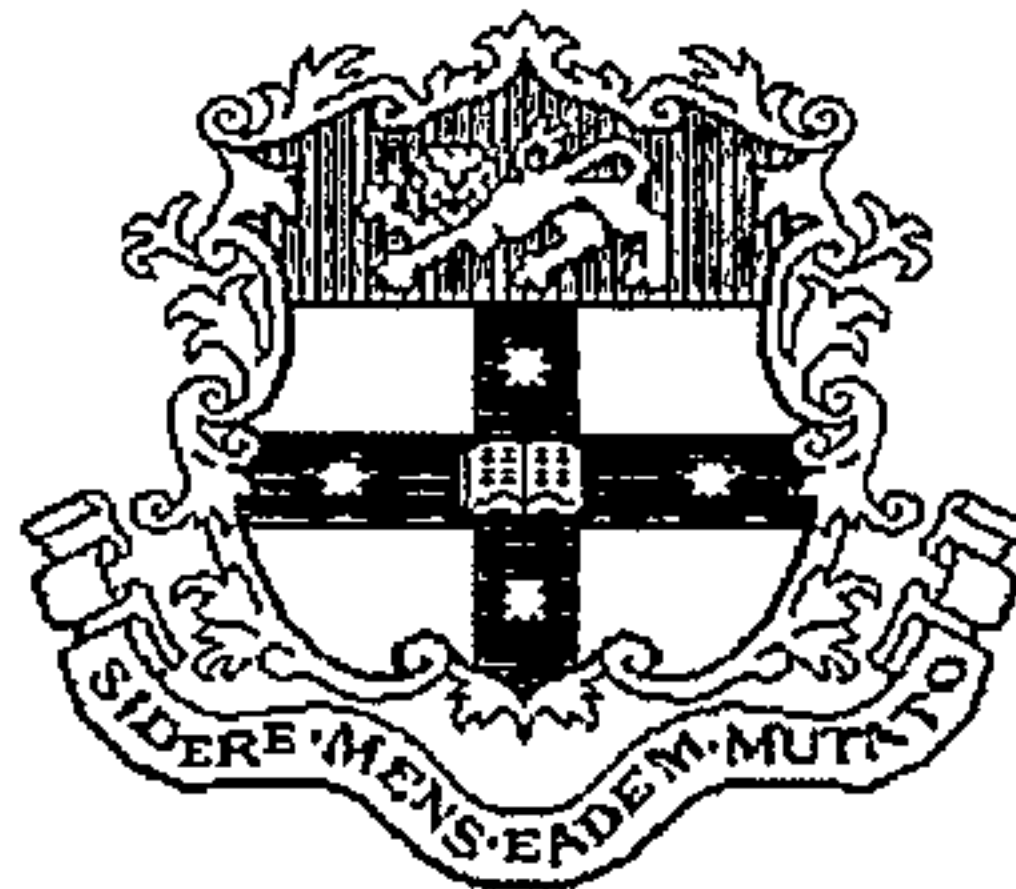


Clinical Significance of Severe Tooth Undercuts in Prosthodontics

A Quantitative Analysis

Ammar A Abdul Razek
BDS GCClinDent

**A Thesis Submitted in Fulfillment of the Requirements
for the Degree of
Master of Science in Dentistry (MScDent)**



**Faculty of Dentistry, University of Sydney
March 2003**

Statement of Authorship

I declare that all the work presented in this thesis is my own, unless otherwise stated.

The work of colleagues is acknowledged in general terms within acknowledgments and specifically within the body of the text, wherever it is appropriate.

A handwritten signature in black ink, appearing to read 'Ammar A. Razek', with a stylized, cursive script.

Ammar A. Razek

March 2003

ACKNOWLEDGEMENTS

I would like to express my deep thanks to all my supervisors:

- Prof. Iven Klineberg, Professor of Prosthodontics and Head of the Jaw function and Orofacial Pain Research Unit for his guidance in writing and for his constructive advice throughout this course.
- Dr. Graham Thomas for his supervision and help at all times, for his foresight and vision in solving the difficulties, and providing a clarity of thought necessary for completion of this work.
- Prof. Mike Swain for his kindness and willingness to participate in supervision, providing clear answers in physics and chemistry to all queries related to my work and keeping me on track.
- Associate Prof. Cyril Thomas for his continuous and valuable advice and encouragement to proceed with this project.

I would like to extend my sincere appreciation to:

- The statistician Ms. Georgina Luscombe for her help and assistance in analysing the results and providing valuable statistical advice.

- Mrs. Tracey Bowerman for her help in ordering the materials and Mr. Armin Roth, Director of Halas Dental Ltd. for his kindness and provision of the materials used in this study.
- Mr. Ken Tyler for making the moulds and Mr. Kamal Wanigaratne and Ms. Terry Whittle for assisting in solving software and technical problems.
- Mr. Nimer Al-Attal, Director of DTK Computers, Jebel-Ali, Dubai, UAE for his help in colour printing and handling of this thesis.
- Last but not the least to my parents, Dr. Ata Abdul Razek and Mrs. Muzaynah Anani, my sister Maysa, and my brothers Mazen and Ahmed who provide great support, understanding, encouragement and inspiration which were essential for this work to be fulfilled.

OVERVIEW

The long-axes of abutment teeth in a partially dentate mouth are often tipped and drifted which accentuates the magnitude of undercuts particularly in molar areas, as the larger surface area of these teeth tends to increase the volume of impression material in the undercut area. In such a situation, tearing of the impression material at the margins of preparations or where it encounters a mechanical lock, presents a problem to dentists. If the undercuts are so great that the tear strength or energy of the impression material is exceeded there will be permanent deformation rendering the impression unusable. The first aim of this study was to measure tooth undercuts on study casts with varying degrees of undercuts utilising two improved methods, in order to create an index to be used in determining or defining undercut severity and this will be correlated with the fit of the prosthesis. It was found that severe undercuts could be defined as being one standard deviation from the mean. Severe undercuts were greater in casts having missing teeth than ones having no missing teeth, and were more in casts having poor fitting prostheses than ones having well fitting prostheses. The second aim was to compare tear energy of alginate impression material utilising a crescent-shaped mould which produced specimens of 10 mm thickness (thick) and a trouser shaped mould which produced specimens of 1 mm thickness (thin). It was found that thin alginate specimens had higher tear energies than thick specimens. The third aim was to compare tear energy of alginate and elastomeric impression materials utilising the trouser-shaped mould and to compare tensile strength and modulus of elasticity of the same materials utilising a universal dumb-bell-shaped mould. In general, elastomeric impression materials had higher tear energies and tensile strengths. Some alginates showed equal or even greater values of elastic modulus than certain elastomers.

TABLE OF CONTENTS

PAGE NO.

1. Introduction	1
1.1 Literature Review.....	1
1.1.1 Surveying and tooth undercuts.....	1
1.1.2 Background of tooth and undercut assessment.....	5
1.1.3 Tooth size studies.....	8
1.1.4 Chemistry and history of relevant impression materials.....	15
1.1.5 The effect of the bulk of an impression material and the degree of tooth undercuts on the accuracy of an impression.....	23
1.1.6 Blocking out undercuts.....	32
1.1.7 The effect of tray design and tray adhesives on the accuracy of an impression.....	34
1.1.8 Tear and tensile properties of impression materials.....	45
2. Hypotheses and aims	58
2.1 Hypotheses.....	58
2.1.A The association between casting fit and magnitude of the averaged undercuts.....	58
2.1.B The association between casting fit and magnitude of undercuts for each surface.....	58
2.1.C Defining a severe undercut.....	59
2.1.D The association between the thickness of alginate impression and tear energy.....	59
2.1.E Tear energy.....	60
2.1.F Tensile properties(strength and modulus of elasticity).....	60
2.2 Aims.....	61

TABLE OF CONTENTS	PAGE NO.
3. Materials and methods	62
3.1 Part I.....	62
3.1.1 Compiling experimental casts.....	62
3.1.2 Surveying.....	64
3.1.3 Methods of quantifying undercuts.....	64
A) The Microscribe 3DX technique (Method one).....	65
B) The Relative Undercut Measurement-RUM technique (Method two).....	67
3.2 Part II.....	68
3.2.1 Tear energy experiment for alginates (Method one: Crescent-shaped mould).....	69
3.2.2 Tear energy experiments for alginates and elastomers (Method two: Trouser-shaped mould).....	72
3.2.3 Tensile tests for alginates and elastomers (Dumb-bell-shaped mould).....	75
4. Results	78
4.1 Statistical analysis of undercut measurements (Microscribe and RUM).....	78
4.1.1 Severity of the undercut measurements.....	78
A) Average undercut.....	78
A1. "Fit" compared with "did not fit".....	79
A2. Maxilla compared with mandible.....	79
A3. Left compared with right.....	79
A4. Anteriors compared with posteriors.....	79

TABLE OF CONTENTS

PAGE NO.

B) Distal, buccal, mesial and lingual surfaces.....	80
B1. Cases compared with controls.....	80
B2. "Fit" compared with "did not fit" groups.....	81
B3. Analyses of cases only.....	81
B3.1 Maxilla compared with mandible.....	81
B3.2 Left compared with right.....	82
B3.3 Anteriors compared with posteriors.....	83
B4. Analyses of controls only.....	83
B4.1 Maxilla compared with mandible.....	83
B4.2 Left compared with right.....	84
B4.3 Anteriors compared with posteriors.....	85
4.1.2 Reliability of method one (Microscribe-3DX).....	86
A) Inter-observer.....	86
B) Intra-observer.....	87
4.1.3 Defining a severe undercut (Microscribe-3DX).....	88
4.1.4 The association between severe undercut and case or control.....	92
4.1.5 The association between severe undercut and casting fit.....	94
4.1.6 Reliability of method two (RUM).....	97

TABLE OF CONTENTS	PAGE NO.
4.2 Statistical analysis of tear energy (method one & method two).....	98
4.2.1 Tear energy (method one: Crescent-shaped mould).....	98
4.2.2 Tear energy (method two: Trouser-shaped mould).....	99
4.2.3 The association between the thickness of alginate impression material and tear energy.....	101
4.3 Statistical analysis of tensile properties of impression materials.....	103
4.3.1 Comparison between the ten materials.....	105
4.3.2 Comparison between the five elastomers and the five alginates.....	106
4.3.3 Comparison amongst elastomers.....	106
4.3.4 Comparison amongst alginates.....	107
5. Discussion	109
6. Conclusions	116
7. References	118

1. Introduction

1.1 Literature review

1.1.1 Surveying and tooth undercuts

There appears to be no satisfactory method to describe the severity of hard tissue undercuts associated with teeth; however, the importance of locating and measuring undercuts has been recognised in dentistry for almost 100 years.

In 1916 Prothero* advanced the "cone theory" which divided molars and premolars into occlusal and cervical cones, where they meet at the greatest circumference or diameter of the teeth (Figure 1). Kennedy (1928)* called it the "height of contour". De Van (1935)* referred to cervically converging surfaces as "infra-bulge" areas and the occlusally sloping surfaces as "supra-bulge" planes. Fortunati (1918)* described "a mechanical device" which could be used for charting correct clasp outlines. Applegate (1940) reported that the first commercial surveyor was designed by Weinstein and Roth (1921)*. Roach (1930)* and Elliot (1940) considered survey lines from an anatomic perspective and described the survey lines of different teeth according to the long-axis of the individual tooth with undercut portions to be determined from figures represented in G.V.Black's "Dental Anatomy". Elliott (1940) described tooth contours in relation to the long-axis. Blatterfein (1951) recognised the tendency of teeth to migrate, which led to his description of "typical" versus "atypical" survey lines.

* Note: These historical references were not cited in their original publications, but were referred to by Lechner (1996).

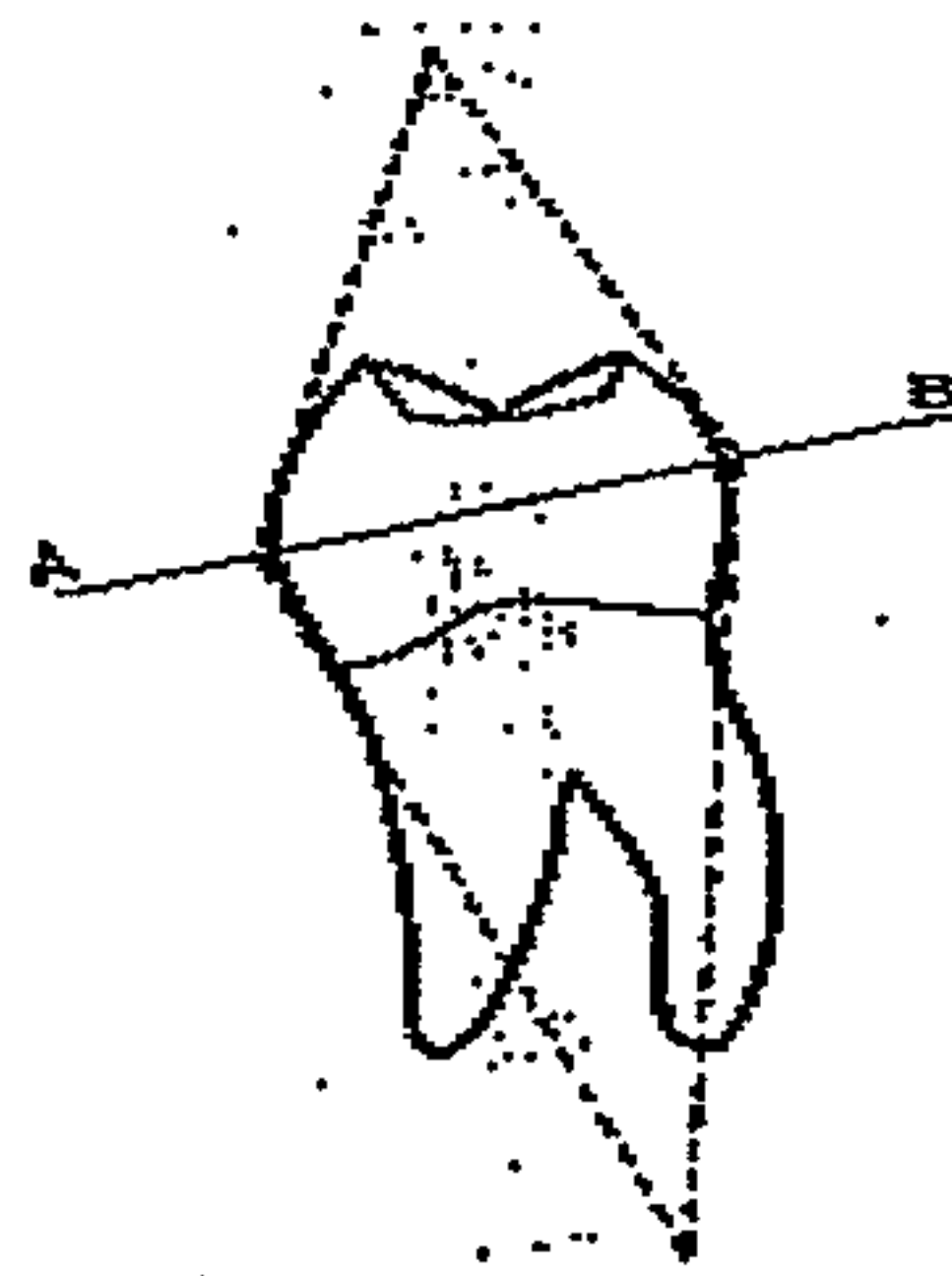


Figure 1 Prothero illustration of his "cone theory". AB line represents the greatest buccolingual diameter (Applegate 1940)

Many authors feel that, wherever possible, the diagnostic cast should be surveyed with its occlusal plane as parallel as possible to the horizontal plane. Others discussed "interferences, retention and aesthetics" as the main parameters to be considered when choosing a path of insertion of a prosthesis and changing the path of insertion results in decreasing the undercuts on one or more tooth surfaces whilst increasing undercuts on other tooth surfaces (Applegate 1940; Henderson et al. 1985; Zarb et al. 1978 and Taylor et al. 1984).

