal width of the frontal elevation was located about 13 mm. from the intercuspal position. The maximal opening achieved by this particular subject was 25 mm.

The right and left lateral open and close movement paths converged to a point at the maximal opening. It can be visualized that if the lateral open and close movements could have been performed by other subjects similar shield-like outline forms would have been traced.

The intercuspal and maximally retruded positions were located on the median line, the former overlapping the latter. The lateral excursion paths in Subject, 'B', (Fig. No. 34) crossed the Y axis and passed at a higher level than the I.C.P. This possibly would be related to the height and type of cusps on the artificial dentures.

The lateral cuspal guidance angles were measured in the same manner as the protrusive cuspal guidance angles (Fig. No. 35) The measurements are shown in Table No. 12.

DISCUSSION AND SUMMARY:

The characteristics of the total envelope of jaw point motion can be summed up as:

1. General Shape and Form of the Total Movement Space:

In both types of subjects, the total envelope of motion is generally rhomboidal in cross-section and inverted pyramidal in form. The rhomboid base of the pyramid forms the superior or the occlusal boundary of the space representing limits of excursions in a horizontal plane with maintained tooth contact. The apex of the pyramid is deflected posteriorly representing the maximally open position of the jaw point.

The four sides of the pyramid are formed by (1) the two right and left anterior faces representing the limits of excursion anteriorly and to the right and left sides of the median plane, and (2) the two right and left posterior faces of the pyramid representing the limits of excursion posteriorly and to the right and left sides of the median plane.

The two anterior faces meet each other at an obtuse angle anteriorly, the junction representing the location of the maximally protruded path of open/close movements. The two posterior faces meet similarly and the junction represents the location of maximally retruded open and close movement path. The right and left anterior faces meet the right and left posterior faces respectively at acute angles laterally, indicating the position of maximally lateral open/close movement paths on the two sides.

The four faces converge into maximally open position which possibly is a point position at least in the one dentulous subject examined.

2. The Occlusal Boundary:

It is the rhombus described by jaw point excursions in a horizontal plane with maintained tooth contact.

In the dentulous subject, the posterior limit of the occlusal boundary is formed by the retruded lateral movement paths. The excursions initiated from the intercuspal position and passed laterally and anteriorly to terminate into the maximal lateral positions on the right and left sides. The movements throughout their course remained either in line with the intercuspal position on the Y axis (in the horizontal view) or passed anteriorly to it. In no instance in the dentulous subject did the excursions pass posterior to the Y axis or the intercuspal position. The jaw point could be shifted 0.5 mm. posterior to the intercuspal position directly along the Z axis, but there was no freedom of lateral movement distal to the intercuspal position. The retruded lateral excursions on the right side passed much closer to the Y axis anteriorly than on the left side.

In all of the edentulous subjects, the posterior limit of the occlusal boundary was located much further posteriorly than in the dentulous subject. The jaw point could be shifted posteriorly from the intercuspal position up to a distance of 0.7 mm. on the Z axis. The retruded sliding contact lateral excursions could initiate from this maximally retruded position but were accompanied by depression of the mandible.

With mandibular depression as little as 0.4 mm. and sliding lateral excursions of 1.0 mm. the jaw point could move as far posteriorly as 1.2 mm. from the Y axis. This capacity for distal movement was much greater on the right side than on the left.

(Figs. No. 29, 30). In the edentulous subjects, freedom of lateral movement without opening of the mouth was lost at the maximally retruded position.

In both the dentulous as well as edentulous subjects, the capacity for lateral movements was greater on the left side than on the right side. The maximal lateral position was closer to the intercuspal position on the right side than on the left side.

In both the dentulous as well as the edentulous subjects, the right lateral acute angle was wider than the left. The increase in the width of the angle on the right side appeared to be due to the right retruded lateral excursion passing closer to the Y axis in the dentulous subject and further posteriorly to the Y axis in the edentulous subjects, than on the left side. This meant that the envelope of motion extended further posteriorly on the right side than on the left side and more so in the edentulous subjects than in the dentulous. All the subjects examined preferred to chew on the right side. (The preference of the chewing side was determined by observing the subject during ad lib. single peanut chewing. The subjects shifted the food to between the right side teeth. This showed up on the mandibulograph records as a deflection of the jaw point to the right side.)

Thus contrary to the observations by Posselt, in both dentulous as well as the edentulous subjects the jaw point could be shifted further distally from the apex of the gothic arch tracing. In the dentulous subject at this maximally retruded position the mandible lost its ability for lateral movement and had to protrude to the gothic arch apex position which was also the intercuspal position for the performance of lateral excursions. In the edentulous subjects lateral excursions were possible from this maximally retruded position. The mandible did not have to move forward to the gothic

arch apex position. It appears that there is some reciprocal relationship between the preference for the side for mastication and further distal extension of the envelope of motion.

If the pyramidal total envelope of movement space could be sliced vertically into four quadrants by two cuts - one in an antero-posterior direction on the Z axis and the second in a medio-lateral direction on the Y axis, both running vertically through the X axis, the two right and left posterior quadrants, being located closer to the centre of the base of the skull can be expected to offer the mandible greater stability and security and greater mechanical advantage than the two anterior quadrants. Considering that (i) the envelope of movement space appears to be rotated on a vertical axis towards the preferred side, (ii) the capacity for distal movement is greater on the preferred side and (iii) it is greater in the edentulous subjects than in the dentulous, it is hypothesised that the posterior quadrant on the preferred side (which in the subjects examined, happened to be the right side) would offer the mandible maximal stability and security and greater mechanical advantage and whenever the mandible is called upon to exercise greater masticatory stresses, it will perform such function in the posterior quadrant on the preferred side. It is further hypothesised that, with the institution of the Edentulous State, the need of the mandible to recede to the posterior quadrant of the total envelope of movement space on the preferred side becomes much greater than in the Dentulous State, and that this need is provided for by the further distal extension of at least the occlusal part of the total envelope of movement space on the preferred side in the Edentulous subjects.

The Simulated and Functional movements were examined in the Dentulous and the Edentulous subjects to verify the validity of the above hypothesis.