Elliot (1940) stated that if a tooth was held in a vertical position and a marking device parallel to the long-axis of the tooth was carried around its circumference, the marker would circumscribe a line or a zone of maximum contour called the "neutral zone". The area above the neutral zone is called "the non-undercut zone" and the area below it is called "the undercut zone". Elliot named that "the dual circle of design" (Figure 2). The line that is established on teeth by the surveying device suggested the name of the method. This line forms a circle that encloses the four axial surfaces of one or more teeth. The second circle, the mucosa circle, is established on the mucosa immediately below the gingiva of the tooth, or teeth, upon which the tooth circle is established - hence the name. The occlusal or incisal convergence zone is used to prevent vertical

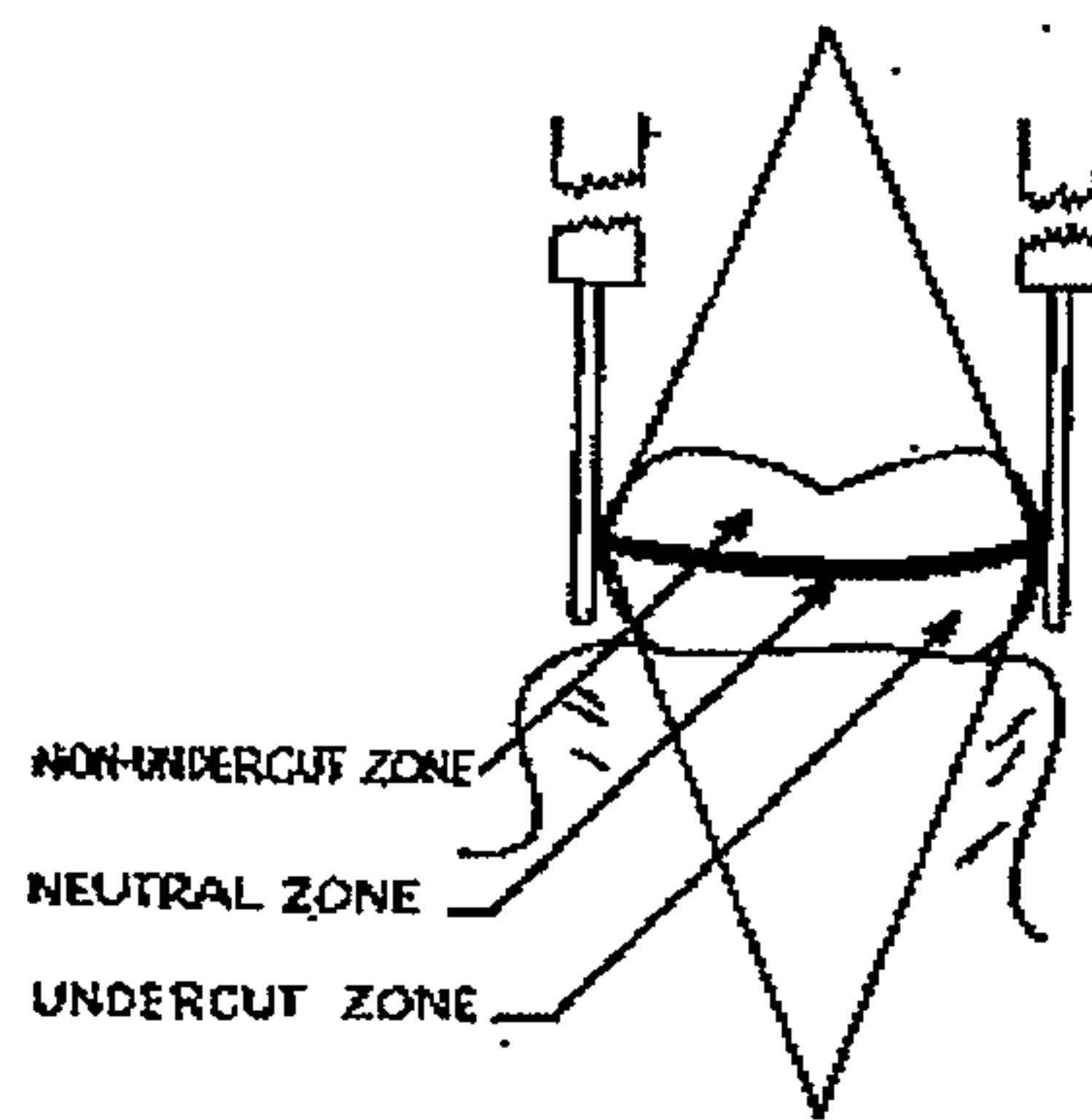


Figure 2 Segregation of basic tooth contours (Blatterfein 1951)

displacement of the partial denture in a gingival direction, and it is used for the occlusal or incisal rest. The neutral zone is used for the lateral resister, the reciprocal bearings of the clasp and tooth-borne bars are designed to occupy a position on the buccal or lingual surfaces of the tooth. The gingival convergence (undercut) zone is used to prevent displacement of the partial denture in an occlusal direction and to retain the other parts of the clasp in position. Active bearing is designed to occupy a position on the proximal surfaces of the tooth immediately below the tooth circle (the mucosa circle) and is used for mucosa-borne bar clasps, as described by Elliot (1940).

Lechner (1996) stated that abutments in a partially edentulous jaw are rarely aligned so that the long-axis is parallel to the path of insertion; they are often tipped or tilted as migration into the edentulous portion of the ridge occurs. McGivney and Carr (2000) in the tenth edition of the text "McCracken's Removable Partial Denture" defined the surveyor as "an instrument that is used to determine the relative parallelism of two or more surfaces of the teeth or other parts of the casts of the dental arch". They further described the purposes of the surveyor as follows:

- (a) Surveying the diagnostic cast to determine the most desirable path of placement that will eliminate or minimize interference to placement and removal of a prosthesis.
- (b) Identifying the proximal tooth surfaces that are or need to be made parallel so that they act as guiding planes.
- (c) Locating and measuring areas of teeth that may be used for retention.
- (d) Determining the most suitable path of placement, thus locating the retainers and artificial teeth to the best aesthetics advantage.
- (e) Permitting an accurate charting of the mouth preparations to be made, i.e. to provide guiding planes, to reduce excessive tooth contours, to eliminate interferences, and to permit more acceptable location of reciprocal and retentive clasp arms. This may be achieved by marking these areas on the diagnostic cast using an undercut gauge to estimate the amount of tooth structure that may be removed, and then trimming them using the surveyor blade. The angulation and extent of tooth reduction could be established before preparing the tooth in the mouth.
- (f) Delineating the height of contour on the abutment teeth, and to locate areas of undesirable tooth undercut that are to be avoided, eliminated, or blocked out.
- (g) Recording the cast position in relation to selected path of placement for future reference by locating three dots or parallel lines on the cast.
- (h) Contouring wax pattern : the surveyor blade is used as a wax carver during this phase of mouth preparation, an undercut of 0.375mm or less is sufficient for retentive purposes. Guiding planes on all proximal surfaces should be parallel to the previously determined path of insertion.
- (i) Surveying ceramic veneer crowns.

(j) Placing intra-coronal retainers.

(k) Placing internal rest seat.

(l) Machining cast restorations.

(m) Surveying the master cast.

The most widely used surveyors according to McGivney and Carr (2000), are the Ney and the Jelenko; both of which are precision-made instruments. The main difference is that the Jelenko arm has a swivel action while the Ney arm is fixed. Another common surveyor is the William's surveyor (McGivney and Carr 2000).

1.1.2 Background of tooth and undercut assessment

Tooth formation is under moderately strong genetic control and final crown size is reached well before teeth erupt into functional occlusion. Teeth are durable, readily accessible for examination, and after eruption are affected by environmental influences of tooth wear and pathological microbiological processes. Proximal and opposing tooth relationships in the permanent dentition are determined during the transitional phase of dental development when the deciduous teeth are replaced and adequate occlusal relationships are established. Tooth loss may be a possible cause of pathological conditions of facial asymmetry, masticatory inefficiency, speech and aesthetic problems (Yardeni 1969). For these reasons, tooth measurements have provided valuable data for studies of human phylogeny and ontogeny. Such measurements have been used by anthropologists to compare prehistoric and modern populations, by geneticists to study

heritabilities and chromosomal influences, and by dentists to study the normal and abnormal development of dental occlusion (Brown, Margetts and Townsend 1980).

Undercut gauges are commonly used for measuring tooth undercuts and widely accepted in dentistry. The exact undercut for the position of retentive clasp arm terminals for removable partial dentures must be measured and marked on the master cast. This can be achieved with undercut gauges. The most commonly used undercut gauges are the Ney and the Jelenko undercut gauges (Figure 3). The amount of undercut is measured in hundredths of an inch up to 0.03 inch (0.75 mm); however, undercuts of 0.01 inch (0.25 mm) are adequate for retention of cast retainers; tapered wrought wire retention may utilise up to 0.02 inch (0.5 mm)(McGivney and Carr 2000).

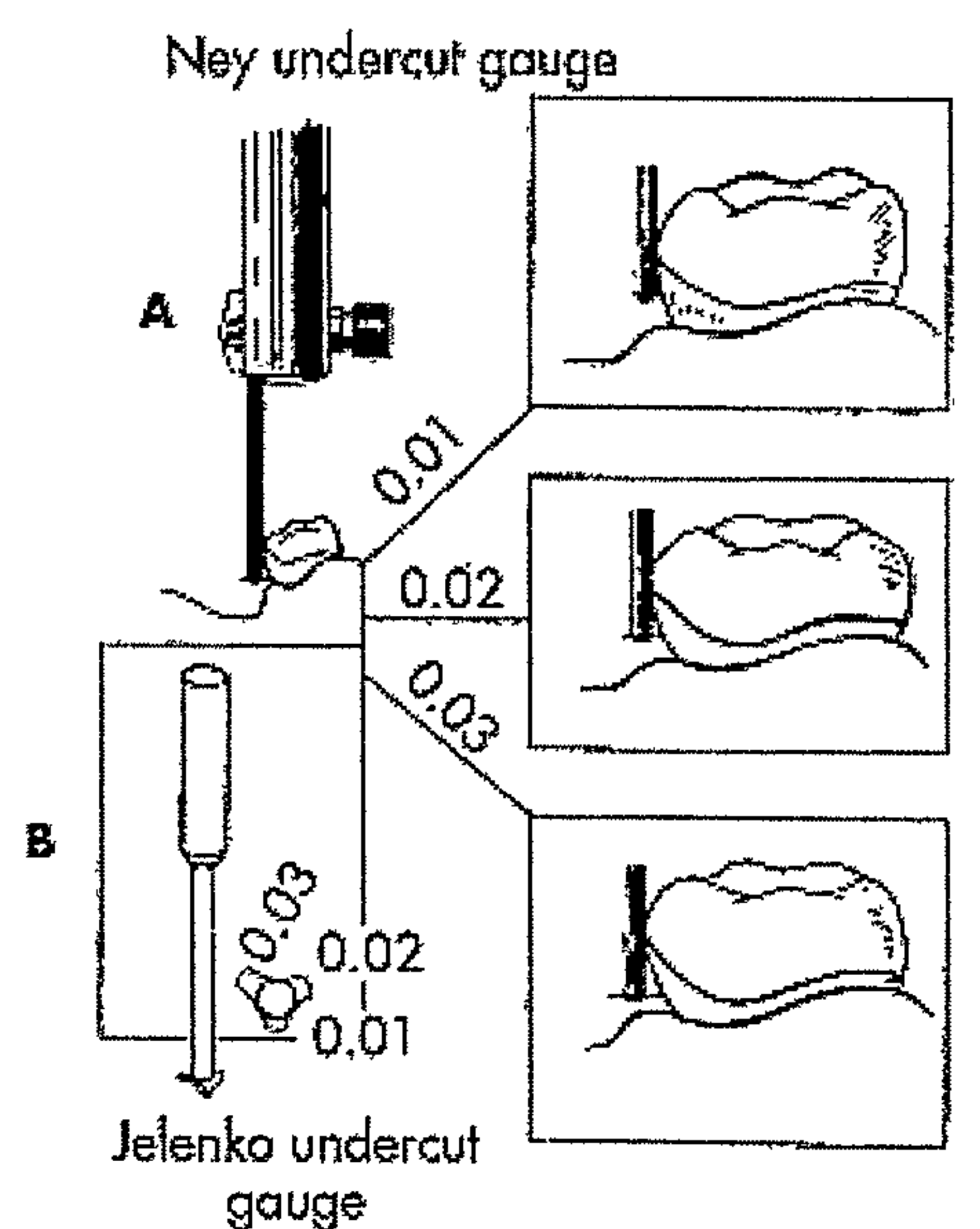


Figure 3 Ney's and Jelenko's undercut gauges (McGivney and Carr 2000).

Two factors that may improve retention and reciprocation in clasp design are: firstly, the length of the guide plane corono-lingually, to adequately reciprocate the action of the retentive arm and secondly, the relationship of the undercut to the guide plane as a means of increased retention (Stern 1975). Stern described the distance of a clasp

travelling in active flexure as “the action distance” and this would determine the distance where reciprocation is required, which is called “the reciprocation distance”. Stern fabricated a cylindrical sleeve having the same diameter as the lip of the Ney undercut gauge (Figures 4 and 5) so that the contour in the infrabulge and suprabulge could be measured.

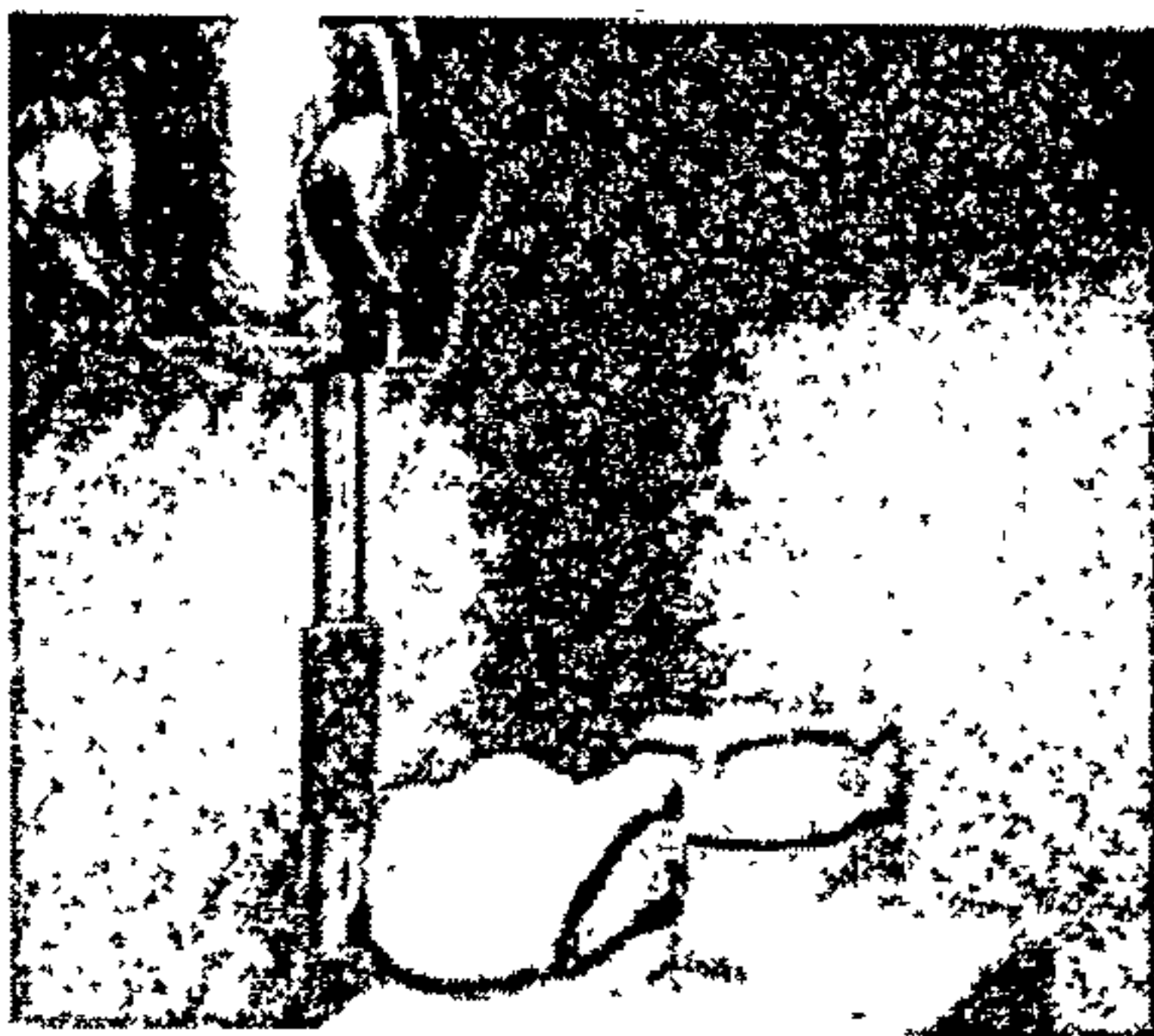


Figure 4
The Ney undercut gauge
with the cylindrical sleeve
(Stern 1975)

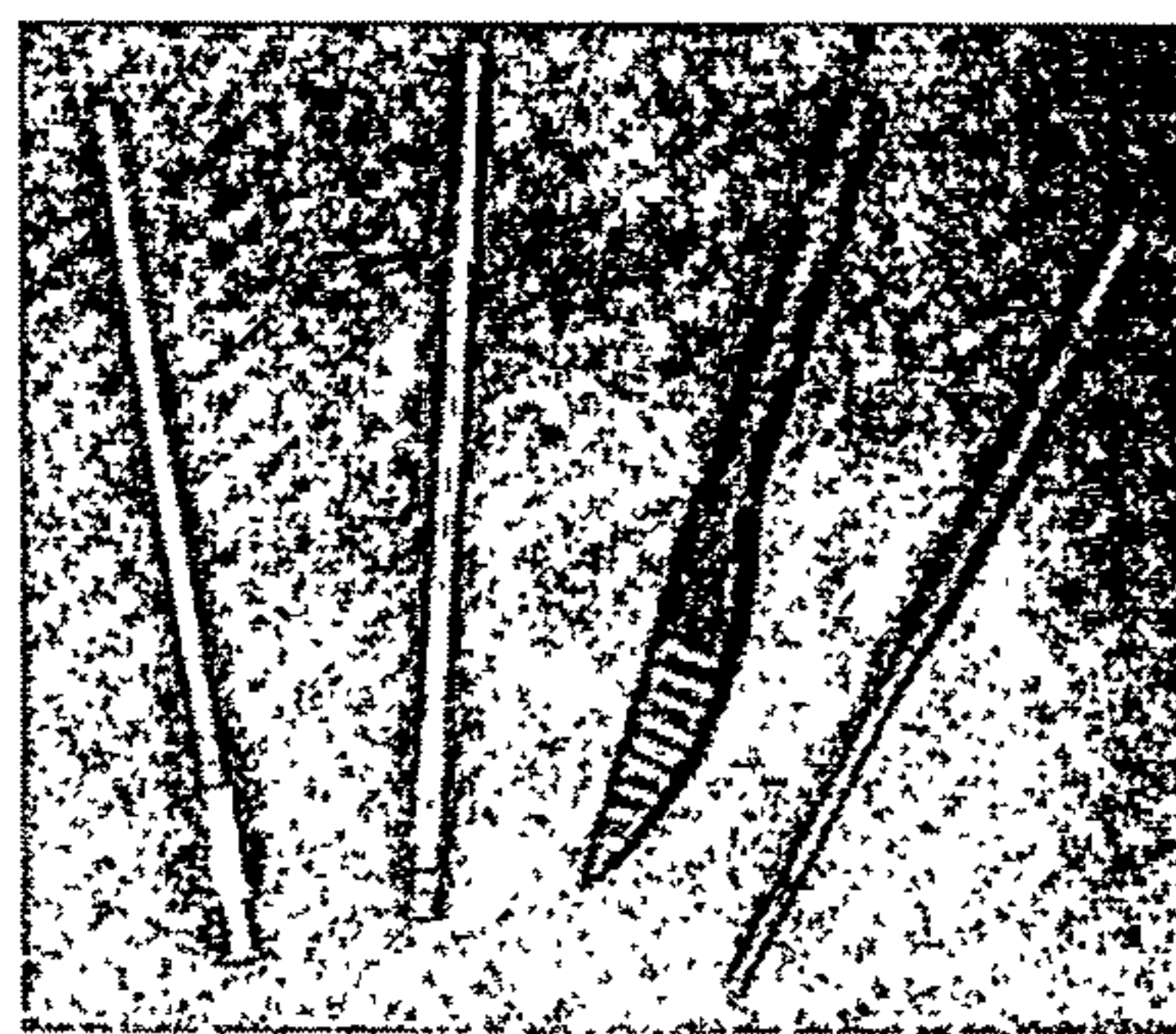


Figure 5
The Ney surveying instruments
(Stern 1975)

Figure 4 shows a Ney undercut gauge with the cylindrical sleeve placed on the position on the tooth to measure the “action distance”. Figure 5 shows the Ney surveying instruments with millimetre (mm) calibrations, which assisted in measuring the “action distance”. Stern concluded that the cylindrical sleeve made it possible to measure suprabulge contours in relationship to undercuts. The “action distance” should be equal to the “reciprocation distance” and the length of the guide plane. Stern further concluded that most teeth did not have enough coronal length for a guide plane of more than 6 mm; for a reciprocating guide plane, the undercut would be limited to 0.010 mm and the guide plane to 5 mm and the concept of “intrinsic retention” of a clasp as a guide plane opposed by an undercut at 180 degrees. Zoeller and Tischler (1995) used a 30-gauge (0.25 mm) orthodontic wire which they attached parallel to the analysing rod of the

surveyor which could be used as a horizontal "feeler gauge" to estimate the adequacy of the retentive undercuts in confined areas where conventional undercut gauges might not fit.

1.1.3 Tooth size studies

Authors used different devices for measuring tooth and tooth position on dental casts including rulers, calipers, dividers, symmetrographs, clear plastic arch-form overlays with millimetre scales, photographs, prints, television images. Some methods are two-dimensional, others three-dimensional.

Savara and Sanin (1969) devised a method which consisted of a modified comparator and a decimal converter, connected to an IBM keypunch. This technique permitted any measurements such as size of the tooth, arch width and length, perimeter, spacing and crowding changes and displaced and rotated teeth to be derived by computer programming. Fertig, Chilton and Varma (1970) compared the two methods of measuring root divergence: the ratio of the projected root length to the actual root length (cosine) or the actual angle itself. In maxillary first molars they concluded that the method of cosine, that is the ratio of the projected length to the actual length, proved to be preferable to the method of the angle itself.

Van der Linden et al. (1972) introduced a three-dimensional measuring system called Optocom - a microscope mounted over a two-dimensional movable table. A dental cast was attached on a sliding table by means of pins and holes with a magnification factor

of ten and field depth of 5 mm. The point to be recorded was aligned with the centre of two cross wires in the microscope. The position of the sliding table was recorded in tenths of a millimetre, by using two measuring rulers with photoelectric screening heads mounted on the base of the sliding table. Seven hand- and two foot-switches transmitted the information to a data converter. To record the third dimension, the bases with the cast were placed in a slot vertically on the beam that carries the microscope. A pointer, mounted on a revolving head was placed on the sliding table to record the z coordinate. A complete dentition involved 387 points and required up to 20 minutes to record one set. Computer programs were developed to check validity of data collected and to spot operator mistakes.

Bjorndal et al. (1974) measured overall length, crown height, root length, and mesiodistal crown diameter and buccolingual crown diameters of all types of teeth except third molars. Teeth were extracted from Caucasian males aged between 17-21 years from the United States Naval Training Centre, Great lakes, Illinois. They excluded teeth with excessive wear and caries and compared measurements with the ones presented by G.V.Black in his "Descriptive Anatomy of the Human Teeth". The mean lengths and diameters were found to be higher than in Black's study; however the range in values in Black's study was larger. Hisamitsu, Iwaku and Fusayama (1978) selected 320 intact extracted teeth (from the Department of Oral Anatomy, Tokyo Medical and Dental University), taking 10 teeth for each of right and left maxillary and mandibular arches. On the photographs of facial and mesial views, the depth and width of the cervical undercuts were measured using the crown axis as the standardised direction. They also measured the inclination of the undercut surface to the crown axis and the food stream surface (cervical undercuts or ridges which are covered by the mucosa). On

the facial and lingual surfaces, their findings were: the depth of the undercut varied from 0.1 to 0.8 mm (being smallest in anteriors) and the vertical width varied from 1.0 to 3.2 mm (being greatest in the bicuspid). The inclination of the undercut surface to the crown axis varied from 6 to 33 degrees (being greatest on the buccal aspect of mandibular molars). The undercut surface/food stream angle varied between 23 and 52 degrees (being large on the palatal surfaces of maxillary incisors and buccal surfaces of mandibular molars). On the proximal surfaces, the depth of the proximal undercut was 1 ± 0.3 mm. The vertical width was 4.2 mm on average, being the greatest in the central incisors (5.8 mm) and the smallest for the third molars (3.3 mm). The undercut surface/crown axis angle was 20 degrees on average, being slightly smaller on the anterior teeth. Ferguson et al. (1978) studied diagnostic casts for 105 Black American children and adolescents aged 10 to 18 years, from students enrolled at the University of Connecticut and from the greater Hartford area (USA). The greatest mesiodistal width of the tooth was measured using automated digital calipers, which were checked with 5 and 12 mm standardized metal blocks for accuracy. They concluded that the correlation between the total mesiodistal width of mandibular permanent incisors and that of the maxillary or mandibular canines and first and second premolars was 0.63 and 0.71 respectively.

Campbell, Zimmerman and Tomlinson (1978) selected a device called a dentometer invented by Tappe to measure the circumference of teeth. The dentometer was accurate to the nearest 0.005 inch (125 μ m). These authors measured teeth on models of 61 patients and excluded malformed teeth and second and third molars. Males and females were separated as well as the right and left quadrants and maxillary and mandibular arches. The maxillary second premolar was chosen as the "predictor tooth", because it

showed high correlation with the remaining teeth in the same set for males. There was high correlation between right and left, with no significant difference in correlation between maxillary and mandibular arches. Central incisors in males and first molars in females showed the lowest correlation with the "predictor tooth".

Macko, Ferguson and Sonnenberg (1979) measured the mesiodistal crown dimensions of permanent teeth of 113 Black Americans (61 males, 52 females) in Connecticut, USA, using an automated digital caliper and checked with 5 mm and 12 mm gauges to ensure accuracy of the electronic instrument. They excluded teeth with caries, fractures, proximal wear, third molars, and teeth with congenital and acquired deformities. They concluded that males had larger mean tooth size than females, for all teeth, except the maxillary and mandibular first premolars. These teeth had the same mean tooth size for both sexes. In the maxillary arch, the central incisors, first premolars and first molars were larger than the lateral incisors, second premolars and second molars, for both sexes. In the mandibular arch, the results were reversed except for the molars. The mean difference in tooth size between males and females ranged from 0.0 mm for first premolars to 0.42 mm for maxillary central incisors. The pattern of tooth size from anterior to posterior teeth in the maxillary and mandibular arches was similar for both arches. There was no pattern of right-left dominance for mean tooth sizes.

Taverne, Amesz-Voorhoeve and Leetouwer (1979) described a method which provided geometric data on occlusal surfaces of dental elements, and allowed comparison between the surfaces and was also designed to facilitate computer processing. A grid was projected on the occlusal surfaces of a tooth or a tooth component and

photographed. An irregularity of the surface caused distortion of the lines of the grid, and provided three-dimensional information in numerical form.

Ghose and Baghdady (1979) measured the mesiodistal crown diameters of permanent teeth of 161 Iraqi (78 males, 83 females) subjects. Two investigators worked independently and measurements were taken to 0.1 mm by means of a sliding caliper with a vernier scale. They concluded that there was variability between the mesiodistal dimension of the corresponding left and right teeth, but none of the measurement differences was significant. The tooth that showed the most stability was the mandibular central incisor, and the teeth that showed the most variability in size were the maxillary lateral incisor and first molar. The mesiodistal measurements of males were larger than those of the females, being most significant in the canines and the lower left first molar. Iraqi teeth have larger diameters compared with those of other similar groups living in the same geographic area. Brown, Margetts, and Townsend (1980) measured the mesiodistal and buccolingual diameters for deciduous and permanent teeth of Australian aboriginal children who enrolled in a growth study between 1951 and 1971 in Yuendumu, Northern Territory. They selected fully erupted teeth with no caries, wear or anomalies, and used a dial caliper fitted with needlepoints, modified with a high precision linear potentiometer (linear motion voltage dividers). The system was wired into an analogue-digital converter, which converted the metric data into punched cards for computer entry. They found that there was a relatively large mesiodistal diameter of the deciduous second molar, which was pronounced in the mandible. There was an excess size of the mandibular deciduous canine and molar group, compared with the corresponding permanent tooth diameters.

Wood (1981) studied the fossil taxonomy of monkeys. He compared the *Australopithecus africanus* (from South Africa) and *Australopithecus (Paranthropus) boisei* (from East Africa). He noted that the amount of tooth wear adversely affected the reliability of dental measurements; however, he cited the “actual” mesiodistal length and “estimated” unworn length. Estimation could be made by a combination of extrapolating the unworn parts of the occlusal surface contour, making an estimate of the lost enamel thickness and correction of the “actual” mesiodistal length by about 5%. He developed a comprehensive metrical and morphological survey of Plio-Pleistocene hominid dental remains and prepared magnified photos of the occlusal view of each tooth. The areas of the crowns were determined by planimetry and compared with areas derived from buccolingual and “estimated” mesiodistal areas and the result was expressed as a percentage of the derived crown area value. Wood found that there was considerable overlap of canine base and molar crown areas between *A. africanus* and *A. (Paranthropus) robustus*, whereas there was no overlap between the values obtained from *A. africanus* and *A. (Paranthropus) boisei*. Analogues from modern primates were used to derive tooth-body size relations for three relative growth factors. The results suggested that increases in body size were usually accompanied by a more rapid rate of increase in the canine size than in molar size.

Ozaki, Satake and Kanazawa (1987) measured the crown height, and crown buccolingual and mesiodistal diameters, root length, and total length in permanent extracted teeth of 452 males and 76 females kept at the Department of Anatomy, University of Tokyo. Measurements were made with a sliding caliper with an accuracy of 0.05 mm. Size differences between mean values obtained for corresponding teeth on the right and left sides were not significant. Mean values of all dimensions were greater

in males than in females and all parameters showed significant differences in different teeth. The largest was for the buccolingual diameter but the authors noticed that differences were few in the mesiodistal crown diameter of both maxillary and mandibular arches. Significant differences were also found in root length and in total length. There were no significant differences in crown dimensions of the maxillary second premolar, but there were differences in root length and total length for this tooth on each side.

Kimura, Sohmura and Watanabe (1990) developed a laser displacement meter with two sensors to measure the shape of teeth with higher efficiency and accuracy. By this method, they claimed that the whole shape of a tooth including the undercut was able to be measured. The gingival and marginal lines which are of special importance when designing crowns were also recognised and the inner and outer shape of a prosthesis could be obtained utilising this technique.

Martensson and Ryden (1992) produced a three-dimensional measuring system on a hologram by superimposing a holographic image on tooth or teeth, and a superimposed holographic images of the same objects. The precision of this system was 0.03-0.43 mm, which was high for the x and y coordinates and satisfactory for the z coordinate. The method has been proposed for studying changes in tooth positions by comparing holograms of dental casts taken at different points of time.

Mornstad, Staaf and Welandar (1994) in their study of age-estimation over a three- year period used panoramic radiographs of 542 children (270 boys and 272 girls) aged 5.5-

14.5 years from the Public Dental Service, Norrbotten, Sweden. Radiographs were mounted on a digitising table. The structures measured were crown height, apex width and root length, and were identified under a cross-hair cursor and the distances between the points were automatically calculated. The measured values were divided by a magnification factor of 1.35. All data were stored in a computer database. With the help of multiple regression models, a linear relationship between these structures and age was shown.

The rapid development of digital computer technology (CAD-CAM) in the early 1980s led to research into related applications in dentistry (e.g., Cerec in 1988 and the Procera all ceramic crown system in the mid 1990s were launched, where the preparation of teeth could be scanned, saved on a disc and sent to a laboratory (Procera) or fabricated in a dental surgery for machined ceramic inlays and onlays such as (Cerec)). It is anticipated that further technologies will evolve, which will hopefully assist in many applications in clinical dentistry.

1.1.4 Chemistry and history of relevant impression materials

Many dental appliances must be fabricated outside the mouth; hence a wide variety of impression materials is available to the practising dentist (Harcourt 1978). Many of these materials have been in use for most of the last century while others have only appeared in the last 10 to 20 years.

Craig and Peyton (1975), Farah and Powers (1997) and others stated that desirable impression materials should have:

- Pleasant odour, taste and colour.
- Consistencies free of toxic or irritant substances.
- Satisfactory viscosity.
- Good wettability (best with hydrophilic materials).
- Good flexibility to remove from the mouth when set.
- Good recovery from deformation, so that the set impressions are sufficiently elastic to be removed from the mouth.
- Adequate tear-strength so that the material resists tearing on removal.
- Good dimensional stability.
- Good reproduction of details.
- Easy to use.
- 4 minute working/setting time.
- Can be disinfected.
- Compatible with cast/die materials.
- Adequate shelf-life.
- Cost effective.
- Accuracy in clinical use.

Impression materials can be classified as non-elastic and elastic materials. Non-elastic materials include plasters, impression compound, and zinc oxide-eugenol. Elastic materials can be divided into (a) hydrocolloids (agar and alginate) and (b) nonaqueous elastomers, such as; polysulphide, silicone (condensation and addition), and polyether (O'Brien 2002 and Asgar 1971).

A brief description of chemistry is given of relevant impression materials used in this study:

- Alginates are most widely used in dentistry. They are used for impressions for removable partial dentures and often for preliminary impressions for complete dentures. Alginates are based on an aqueous reaction between a soluble calcium salt (calcium sulphate dihydrate), and an alginate salt derived from seaweed. They contain fillers such as diatomaceous earth to increase rigidity and facilitate mixing, a retarder such as tetrasodium pyrophosphate, a pH modifier such as magnesium oxide, and setting aids such as sodium fluorosilicate (Cook 1986)
- Addition silicones (vinyl polysiloxane) are moderately low-molecular mass silicones that contain silane groups; the accelerator has vinyl terminal groups, filler and catalyst (chloroplatinic acid).
- Polyethers have two component materials: A base which includes a polyether, silica filler and plasticiser, and the accelerator which contains a cross-linking agent. Rubber is formed by cationic polymerisation. They are similar to addition silicone in properties, and have low flexibility; thinners may be added to increase working time and flexibility (O'Brien 2002). Comparison of three impression groups is shown in Table 1.

Hansson and Eklund (1984) reviewed the literature on the history of reversible and irreversible hydrocolloids and addition silicone from 1940 to 1983 and reported: alginate hydrocolloids were developed during World War II when agar hydrocolloids became scarce as most came from Japan.

Table 1 Comparison of various properties of relevant impression materials (O'Brien 2002)

Property	Alginate	Addition silicone	Polyether
Preparation	Powder and water	2 pastes	2 pastes
Handling	Simple	Simple	Simple
Ease of use	Good	Good	Good
Patient reaction	Pleasant	Pleasant	Unpleasant
Ease of removal	Very easy	Moderate	Moderate to difficult
Working time (min)	2.5	2-4.5	2.5
Setting time (min)	3.5	3-7	4.5
Stability	Immediate pour	Up to 1 week	1 week kept dry
Elastic recovery (%)	97.3	99.9-99.0	99.0-98.3
Flexibility (%)	12	1.3-5.6	1.9-3.3
Flow (%)	----	<0.05	<0.05
Reproduction limit (µm)	75	25	25
Shrinkage 24 hours (%)	----	0.01-0.2	0.2-0.3
Tear strength (g/cm)	380-700	1640-5260	1700-4800
Wetting and ease of pouring	Excellent	Fair to good	Good
Die material	Stone	Stone	Stone
Electroplating	No	Yes	Yes
Disinfection	Poor	Excellent	Fair
Comparative cost	Very low	High to very high	Very high

In 1940 the Amalgamated Dental Co. was granted a British patent for a new hydrocolloid composition. The product was “Zelex” (Jorgenson 1978). Dolder (1940) and later Schoonover and Dickson (1943) introduced the irreversible hydrocolloids. Eisenstark (1947) described a method for gold inlays construction by using alginate. Pfeiffer and Jeffreys (1950) and Phillips, Price and Reinking (1953) used iced water instead of room temperature water. The bowl, spatula and syringe were also chilled and as a result the gelling time was extended from five to seven minutes. Schwartz (1951) combined agar and alginate hydrocolloids, as did Skinner and Hoblit (1956). The union between the two hydrocolloids was found to be mechanical only. Skinner and Carlisle (1956) used chemical retarders instead of iced water to increase gelling. In 1981 Svedia Dental Industri AB (Sweden) and Buffalo Dental Mfg (USA) offered modified alginates for crown and bridge impressions. Addition polymerisation silicones or polyvinylsiloxanes were developed as a result of the Apollo space programme. The material required high stability. The first material was President in 1975 followed by

Permagan, Reflect, Reprosil, and others. Materials changed from fluid into elastic solid by crosslinking. This was possible without the production of by-products, as occurred with the condensation type of silicones, and explained the exceptional stability of these materials. Hansson and Eklund (1984) further reported that: Skinner and Pomes (1947) compared the accuracy of reproduction of eight irreversible hydrocolloids and two reversible hydrocolloids and found that these materials produced more accurate impressions when allowed to remain in contact with the model for two or three minutes after gelation. Premature removal is a common cause of distortion and fracture. If the alginate is held in the mouth too long, the material loses some elasticity and distortion may result, thus rendering the time of removal as critical. These findings were later confirmed by Phillips (1953 and 1955). The water and powder must be proportioned accurately, the impression removed rapidly and placed in a fixing bath for a period of at least ten minutes; it may then be immediately poured (Skinner and Pomes 1947). Kendrick (1950) studied the effect of the water temperature on the cooling of reversible hydrocolloids and recommended a temperature below 21°C. Skinner, Cooper and Beck (1950) could not find any difference in the accuracy of impressions made with either alginate or agar hydrocolloid materials. Phillips and Ito (1951) confirmed that the greater the undercut, the greater the distortion, and the impression must be removed with a "snap". To minimise stress, the tray should be well centred in the mouth. Phillips, Price and Reinking (1953) discovered inaccuracies in some castings of multiple restorations. Skinner and Hoblit (1956) repeated the investigation of 1947 and 1950 and again found no difference in accuracy between the reversible and irreversible hydrocolloids. They also found that a large bulk of impression material increased impression accuracy. Phillips (1953) also concluded that alginate materials were not as reliable as agar materials. Skinner and Carlisle (1956) determined that impressions

obtained with the alginate materials were found to be more accurate than those obtained with agar, and found considerable error when:

- 1) the alginate impression was dried with an air blast,
- 2) the model surface was dried before the impression was taken,
- 3) water of room temperature was employed instead of iced water.

They found that when chemical retarders were added to alginates, the accuracy was increased. Hosoda and Fusayama (1961) compared alginates with mercaptan rubber-base impressions, and reported that the distortion effect of undercuts of adjacent teeth was negligible when an irreversible hydrocolloid was used and slight when a mercaptan was used. Irreversible hydrocolloids showed less distortion than mercaptan when made at mouth temperature and poured at room temperature. Sawyer, Sandrik, and Neiman (1976) studied the accuracy of casts made of two alginates, an agar hydrocolloid, and a polyether rubber and found that the alginate materials deviated from the master die by an amount considered to be clinically unacceptable. Khaknegar and Ettinger (1977) studied the effect of removal time and pouring time *in vivo* on the accuracy of irreversible hydrocolloids; the alginate accuracy was found to be clinically acceptable if the stone casts were poured within two to four minutes after impression removal. Fusayama and associates (1982) investigated a combination technique of a reversible hydrocolloid and concluded that the combination technique was accurate and eliminated the disadvantages of both materials when used individually. Jorgensen (1982) studied the precision of reversible and irreversible hydrocolloids and an addition-curing silicone and found that with traditional handling, agar hydrocolloids were more accurate than alginates and silicones. Wiktorsson and Feder (1983) took impressions of steel blocks attached to a cap splint seated in the mouth, using a new two-phase alginate and a

conventional alginate with another impression material and found that the difference between the impression materials was not significant.

Fung and Osborne (1972) investigated two alginates and reported that both the working time and the setting times decreased with a rise in temperature, although there did not appear to be a linear relationship. They suggested that 30°C - 37°C represented a realistic temperature range for testing setting characteristics.

Eames et al. (1979) assessed the accuracy and dimensional stability of elastomeric impression materials according to ADA specification No 19 where the percentage of negative linear change was measured at 30 minutes and at 24 hours from the start of the mix. The amount of contraction that all materials exhibited at 30 minutes ranged from 0.11% to 0.45%. In general, the silicones demonstrated greatest change. At 24 hours, stability ranged from 0.18% to 0.84%. Polyethers and polysulphides were generally more stable and silicones were least stable. Peutzfeldt and Asmussen (1989) determined the accuracy of three alginates and seven elastomeric impression materials. Impressions were taken of a truncated cone and poured with die stone. A steel ring fitting the steel cone was placed over the dies, and the discrepancy between the top surface of the ring and the die was measured. The inaccuracy of the alginates varied between 44 and 188 µm. Inaccuracy for elastomers varied between 39 and 130 µm. Generally, the addition-cured silicones were more accurate than the polyethers. Tjan and Heisler (1992) found that intermixing brands of putty and light-bodied addition silicones in a putty-wash impression, did not adversely affect either the bond or the accuracy. Peters and Tieleman (1992) stated that for reversible and irreversible hydrocolloid systems studied,

a 3-hour pouring time could be used for transportation to a commercial dental laboratory, provided that the impressions were stored in 100% relative humidity.

Cohen et al. (1995) emphasised the importance of dimensional accuracy. They evaluated the dimensional stability of three different alginate impression materials- Jeltrate, Hydrogum, and hydrophilic alginate material (Essential Dental Systems), under five different storage conditions. Measurements of casts were made buccolingually, mesiodistally, and diagonally immediately. These authors found that of 160 casts, the new hydrophilic alginate resulted in similar dimensional accuracy compared with Jeltrate and Hydrogum (with incorporation of 25% less water).

Hochman and Yaniv (1998) clinically evaluated the fit of removable partial dentures (RPD) made from impressions with either irreversible hydrocolloid (alginate) or condensation silicone materials. Two impressions were made for each patient using accurately fitting, rigid, perforated stock trays. One impression was made with the irreversible hydrocolloid alginate Aroma Fine (dust-free, normal set, alginate impression material), and the other with the condensation silicone Optosil / Xantopren. It was found that 73% of the patients preferred partial dentures constructed from alginate impressions. However there was no statistical difference between the groups.

Ragain et al. (2000) used the ADA/American National Standards Institute (ANSI) specification 10 metal master die to compare detail reproduction, contact angles, and die hardness of elastomeric impression and gypsum die material combinations. Impression materials tested were: polyvinyl siloxane (addition silicone), condensation silicone,

polyether, polysulphide and reversible hydrocolloid. Regardless of the die material used, polyvinyl siloxane, condensation silicone, polyether, and polysulphide impression materials each ranked higher in the thinnest continuous line observed (24 μm) than the hydrocolloid impression material, where only 20% of the specimens continuously reproduced the thinnest line. Nissan et al. (2000) found that polyvinyl siloxane of 2-step and 2 mm relief putty-wash impression technique was the most accurate for fabricating stone dies.

1.1.5 The effect of the bulk of an impression material and the degree of tooth undercuts on the accuracy of an impression

Undercuts, sharp line angles, and interproximal spaces all influence the elastic deformation of impression materials and are not always under the control of the dentist. On the other hand, certain controllable influences (such as, tray design, bulk of impression material, and rate and direction of removal of the impression from the mouth) may be used to prevent permanent deformation (Collard et al. 1973). The presence of a marked undercut on a tooth will result in a strain which is large at the cervical part at the time of removal of the impression, and may result in an elongated tooth crown and compression of the cervical region.

There are limited studies on the effect of material bulk and degree of undercut on the accuracy of an impression *in vivo*. All available studies in literature were *in vitro* and utilised metal dies. Ragnarson and Astrand (1965) investigated the ability of rubber impression materials to reproduce a master model with undercuts. The diameters of the stone dies were studied in a measuring microscope and compared with the corresponding values for the master cast. They also studied the effect of the layer

thickness of the impression material by using non-perforated trays and allowed a layer-thickness of the material of 1, 2, and 4 mm. They tested two silicone materials and two thiokol materials. No statistical difference between the trays in their ability to reproduce the master cast could be observed. The tray with 2 mm thickness of impression material however gave the lowest values for standard deviation.

Rosenstiel (1968) stated that inlay and crown preparations must be free from undercuts in the line of withdrawal before a wax pattern could be removed. Moreover retention would be best in either cutting back until the undercut was eliminated or in blocking it out with cement. He claimed that with the invention of flexible impression materials, it had become possible to make accurate replicas of preparations as long as these undercuts only involved the 'inside' of the preparation and not any of the cavosurface angles.

Collard et al. (1973) used a series of two-dimensional polycarbonate dies to simulate the contours of a mandibular first molar. They represented three percentages of undercuts: 0, 10, and 25 per cent to achieve a clinical range of undercuts. Bulk configurations of 3, 6, and 9 mm of trays were used. Two forms of impression trays were used- flexible and rigid. An Instron testing machine crosshead removed the impressions at a rate of 20 inches (508 mm) per minute. Photoelastic observations were made with a circular-transmission polariscope arrangement. It was found that for undercuts in a range of 0 to 10 per cent with a 6 to 9 mm bulk of impression material, approximately equal stresses were developed in mercaptan rubber impression with either flexible or rigid trays. A bulk of 3 mm contained in a rigid tray, developed high stresses with undercuts at the 10 per cent level. For undercuts above 10 per cent, combinations of tray flexibility and

bulk of impression material become more important in minimising stresses during removal of the impression. Differences between tray bulk configurations should be taken into consideration for undercuts beyond 10 per cent, and digital pressure on flexible trays should be considered because of the increased stress during impression removal. Eames et al. (1979) used a stainless steel master die representing a complete crown preparation with 12 degree taper. Plastic trays providing 2, 4, and 6 mm spaces for the impression materials were used. Three minutes after taking the impression, it was measured using a Gaertner linear microscope with a micrometer stage, using the length of the crossbar of a figure "H" reproduced in the impression from the scored surface of the occlusal aspect of the master die. Materials were: three polysulfides, two polyethers, two silicones. The study concluded that the interface space of 2 mm produced the most accurate impressions for all the materials tested.

Gold (1985) described a new type of guiding device for dental handpieces, which would ensure parallel axes and the correct taper of prepared tooth walls for each tooth and among multiple abutments; it was based on the assumption that dentists are unable to prepare teeth with the minimal tapers recommended in the literature, particularly in multiple abutment prostheses, when freehand methods are used. A protractor was used by securing it into a parallel position on the sliding vertical member of the surveyor (Ney's surveyor). It was found that the average degree of opposing abutment wall convergence ranged from 18.2 to 22.4 in 20 casts prepared by various dentists, which put the teeth in the category described by Jorgenson (1955) as having two-thirds loss of retention with tapers that ranged from 12 to 49 degrees. Gold's handpiece guiding instrument consisted of three parts, including an intraoral surveying accessory. The instrument allowed freedom of movement of the cutting instrument in the vertical and

horizontal planes to enable it to circumscribe the tooth and follow the gingival contour. An extension arm that consisted of a fixed bearing post at one end, and a parallel vertically adjustable bearing tube at the other, aided in reaching inaccessible locations and increased vertical and horizontal movement. The paralleling instrument allowed all cuts in an axial direction to be parallel to all other cuts, with the desired degree of taper controlled only by the taper of the cutting instrument. Gold claimed that this new instrumentation for preparing abutment teeth eliminated the inaccuracies caused by traditional techniques of using freely held handpieces and visually assessing the finished preparations.

Hansson and Eklund (1988 and 1984) detected differences between four groups of impression materials (two alginates, two alginates plus silicone, two agars and two addition-cured silicones) in two simulated clinical situations:

- a) reproduction of unblocked, relatively large undercut areas; and
- b) reproduction of small undercuts between narrowly set adjacent abutments.

The authors used stock trays for alginate and agar, and custom trays for silicones for impressions of abutments of stainless steel dies with simulated clinical undercuts. Some abutments were prepared for full cast crowns with knife-edge margins and a 6 degree taper of tooth and undercut, and others were prepared with a 10 degree taper. Cervical unblocked undercuts were best reproduced by addition-cured silicone, and then the alginate plus silicone, and the last was the agar and alginate. Even though agar, alginate and alginate plus silicone groups showed similar results, yet they were inferior to addition-cured silicones in reproducing the narrow spaces between some abutments.

Johnson and Craig (1985) used a stainless steel master cast simulating two full crowns fixed partial denture abutment preparations. The abutments had a 6-degree angle with the vertical axis. Preparations were identical with the exception that one had a v-shaped undercut below the gingival margin to evaluate the effect on the elastic recovery of the impression after removal. They measured distances between preparations, diameter of base of non-undercut post, diameter of base of undercut post, diameter of undercut, occlusal-gingival height of non-undercut post, occlusal-gingival height of undercut post and angle of undercut. Impression materials studied were; addition-cured silicone, condensation silicone, polysulphide and polyether. The accuracy was assessed as a function of model location, time of pouring, and repetition of pouring. They concluded that the stone post was larger than the standard for the addition-cured silicone and polysulphide materials and was unchanged or smaller than the standard for the condensation silicone and polyether. The vertical dimensions of stone posts were, in general, shorter than the standard for all materials. The addition-cured silicone and condensation silicone products demonstrated the best recovery from undercuts and the least change in dimensions between an initial and second pour of an impression. The addition silicone and polyether were the least affected with delays of 1, 4, and 24 hours in pouring the impression.

Murakami et al. (1989) prepared five types of stainless steel master dies with various amounts of undercuts and impressions of these dies were made using impression trays filled with addition type silicone, polysulphide or alginate impression materials. The inside tray diameter was 20 mm with a thickness of 5 mm around the global parts. Master dies and the stone dies prepared from the impressions were shadow-photographed, their silhouettes printed after magnifying about 16 times, and were then

superimposed on those of the stone dies, to measure the dimensional changes with a comparator. They concluded that, in general, deformation of stone dies was greater in proportion to the amount of undercut. The stone dies prepared from the addition type silicone rubber impression showed the least deformation. The polysulphide impression produced stone dies with small deformation. However large deformation occurred when the master die contained an undercut. The alginate impression produced a large deformation in all dies.

De Araujo, Jorgensen and de Araujo (1990) studied the effect of undercuts on the accuracy of reheated addition-reaction silicone impressions (President Regular). A truncated chromium steel cone die with an 8 mm base diameter and 8 mm in height was used. The die had an undercut apical to the gingival margin, which could be adjusted to heights of 1 and 3 mm, corresponding to depths of 0.5 and 1.5 mm respectively. Perforated stainless steel trays were used for the impressions. Inside diameter of 10 or 16 mm allowed impressions with a respective thickness of 1 or 4 mm measured from the tray to the gingival margin of the preparation. A distance of 2 mm between the top surface and the top of the trays was accomplished by using a spacer. Data indicated that the increase in thickness of the impression material from 1 to 4 mm caused a greater distortion than the depth increase of the undercut from 0.5 to 1.5 mm. An increase in bulk of impression material resulted in greater inaccuracy of the impression. Pouring the dies at 37°C significantly reduced the effect of material bulk on the accuracy of President impressions. The authors concluded that in impressions of undercut preparations, the reheating of the impressions improved their accuracy, and that the depth of undercut had a definite but small effect on the accuracy of the stone dies.

Wada (1992) designed a metallic model in such a way that the amount of undercut and distance between the adjacent teeth could be changed. Reference points allowed comparison of the master model and the working casts for measuring dimensional accuracy under the same conditions. The master model simulated an abutment for a full veneer crown with undercuts between the adjacent teeth. As a result, a small distortion of the working cast due to the undercuts was observed by the technique of using an individual tooth tray and polysulphide rubber impression material. There was no significant dimensional change in the working casts made with silicone rubber base material. The working casts made with hydrocolloid-alginate combination technique showed greater dimensional change and distortion was observed in the abutment cast when the undercuts of the adjacent teeth were large; the distortion was less when the undercuts were small.

Wassell and Abuasi (1992) reviewed the specification tests of the American Dental Association (ADA) No.19 and British Standards Institution (BSI) No.4269 which were designed to consider individual properties of impression materials which included the effect of the undercuts in dies only, and dies and adjacent teeth. They concluded that among the various simulatory methods of assessing impression accuracy, no technique has been proven to be entirely satisfactory. Measurements made directly on the impression material were of limited relevance, if a clinically unrealistic die had been used. The risk of die or casting abrasion was particularly difficult to eliminate and the poor fit of a loose casting could not be easily quantified. The master and stone dies must be precisely aligned to prevent parallax error. If the die could be reproducibly located then profile measurements would offer a good alternative. The authors advised that comprehensive measurements should include the finishing line width, occlusal diameter

and die height and should be made in two planes to give a useful indication of differential die distortion. They asserted that inter-die relationships were difficult to resolve. Two-dimensional measurements were of limited value as distortion might occur in the third dimension. Three-dimensional measurements would be ideal to characterise inter-die distortions, but required sophisticated instrumentation. Authors also concluded that in order to give the best simulation, master dies and models would have to be constructed to copy oral morphology and would have to be temperature-controlled. The commercially available phantom head typodonts provided teeth of standard shape, so those undercuts of known dimensions could be incorporated. The undercuts of the adjacent teeth gave a good test for single dies, while a one-piece partially dentate arch was a better test for inter-die relationships.

Idris, Houston, and Claffey (1995) used a stainless steel base to which three metal tapered abutment preparations were attached and used as the master cast for the two impression techniques compared in this study. These abutments simulated full-crown preparations with cross-grooves on the occlusal surfaces as reference points and had three designs: no undercut, V-shaped undercut 1 mm deep located below the cervical finishing line and wide C-shaped undercut of the same depth located below the cervical finishing line. President was the addition-cured silicone chosen and was used in perforated metal trays. Tray adhesive was applied over the inner surface of the tray and extended approximately 2 mm on the outer surface along the periphery of the tray. Putty/wash 1 step and 2 steps were sufficiently accurate in conjunction with the addition silicone material tested for the fabrication of stone dies of single castings and fixed partial dentures. The authors further concluded that the inter-abutment distances increased slightly compared with the stainless steel model for both techniques. The

intra-abutment measurements for the abutment without undercut increased, whereas abutment measurements with undercuts decreased.

Leles and Compagnoni (2001) stated that during abutment tooth preparation for fixed partial dentures, the presence of undesirable undercuts, due to clinically complicating factors such as poor visibility and access, was frequently observed. The presence of undercuts could hinder the complete seating of the cast restoration, resulting in the need to recontour the prepared tooth and take a new impression. Their study presented an easy and quick method for evaluating single or multiple tooth preparations to detect undercuts before making the final impression. A pencil was used for drawing two lines that encompassed the circumference of the prepared tooth on the study cast. An alginate impression of the prepared tooth was then taken and poured up with fast set stone. The first line had to be coincident with the junction between the axial wall and cervical margin, and the other had to correspond with the junction between the axial reduction and external cusp reduction. An occlusal view of the cast allowed visualisation of the convergence of single or multiple prepared teeth. Undercuts or excessive convergence angles could be detected when the relative positions of the two drawn lines were observed. The authors claimed that this method allowed determination of proper abutment convergence and a common path of insertion in multi-abutment preparations. Undercuts could be detected and corrected in the same clinical visit, before the final impression was made.

1.1.6 Blocking out undercuts

An important quality of an elastic impression material is that it should be easy to pull away from undercuts without rupture or distortion. Extreme distortion of a set impression material can occur in special situations, such as when an impression is made of the following: a large unblocked area, where a papilla is missing, resin-bonded retainer, a pinledge attachment, a three-quarter crown and an impression made for a removable partial denture. Gingival embrasures can become patent and enlarged. The cause of these enlarged spaces is varied and can result from increased crown length after periodontal surgery, increased gingival recession, supra-eruption, or improperly aligned and/or angulated teeth. Such open spaces should therefore be blocked out (Hansson and Eklund 1988, Reeves 1992 and Hummert and Kaiser 1999).

Many different methods of blocking out hard tissue undercuts have been described to eliminate distortion and tearing of set impression materials and minimize the trauma of removal from intraoral tissues. The ideal blockout material should: (a) be quickly and easily placed, (b) maintain positional stability during impression procedures, (c) be easily removed, and (d) be compatible with the impression materials used (Baker and Beatty 1989). These authors described a technique for intraoral undercut blockout before impression procedures by using temporary cement placed in the desired regions and allowed to set, and kept dry whilst the material set (3 to 5 minutes). They recommended this technique in areas with large interproximal embrasures, splinted teeth, pontics, bars and mobile teeth. Reeves (1992) introduced a one-step impression technique for patients with severe undercuts, and stated that this problem is especially acute if a stiff elastomeric impression material was used, such as polyether or vinyl polysiloxane. Reeves also stated that if a custom tray was used, increased flexibility could be achieved

by increasing the space between the tray and the teeth from 2 to 4 mm. This method utilised a putty catalyst material in a disposable plastic tray, followed by the wash material of vinyl polysiloxane which was placed onto the preparation and into the tray, then the tray was placed in the mouth.

Luk and Chen (1993) described an undercut blocking device which consisted of three parts: (a) an acrylic resin block; which fixed the other two parts and could be mounted with dental stone in the subsequent blockout procedures; (b) a rotation axis made of an 0.040 inch (1 mm) round wire fixed on the acrylic resin block which could be rotated individually; and (c) a functional part, which consisted of two metal plates soldered onto either side of the rotation axis and enveloped with resin to which auxiliaries can be attached with self-curing acrylic resin. These authors claimed that this device, and the technique described for its use, could produce a more accurate blockout result for a rotational path removable partial denture, because it changed the rotation centre to a rotation axis and therefore the rotation radius and direction could be more precisely controlled.

Permanent deformation may ensue if the strain exceeds the elastic range of the impression material (Figure 6). Therefore, an impression material that possesses a large tolerable strain in the elastic range allows the impression to flex over tissue undercuts without permanent dimensional distortion (Chai, Takahashi and Lautenschlager 1998). The degree of recovery after deformation from undercuts of agar and alginate (hydrocolloids) impression materials is shown in Figure 6

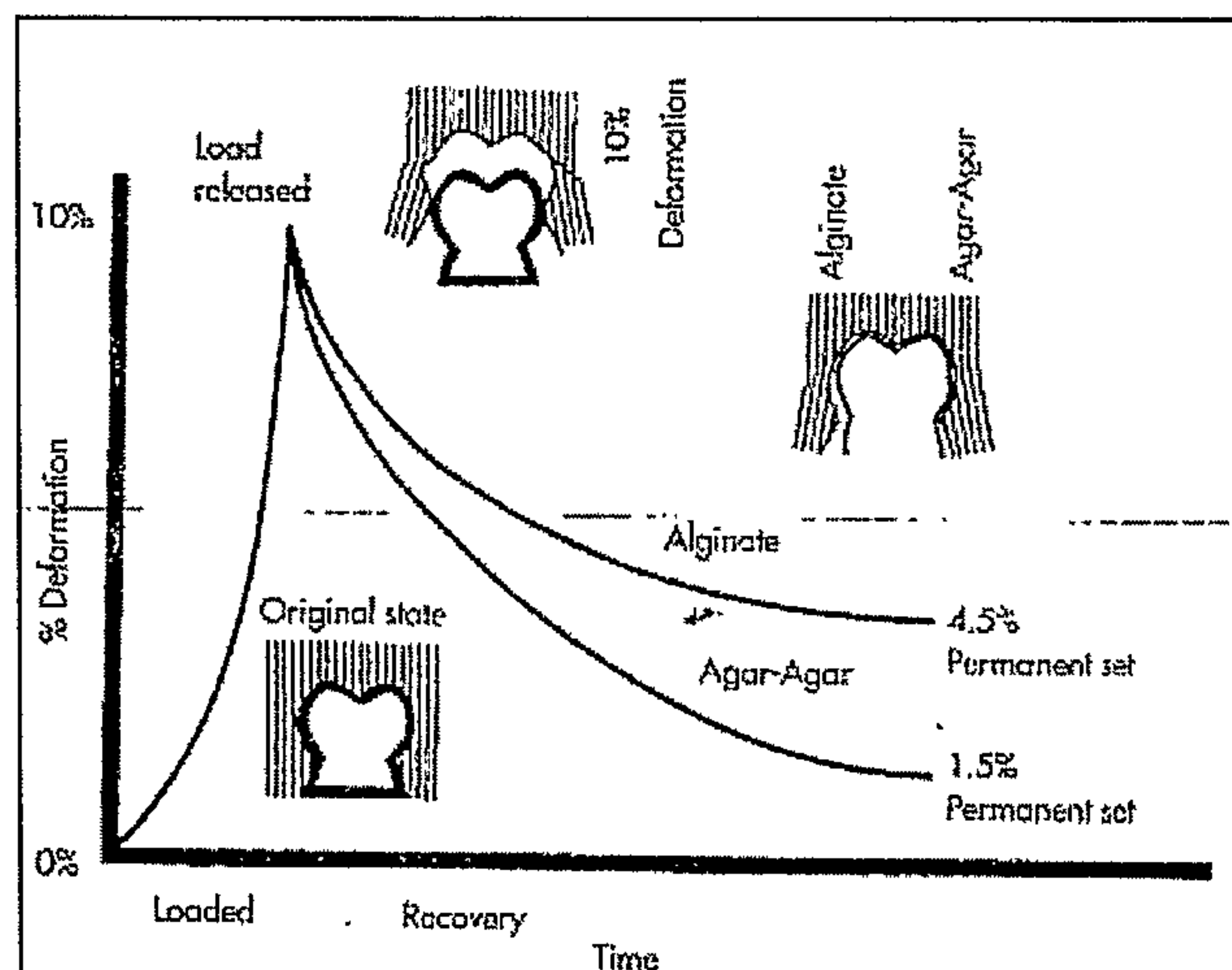


Figure 6 Recovery from deformation of agar and alginate hydrocolloid materials from undercuts (O'Brien W.J. 2002- Dental materials and their selection-third edition).

Hummert and Kaiser (1999) stated that there are various materials which might be used to minimise the effect of undercuts, such as wax or temporary cement material. These materials might be placed quickly, and easily displaced and could result in distortion. In order to block out gingival embrasures, the authors injected polyvinyl siloxane impression material into the embrasures to form custom blockout wedges and stated that by providing these customised blockout of potentially damaging undercuts, distortion of impressions and casts could be prevented. Sato and Sato (2001) described a method by which the interproximal embrasure may be blocked out with soft wax.

1.1.7 The effect of tray design and adhesives on the accuracy of an impression

Tray design and impression techniques are important parameters for an accurate impression. Stock trays are useful for some procedures, but their flexibility and construction vary. In addition, the varying thickness of impression material in a stock tray may cause dimensional changes and inaccuracies in the cast (Wang, Nguyen and Boyle 1995). On the other hand custom trays improve the accuracy of elastomeric

impressions by limiting the volume of the material, thereby reducing two sources of error: stresses during removal and thermal contraction during setting. The opposite is true in the case of reversible hydrocolloid, where dimensional changes might take place from syneresis and imbibition at the surface, so that bulky impressions have less dimensional changes (Rosenstiel, Land and Fujimoto 1995).

Generally a custom tray is made from auto-polymerised resin, thermoplastic or photopolymerised resins. Light polymerised resin is less susceptible to distortion in moisture and there is no need for complete polymerisation making it possible to electroplate the die with any system. The main disadvantage of light polymerised resin is the tray flexibility, which might lead to impression distortion. To obtain adequate rigidity, resin thickness of 2-3 mm is needed; however greater clearance is necessary for materials such as polyethers (Rosenstiel, Land and Fujimoto 1995).

Elastomeric impression materials are widely used in the fabrication of indirect restorations since they deform reversibly when withdrawn from undercut areas. Addition cured silicones exhibit exceptional dimensional stability because by-products are not formed during polymerisation. However an impression made with a highly accurate material can be useless if it detaches from the tray when the material is withdrawn from the oral tissues (Bindra and Heath 1997 and Leung et al. 1998). During withdrawal the bond between the impression material and the tray is stressed in both tension (e.g., at the base of the tray) and shear (e.g., at the sides of the tray). For these reasons, it is extremely important that the adhesive bond between the impression material and tray should be of sufficient strength to withstand the forces generated

during removal of the set material from contact with the oral tissues (Bindra and Heath 1997).

Perforated trays are generally used when taking alginate impressions to aid in retention. Fusayama and Nakazato (1969) reviewed previous literature on this matter and reported that Jordan (1945) preferred unperforated metal trays coated with beeswax in which cotton fibres were attached to retain the impression materials. Atkinson, Gill and Shepherd (1958) reported that the retention of alginate impression materials to unperforated trays coated with molten sticky wax was two to three times greater than the retention to perforated trays. Wilson and Smith (1963) claimed that sticky wax could distort the impression by affecting the gelation of alginate, and they recommended that trays be coated with a resinous adhesive. Skinner and Phillips (1960) suggested that the proper retention of an impression would be affected by the size and number of perforations and their location and distribution in the tray.

Adhesives are usually added to impression trays as an adjunct to the mechanical retention of alginate. Previous research on the effectiveness of adhesives is limited (Leung et al. 1998). Wilson and Smith (1963) stated that in the palatal region the bond between impression and tray is stressed in tension, whilst the bond at the walls of the tray is stressed in shear. These authors used pairs of plain and perforated 70 mm square plates constructed in stainless steel, chromium plated copper (2.5 mm diameter at 4 mm intervals) and self-cured acrylic resin (2.5 mm diameter at 8 mm intervals) and found that adhesives used in conjunction with plain trays gave better results than perforated trays in tension, whilst the reverse was true in shear.

Fusayama and Nakazato (1969) experimentally and clinically studied the influences of size, number, interval and total area of tray perforations, on the retention of irreversible hydrocolloid impressions. Trays of 30 mm square were made of brass plate 0.5 mm thick, and they were perforated and non-perforated with various diameters and intervals of perforations, and the mix of alginate impression material was pressed between the two plates for the experiments. For the clinical work the trays were segmental with five different types of retention. They concluded that there was an increase in the total area of perforations by decreasing the interval between them and an increase in their number without changing their diameter increased the retention force. A decrease in the diameter and an increase in the number of perforations without changing their total area also increased the retentive force remarkably. Authors further concluded that perforations of 2 mm in diameter and at 2 mm intervals seemed to be adequate for clinical use and the retention provided by the unperforated rimmed trays was comparatively high in the tensile test and low in the shear test.

Hedegard, Hedegard and Harcourt (1985) studied the retention of alginate impression materials using a polyester fibre-mat textile. The textile polyester mat was stuck to flat perforated plates of resin material similar to disposable trays and they found that the retentive force was higher for the polyester material than for perforations, and that smaller perforations (1.6 mm diameter) were more effective retainers than larger ones (2 mm diameter). With a thinner mix of alginate, the retentive force decreased significantly when perforations were used, but with the polyester material, no significant decrease could be detected.

Several authors have evaluated the strength of tray adhesives with a variety of test methods, and they painted adhesives on acrylic resin trays and allowed them to dry for different times and stated that clinicians should allow the adhesive to set before commencing to take an impression, to achieve greater bond between the tray and the impression material and production of more accurate impressions. Samman and Fletcher (1985) used alginate, silicone rubber, polysulphide and polyether materials and their respective adhesives and designed a study to evaluate and to compare the bond strength of the adhesive obtained using plane and perforated trays of 50 mm diameter. Trays were made from brass and acrylic and coated with adhesive and allowed to dry for either 4, 10 or 20 minutes. Findings revealed that the adhesive solutions were definitely effective and improved the bonding of the impression material to the tray, and they were most effective under tensile loading. Perforations were effective against shear stresses. Authors further concluded that trays should have perforated vertical walls, and the adhesive should be applied over the entire fitting surface and outer borders of the tray, and allowed to dry for at least four minutes before loading the impression material.

Chai et al. (1991) studied the effect of saliva contamination on the tensile adhesive bond strengths of four impression adhesive systems: polysulphide, polyether, polyvinylsiloxane, and condensation silicone impression adhesive, and concluded that saliva contamination was likely to affect the ability of tray surface or adhesive film to retain the impression material and contamination of all impression adhesives resulted in a significantly lower bond strength. Polyether and polyvinylsiloxane impression materials had significantly greater shear bond strength values than polysulphide impression materials to both types of tray material.

Saunders et al. (1992) studied the accuracy of stone casts poured from impressions made from the medium-bodied monophase polyvinyl siloxane material (Imprint, 3M Dental) using different custom tray designs (stops, perforated, perforated and stops, and other trays were as produced from the manufacturer). They prepared impressions of an acrylic master cast of the mandibular arch with two extracoronary crown preparations with reference points for later measurements (tooth 35 and tooth 37) and one intracoronary inlay preparation (tooth 46). Custom trays and stock perforated polycarbonate trays were used with the adhesive material coated on the inner surfaces and 2 mm onto the outer surface and allowed to dry for five minutes. It was found that neither the design of tray nor the impression technique employed had any significant effect on the accuracy of impression made with the polyvinyl siloxane material tested. There were no significant differences between the casts produced from any of the designs of stock trays and between these and the acrylic model for any of the three distances measured, however there was a significant difference between the acrylic model and the casts produced from the unperforated tray with no stops between tooth 37 and tooth 35 and also between the casts from the unperforated trays with no stops and the perforated trays with stops for the same distances.

Dixon et al. (1993) investigated the tensile bond strength of one type of impression adhesive with three different custom tray materials: one autopolymerising (Fastray) and two light-polymerising (Triad and Extoral) and reported that Triad tray materials groups with different surface treatment showed significantly higher adhesive tensile bond strength of impression material than the autopolymerising tray resin and the Extoral light polymerising material.

Moseley, Dixon and Breeding (1994) reported that all resins used in making custom trays exhibited plastic deformation. They developed a mathematical model of a custom tray to predict stress distribution and indicated that stresses would be smaller than the yield stress for polymethyl methacrylate resin or light polymerised resin. They concluded that thermoplastic resins would not be permanently deformed and should be approximately 4 mm thick to achieve the same resistance to permanent deformation as polymethyl methacrylate custom trays.

Payne and Pereira (1995) tested two types of nonaqueous elastomeric impression material-adhesive combinations (Hydrosil, Permadyne) for bond strength to two thermoplastic resin tray materials (Hydrotray, Tak Systems). It was found that;

- Hydrosil and Permadyne impression materials had a significantly greater bond strength to Hydrotray thermoplastic resin than the Hygenic tray dough resin.
- Surface roughening of Hydrotray thermoplastic resin specimens showed a significant reduction in bonding strength to the monophasic addition silicone impression material (Hydrosil) but an increased bond strength to the medium-body polyether impression material (Permadyne).
- Bond strengths of Hydrosil and Permadyne impression materials to unaltered Hygenic tray dough resin specimens was substantially lower than reported bond strengths to other types of custom tray materials.

Sotiriou and Hobkirk (1995) investigated *in vivo* seating and removal forces associated with impression recording in dentate patients. The study consisted of 10 subjects; four impression materials in metal stock trays and disposable plastic trays. The load rate was measured with strain gauges mounted on the tray handles. Authors used alginate,

polysiloxane of medium viscosity, polyvinyl siloxane and polyvinyl siloxane impression material, type I wash (low viscosity). They concluded that:

- Forces recorded on the metal tray were greater than those applied on the disposable trays.
- The greater the viscosity of the material, the greater the load rate.

Cho et al. (1995) studied time-dependent bond strength of two polyvinyl siloxane impression materials and the supplied adhesives, to autopolymerising acrylic resin discs to determine the optimal time for maximum bond strength. Six groups were tested with varying adhesive drying times of 0, 7, 15 and 60 minutes and 8 and 24 hours before testing. It was found that the bond strength was significantly weaker with both materials when the adhesive was applied and the impression taken immediately, than when the adhesive was allowed to dry for 7 minutes. These authors recommended that the adhesive should be allowed to dry for at least 7 to 15 minutes after application before taking the impression.

Wang, Nguyen and Boyle (1995) compared adhesive shear bond strength of three selected impression materials with that of thermoplastic and acrylic resin tray materials in relation to surface preparation. Polyether, polyvinylsiloxane and polysulphide impression materials were evaluated on smooth, rough, and contaminated tray surfaces. Smooth surface samples were formed against glass and served as the control groups. Their conclusions were;

- Thermoplastic tray material had greater adhesive shear bond strengths than those of the acrylic tray resin for all groups.

- Regardless of the tray adhesive and impression material used, tray abrasion by aluminium oxide before the adhesive was applied resulted in greater bond strength.
- Contamination by artificial saliva decreased the adhesive shear bond strength regardless of the tray impression material used.

Bindra and Heath (1997) tested the tensile and shear adhesive bond strengths of two addition cured silicones (Provil and Express) and a polyether (Impregum) impression material to brass, polymethylmethacrylate and visible light-cured (VLC) tray resin.

A single application of the adhesive solution was applied over a period of 1 min and allowed to dry at room temperature (23°C) for a further 15 min. It was found that:

- Adhesive application significantly increased the bond strength.
- Provil and Express adhered most strongly to brass
- Impregum-VLC combination produced the strongest bond and VLC resin generated more adhesion than acrylic resin.
- Exchanging adhesives specified for each silicone material generally resulted in high bond strengths.
- No correlation was established between speed of separation of the test surfaces and bond strength.

Carrotte, Johnson and Winstanley (1998) studied the influence of tray on the accuracy of impressions for crown and bridgework by preparing a master cast from ivory teeth in a mandibular model. Impressions were taken using four different types of impression tray and two different viscosities of silicone putty with a wash. They concluded that metal and rigid plastic stock trays gave greater accuracy in the putty/wash silicone twin

mix impression technique, compared with flexible plastic trays for crown and bridgework.

Leung et al. (1998) designed and machined three test assemblies in stainless steel for tension, shear and cleavage tests for alginates. Alginate adhesive was applied thinly and dried for 5 min. Alginate was then loaded and allowed to set for 5 min before testing. The force at failure was measured by an Instron machine with a cross-head speed of 50 mm/min. It was found that alginate adhesiveness to stainless steel increased in tension up to 53%, in shear up to 37%, and in cleavage up to 270%.

In the study by Nishi et al. (2000), the pressure differences against the labial and lingual surfaces of teeth during the impression procedure were examined, using a mandibular plastic cast with six anterior teeth. A simulated periodontal ligament was applied to the root portion of the left central incisor (mobile incisor); the right central incisor (fixed) and the right canine (fixed) were used as control teeth. Pressures were measured using six diaphragm pressure transducers. Twelve trays were designed by varying the thicknesses of the space between the tray and the teeth and by varying the location of the perforations in the region of the remaining anterior teeth. It was found that:

- the impression pressures against the labial and lingual surfaces of the mobile incisor were less when thicker spacers and escape holes were used,
- the location of the escape holes reduced the rate of impression-pressure differences,
- escape holes on the lingual surfaces of lower incisors were more effective than those on the labial surfaces when the impression pressure on the lower incisors were reduced, and

- there were almost no differences in the impression pressures against the labial and lingual surfaces comparing the mobile incisor and the fixed incisor; however the impression pressures against the labial and lingual surfaces of the fixed canine were affected by tray design.

Ortensi and Strocchi (2000) described a modified custom tray fabrication method using autopolymerising acrylic resin. The custom tray was made by intraoral relining with autopolymerising resin that was polymerised extraorally. A 2 mm clearance was allowed for the elastomer. They reported that this procedure was time-saving because it reduced the need for retraction cord, and minimised inaccuracies.

Breeding and Dixon (2000) compared the accuracy of stone casts of a full coverage gold crown preparation, using two types of dual-arch impression tray/impression material combinations of the maxillary left first molar on a dentoform. They used plastic or metal trays and polyether or vinyl polysiloxane impression material. It was found that the plastic trays produced tooth replicas that were larger than the tooth and the metal trays produced replicas that were smaller and no differences in accuracy were shown between the vinyl polysiloxane and polyether impression materials used.

This review suggests that the use of special trays is recommended for elastomeric impression materials. Special trays should be rigid, adequately spaced (2-3 mm in thickness) and if necessary, perforated and preferably in the vertical walls of the trays for alginates to provide more retention (perforation size of 2 mm and 2 mm intervals is recommended) with suitable stops. Adhesives should be applied over the entire surface

and 2-3 mm at the outer borders of the trays and allowed to dry for at least 3-5 minutes before taking the impression.

1.1.8 Tear and tensile properties of impression materials

- Tear strength: This can be defined as the measure of the resistance of a material to tearing forces. It is an important property of dental polymers used in thin sections such as flexible impression materials in interproximal areas, maxillofacial materials, and soft liners for dentures.
- Tear energy: Is a measure of the energy per unit area of a newly torn surface (Craig and Powers 2001).

Some clinical situations where tearing of an impression material can take place are shown in Figure 7.

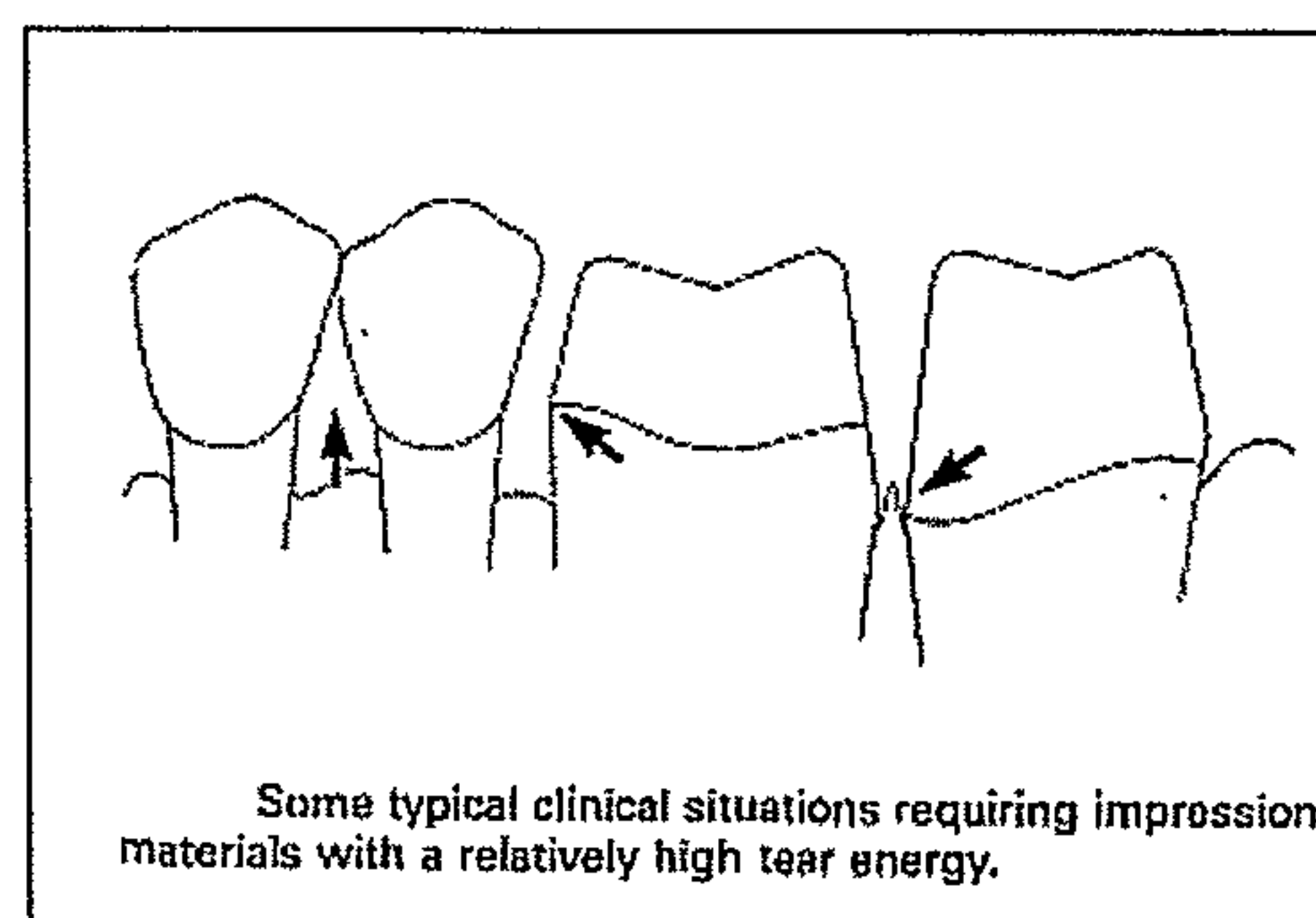


Figure 7 (Vrijhoef and Battistuzzi 1986)

- Tensile strength: Is the maximum tensile stress applied in stretching a specimen to rupture.
- Ultimate elongation: Is the elongation at which rupture occurs in the application of continued tensile stress.

- Yield point: Is that point on the stress-strain curve, short of ultimate failure, where the rate of stress with respect to strain goes through a zero value and may become negative (ASTM D412-98a, referring to ASTM D1566).

Tensile strength and tear resistance of the elastic impression materials are important factors in determining whether an impression is a success or failure (Herfort et al. 1978). The tear energy of elastomeric impression materials has been well documented in the literature. However there is little information on other mechanical properties such as the rigidity (modulus of elasticity) and the maximum allowable stress and strain within the elastic range of the polymerised impression material. Knowledge of these clinically relevant mechanical properties facilitates the selection of impression materials in various clinical situations (Chai, Takahashi and Lautenschlager 1998).

Generally, it is agreed in the literature that in order to measure tear strength or energy, there are two commonly used moulds:

1. Crescent-shaped mould (mould 1) which has 90° on one side and a semi-circle or crescent shape on the other side which was incorporated in the Australian Standards AS1282-1972 and the American Standards ASTM D1004-93 and ASTM D 624-00 Die C.
2. Trouser-shaped mould (mould 2) described by Rivlin and Thomas (1953) who introduced this simple extension tear test piece which was adapted to investigate dental impression materials by Webber and Ryge (1968).

Two equations are commonly used to calculate tear energy:

Equation 1: $T = F (\lambda_T + 1)/h$

where T is tear energy, F is mean applied force, λ_T is the observed extension ratio and h is the sample thickness (Webber and Ryge 1968).

Equation 2: $T=2F/d$

where T is tear energy, F =mean force applied and d =sample thickness.(Chai et al. 1998).

A universal dumb-bell-shaped mould is used in literature to test or measure tensile strength. Specimens used for measuring tear and tensile strengths are tested either in an Instron testing machine or tensile testing machine at various speed rates and various temperatures depending on the nature of the material and time taken to set, or to complete polymerisation.

Greensmith (1960) stated that the energy to initiate tearing at an incision with a tip of semicircular form was approximately equal to Ed - E being the work to break/unit volume as measured in a tensile rupture test, and d the diameter of the tip of the incision. Braden (1963) employed a simple extension tear test piece to evaluate the tear strengths of silicone, polysulphide, and irreversible hydrocolloid impression materials. He stated that the criterion of rupture was first established for amorphous solids by Griffith (1920 cited by Braden 1963). This criterion was based on the observation that rupture involved the propagation of a crack, and hence cleavage surfaces, across a solid. Griffith proposed that the physical property relevant to this process was the energy per unit area that is required to produce cleavage surfaces. In a normal tensile strength test, the energy expended comprised of what was required to deform the test-specimen as a whole, as well as the actual rupture energy. He stated that the problem then was to devise a test-specimen by the use of which the characteristic surface energy for rupture

alone was directly obtainable from the experimentally determined rupture force and he concluded that controlling the mode and rate of rupture was essential. Braden also discussed the effect of rate tearing and temperature on the 'T' value and concluded that the 'T' value increased with the rate of tearing. It was found that the mercaptan rubber was 'stronger' than the alginate and this depended on the rate of tearing considered. With silicone and alginate, the rate of tearing was very sensitive to 'T'. Similarly 'T' was sensitive to specimen thickness. He concluded that measurements at room temperature were not a reliable guide to behaviour at oral temperatures, and explained that all rubbers, at some well defined temperature below room temperature, change suddenly from a soft resilient solid to a hard material very similar in properties to that of a glass. This temperature was called 'rubber-to-glass' or 'second-order transition temperature'. Silicones, on the other hand, have very low transition temperatures, so that, they were not so sensitive to temperature changes and rate of deformation.

In his experiments on the tear criterion Thomas (1960) stated that a criterion for the tearing of rubber was based on an energy balance. This criterion implied that the energy required to deform unit area of surface by tearing should be a constant for the material, and could be tested as to whether tearing results from test pieces of different shapes were consistent. This relation was used to compare the effects of the speed of test on tear and tensile rupture measurements. The variation of the work to break/unit volume with the speed of test adequately accounted for the effect of the speed of test on the energy to initiate tearing at incision with tips of semi-circular form.

Macpherson, Craig and Peyton (1967) tested alginates, rubber base, and agar impression materials and found that tear and compressive strengths of alginates were shown to

increase with: (a) an increase in rate of loading (as confirmed earlier by Braden (1963)), (b) an increase in the amount of alginate in the mix, and (c) an increase in the time between mixing and testing. The tearing resistance of alginates was much lower than the mercaptan rubber and alginates had higher tear strengths, the stiffer the consistencies.

An important property of elastic impression materials is their ability to be withdrawn over severe undercuts without rupture (Chong, Chong and Docking 1971). These authors utilised five metal posts specified in the Australian Standards T15, three of which had undercuts representing extensions in diameters of 23, 45 and 75 per cent respectively. Impressions of these posts were then examined for evidence of rupture two minutes after the predetermined setting time. They tested 26 brands of alginates including Kromopan and Palgat (two of five brands used in this study) and found that both of them had ruptured and showed an extension at tear of 9.4 mm and 7.3 mm respectively. It was concluded that the rupture test did not give a quantitative basis for comparing the rupture resistance of different materials. They added that the present quantitative specification tests such as strain in compression, set after 10 per cent strain, strength and deformation at failure were all compressive and not tensile in nature and, none was found suitable in effectively separating the materials that ruptured from those that did not rupture in the impression taking test. They concluded that the problem was more related to the behaviour of the material in tension rather than in compression and specimen extension had to be the property of choice in evaluating the rupture resistance of alginate impression materials. Herfort et al. (1978) tested the tear energy of polysulphide, silicone, and polyether rubbers and concluded that: (a) the maximum tear strength of those materials was reached in 10 to 15 minutes, (b) the polysulphide

materials showed three to six times the tear strength of the silicones, (c) the polyether materials displayed a tear resistance slightly higher than that of the silicones but one third to one fifth as high as that of the polysulphides. Sneed, Miller and Olson (1983) tested ten different elastomeric impression materials where at least one example of each type was included and advised that, when dentists need a strong impression material for a specific clinical procedure and where the material may be thin and/or in an area of stress, they should consider either a polysulphide or a single-mix polyvinylsiloxane system. Sandrik and Vacco (1983) tested the tensile properties of putty and wash elastomeric impression materials and the bond strength between them and concluded that addition reaction silicone impression materials had the greatest bond strength between materials of putty and wash consistency (1.62 MPa). Cook et al. (1984) investigated tear strength, tensile strength, ultimate extension ratio, and the elastic modulus of a range of characterised elastomeric impression materials. It was found that the tensile strength did not show any specific trend and the dependence of the tensile strength and the ultimate extension ratio with curing time was consistent with the development of the polymeric network, while the tear energy showed only minor variation. They concluded that, for tear energy and ultimate extension, the range of elastomeric impression materials was found to increase in the order: Agar $\leq$ Alginate < Condensation silicone $\leq$ Addition silicone $\cong$ Imine terminated polyether < Polysulphide.

The clinical tear performance of a given material involves a complex relationship between polymer and filler types, flow to a particular film thickness, release properties (adhesion) from tooth and soft tissue, the presence of internal and surface defects, and the rate of impression withdrawal (Keck and Douglas 1984). These authors tested four brands of addition-cured vinyl polysiloxane. One brand each, from the polysulphide and

polyether groups, and two of the condensation-cured polysiloxanes, were tested to determine tear energy and they found that polysulphides ranked highest and condensation-cured polysiloxanes ranked the lowest in tear energy. All addition-cured polysiloxanes tested had significantly higher tear energy than the condensation-cured polysiloxanes. Additional curing time did not yield higher tear energies. Vrijhoef and Battistuzzi (1986) and Vrijhoef, Lourens and Leydekkersgovers (1986) found that some alginates exhibited values of tear energy which were not much lower than those for certain elastomeric materials, and polyether materials had values in the range of the silicone impression materials. They also added that tear energy of silicones, polyethers and alginate impression materials increased by 50% when the tear rate increased from 2 to 500 mm/min, whereas the increase for polysulphides under the same conditions was in the order of 400% and the differences between similar materials of different consistencies might be significant in those cases in which insufficient bulk of material was present in critical tear failure areas. In such situation they recommended a two-stage, rather than a mono-phase, impression technique. Salem, Combe and Watts (1988) found that the tear energy of heavy body silicone gave the highest values followed by regular then light bodied. Putty materials showed less values than heavy bodied; polyether showed approximately similar results to regular grade silicones. The modulus of elasticity in general, gave putty consistency the highest values, followed by heavy, regular, and light bodied, in that order. Polysulphides were more extensible, had lower tensile strengths, moduli of elasticity and greater tearing energy than silicones. Both types of silicones were similar in properties; addition cured appeared stronger in tension. The polyether material resembled the silicones more than the polysulphides.

Cullen and Sandrik (1989) determined the tensile strength, as a part of the study, which examined bond strength of seven brands of condensation polymerisation polysiloxanes, addition polymerisation polysiloxanes, polyethers, and a light-cured polyether urethane dimethacrylate and their tensile strengths and concluded that for bond strength, there was no advantage of the impression relining technique over the simultaneous cure technique. Tam and Brown (1990) determined the tear energies of polysulphide, polyether and addition-reaction silicones and the effect of system modifiers on tear energy and found that no single type of impression material had demonstrated superior tear resistance. Selection of a material on the basis of the requirement for high tear resistance must consider type and brand. As a group, monophasic materials failed to demonstrate superiority in tear resistance values over low-viscosity materials. Retarders and thinners reduced the tear resistance values of the materials tested. Klooster, Logan, and Tijan (1991) measured tensile strength of three polysulphides, one condensation silicone and one addition silicone at three speed rates 100, 200 and 500 mm/min and concluded that the polyether material exhibited less permanent deformation, followed by silicone materials. The polysulphide materials exhibited lower ultimate tensile strength but exhibited a greater amount of elongation at break than the polyether or silicone materials. Higher ultimate tensile strengths were observed with the higher strain rate.

Blomberg et al. (1992) designed a study to determine the temperature change within the setting material, the time taken to remove the impression and to strain the elastomer and the thickness of the syringe material in impressions. Polysulphide, condensation silicone, polyether and polyvinylsiloxane were used. For the clinical study, custom-made acrylic trays with occlusal stops were fabricated, and spaced to provide an

elastomer thickness of approximately 2 mm. Temperatures were recorded with a thermistor probe lingually placed to a maxillary central incisor and to a maxillary first molar. For the *in vitro* study, plastic and metal moulds were designed for the subsequent elasticity tests (compression, tensile, bend and torsion) and temperatures were recorded by placing the probe sensor in the approximate centre of the specimen. The times taken to remove full arch impressions were also measured. The clinical temperature rise was 2-3 °C and found to be higher in molars than anteriors except for the polysiloxane. The temperature range attained in the set materials varied from 29 °C to nearly 35 °C for clinical and *in vitro* specimens. The average time taken by a group of operators to remove impressions from the mouth was five seconds. The syringe material layer was only 0-0.15 mm thick and the heavy viscosity material provided the elastic components of the impression. These authors recommended the use of a temperature range of 30-31 °C for preparing specimens for testing to simulate clinical situation.

Lepe, Sandrik, and Land (1992) tested the tensile strength of the irreversible hydrocolloid and the bond strength between the reversible and irreversible hydrocolloid. It was found that the range for tensile strength for irreversible hydrocolloid varied from 220 kPa to 267 kPa. Heisler and Tjan (1992) designed an accuracy study with a stainless steel model representing two teeth prepared for a fixed partial denture using reversible and irreversible hydrocolloids. It was found that the bond strength between reversible and irreversible hydrocolloid was similar to the tear strength of the reversible hydrocolloid (from 1 kPa to 0.75 kPa).

Hondrum (1994) conducted a study to determine and compare: (a) tear energy; (b) permanent deformation on extension; (c) energy absorbed prior to permanent

deformation and; (d) the extent of permanent deformation upon tear formation of polysulphide light-bodied, polyether and addition silicone light-bodied impression materials. Hondrum concluded that; (a) polysulphide impression materials had a higher tear energy than either polyether or addition-reaction silicone materials when tested by traditional methods; (b) energy absorbed at 0.4% and tear at a point of minimal permanent deformation (0.4%) favoured the addition-reaction silicone materials, followed by the polyether materials. Chai, Takahashi and Lautenschlager (1998) tested tear energy and tensile strength of six polyvinyl siloxane (PVS), two polysulphide, and one polyether impression materials. It was concluded that because of the high rigidity of the polyvinyl siloxane putty impression material, its use should be cautioned in situations with severe tissue undercuts or dies with thin sections; however data also indicated high yield strength, moderate strain tolerance, and moderately low tear resistance. Data indicated: (a) the polyvinylsiloxane tray and syringeable materials displayed relatively low rigidity, moderate yield strength, and high strain tolerance, but relatively low tear resistance; (b) polysulphide materials had low rigidity, low yield strength, and low strain tolerance, but high tear resistance; (c) polyether material displayed moderate yield strength, relatively low strain tolerance, and moderately high tear resistance. The moderate rigidity of polyether limits its use where impression material rigidity is a concern. Cohen et al. (1998) investigated the tear strength of four irreversible hydrocolloid (alginate) impression materials (Tare-Free alginate, Jeltrate, Identac and Kromopan) and found that Tare-Free alginate had significantly higher tear strength value compared with Kromopan, but there was no significant difference between Jeltrate, Identac or Kromopan.

Testing conditions for tear energy and strength of reviewed literature from (1963) to (1998) are summarised in Table 2.

Table 2

	Speed rate	Temperature & humidity	Mould & equation (1or2)
Braden (1963) [#]	0.06–600 mm/min	20°C*-40°C	Mould 2 & equation 1
Mac Pherson et al. (1967) [□]	0-500 mm/min	23 ±2°C & 100%*	NA
Webber and Ryge (1968) [#]	20 mm/min	NA & 100%*	Mould 2 & equation 1
Chong et al. (1971) [□]	500 mm/min	NA	Mould 1 & equation not specified.
Herfort et al. (1978) [#]	50 mm/min	37°C	Mould 2 & equation 1
Sneed et al. (1983) [#]	50 mm/min	37°C	Mould 2 & equation 1
Cook et al. (1984) [#]	50 mm/min	22 ±1°C & 50±10%	Mould 2 & equation 1
Keck and Douglas (1984) [#]	20 mm/min	21 ±1°C & 50±2%	Mould 2 & equation 1
Vrijhoef et al. (1986) [#]	10 rates from 2-500 mm/min	NA	Mould 2 & equation 1
Vrijhoef and Battistuzzi (1986) [#]	50 mm/min	NA	Mould 2 & equation 1
Salem et al. (1988) [#]	30 mm/min	20 ±2°C	Mould 2 & equation 1&2
Tam and Brown (1990) [#]	50 mm/min	37±1°C & 80%	Mould 2 & equation 1
Hondrum (1994) [#]	20 mm/min	NA	Mould 2 & equation not specified
Chai et al. (1998) [#]	50 mm/min	32°C & 50±5%	Mould 2 & equation 2
Cohen et al. (1998) [□]	NA	NA	Mould 1 & equation 2

#: Tear energy study

□: Tear strength study

*: Alginates only

NA: non applicable (not examined, not mentioned or authors referred to specified standards).

Tear energy and strength results of reviewed literature from Braden (1963) to most Recent study of Cohen et al (1998) are summarised in Table 3.

Table 3

	Alginate	Polyvinyl siloxane or silicone	Polyether
Braden (1963) [#]	0-0.05 KN/m	0.4-1.1 KN/m	NA
Macpherson et al. (1967) [□]	0.075-0.37 KN/m	NA	NA
Webber and Ryge (1968) [#]	0.066 KN/m	1.4 KN/m	NA
Chong et al. (1971) [□]	0.3-0.94 KN/m	NA	NA
Herfort et al. (1978) [#]	NA	0.4-1.15 KN/m	0.64 KN/m
Sneed et al. (1983) [#]	NA	0.627-1.25 KN/m	0.79-0.88 KN/m
Cook et al. (1984) [#]	0.103-0.318 KN/m	0.447-1.062 KN/m	0.671-0.844 KN/m
Keck and Douglas (1984) [#]	NA	0.47x-0.84 KN/m	0.64 KN/m
Vrijhoef et al. (1986) [#]	0.37 KN/m	1.07 KN/m	1.04 KN/m
Vrijhoef and Battistuzzi (1986) [#]	0.1-0.3 KN/m	0.4-1.3 KN/m	0.6-0.9 KN/m
Salem et al. (1988) [#]	NA	0.25-0.75 KN/m	0.469 KN/m
Tam and Brown (1990) [#]	NA	0.47-1.89 KN/m	0.45-0.85 KN/m
Hondrum (1994) [#]	NA	0.81 KN/m	0.89 KN/m
Chai et al. (1998) [#]	NA	0.4378-1.1526 KN/m	1.8189 KN/m
Cohen et al (1998) [□]	0.2899-0.5145 KN/m	NA	NA

#: Tear energy study.

□: Tear strength study.

NA: non applicable (not examined).

Tensile strength and modulus of elasticity results for the reviewed literature from 1983 to 1998 are shown in Table 4.

Table 4						
	Alginate		Polyvinylsiloxane		Polyether	
	<i>Tensile strength</i>	<i>Modulus of Elasticity</i>	<i>Tensile strength</i>	<i>Modulus of Elasticity</i>	<i>Tensile strength</i>	<i>Modulus of Elasticity</i>
Sandrik and Vacco (1983)	NA	NA	1.76-2.66 MPa	NA	NA	NA
Cook et al. (1984)	0.45-0.64 MPa	0.063-0.079 MPa	3.53±0.061 MPa	1.58 MPa	1.04-1.39 MPa	0.59-1.15 MPa
Salem et al. (1988)	NA	NA	1.65-2.82 MPa	2.42-8.40 MPa	1.67 MPa	4.49 MPa
Cullen and Sandrik (1989)	NA	NA	2.7-4.6 MPa	NA	1.71-3.55 MPa	NA
Klooster et al. (1991)	NA	NA	2.016 MPa	NA	NA	NA
Lepe et al. (1992)	0.44-0.53 MPa	NA	NA	NA	NA	NA
Chai et al. (1998)	NA	NA	NA	1.49-7.06 MPa	NA	4.21 MPa

NA: non applicable (not examined).

2. Hypotheses and aims

2.1 Hypotheses

2.1.A The association between casting fit and magnitude of the averaged undercuts (averaged across all surfaces)

Hypothesis 1

The magnitude of the averaged undercut in cases (casts having missing teeth) will be greater than controls (casts with no missing teeth).

Hypothesis 2

The magnitude of the averaged undercut on casts with poor fitting prostheses will be greater than undercut in casts with well fitting prostheses.

2.1.B The association between casting fit and magnitude of undercuts for each surface (distal, mesial, buccal, lingual)

Hypothesis 1

Cases will have a greater magnitude of undercut than controls for distal, mesial and lingual surfaces, but not for buccal surface.

Hypothesis 2

There will be a greater magnitude of undercut for distal, mesial and lingual (but not buccal) surfaces for casts which have casting fit problems than for casts with accurately fitting prostheses.

Hypothesis 3

There will be no differences in the magnitude of undercut between teeth on either side of the arch (right and left).

Hypothesis 4

There will be no differences in the magnitude of undercut between maxillary and mandibular casts.

Hypothesis 5

The magnitude of undercut on the buccal surface of anterior teeth will be greater than for posterior teeth. On distal, mesial and lingual surfaces, the magnitude of undercut will be greater on posterior than anterior teeth.

2.1.C Defining a severe undercut

Hypothesis 1

The proportion of teeth with a severe undercut (greater than 1 SD above the mean) will be greater in cases than controls.

Hypothesis 2

The proportion of teeth with a severe undercut (greater than 1 SD above the mean) will be greater in the non-fit group versus the fit group.

2.1.D The association between the thickness of alginate impression material and tear energy

Hypothesis 1

Tear energy of alginate impression materials will be greater, the greater the thickness (method one compared with method two).

2.1.E Tear energy

Hypothesis 1

There will be no significant difference in tear energy between the five different brands of alginate examined in this study.

Hypothesis 2

Tear energy of polyvinylsiloxane group will be greater than that of alginate.

Hypothesis 3

Tear energy of polyether will be more than that of alginate and polyvinylsiloxane.

2.1.F Tensile properties (strength and modulus of elasticity)

Hypothesis 1

There will be no significant difference in tensile properties between the five brands of alginate examined in this study.

Hypothesis 2

Tensile properties of polyvinylsiloxane group will be greater than that of alginate and polyether groups.

2.2 Aims

1. To measure undercuts of teeth from study casts in order to create an index to be used in determining or defining a severe undercut and this will be correlated with prostheses fit.
2. To calculate tear energy of five brands of alginate material by two methods, and to compare the results in relation to specimen thickness.
3. To calculate tear energy of two groups of elastomers, i.e. polyether and polyvinyl siloxane (three materials) commonly used in the Faculty of Dentistry, University of Sydney and to compare data with those obtained for alginates.
4. To calculate and contrast tensile strength, modulus of elasticity, yield stress and strain of the five alginates and the five elastomers.

3. Materials and methods

3.1 Part I

3.1.1 Compiling experimental casts

This part of the research was based at Westmead Centre for Oral Health, Westmead Hospital, and the United Dental Hospital, Surry Hills, the two teaching hospitals of the Faculty of Dentistry, University of Sydney, NSW, Australia. A questionnaire was given to undergraduate and postgraduate dentistry students, which was used to select casts with problematic (significant) undercuts. These were defined as impression difficulties, which resulted in recasting of chrome-cobalt (Cr-Co) frameworks. A total of 31 casts were selected and divided into cases (casts with missing teeth) and controls (casts with no missing teeth). Details of the distribution are shown in Table 5.

Casts distribution and numbers	Table 5				
	Cases			Controls	
	<i>Group A Did not fit</i>	<i>Group B Did fit</i>	<i>Group C Don't know</i>	<i>Group D No missing teeth</i>	<i>Group E Orthodontically treated cases</i>
Maxilla	1	4	6	2	2
Mandible	4	0	8	2	2
Total	23			8	

Selected severe undercuts from Group A are shown in Figures 8-15



Figure 8



Figure 9

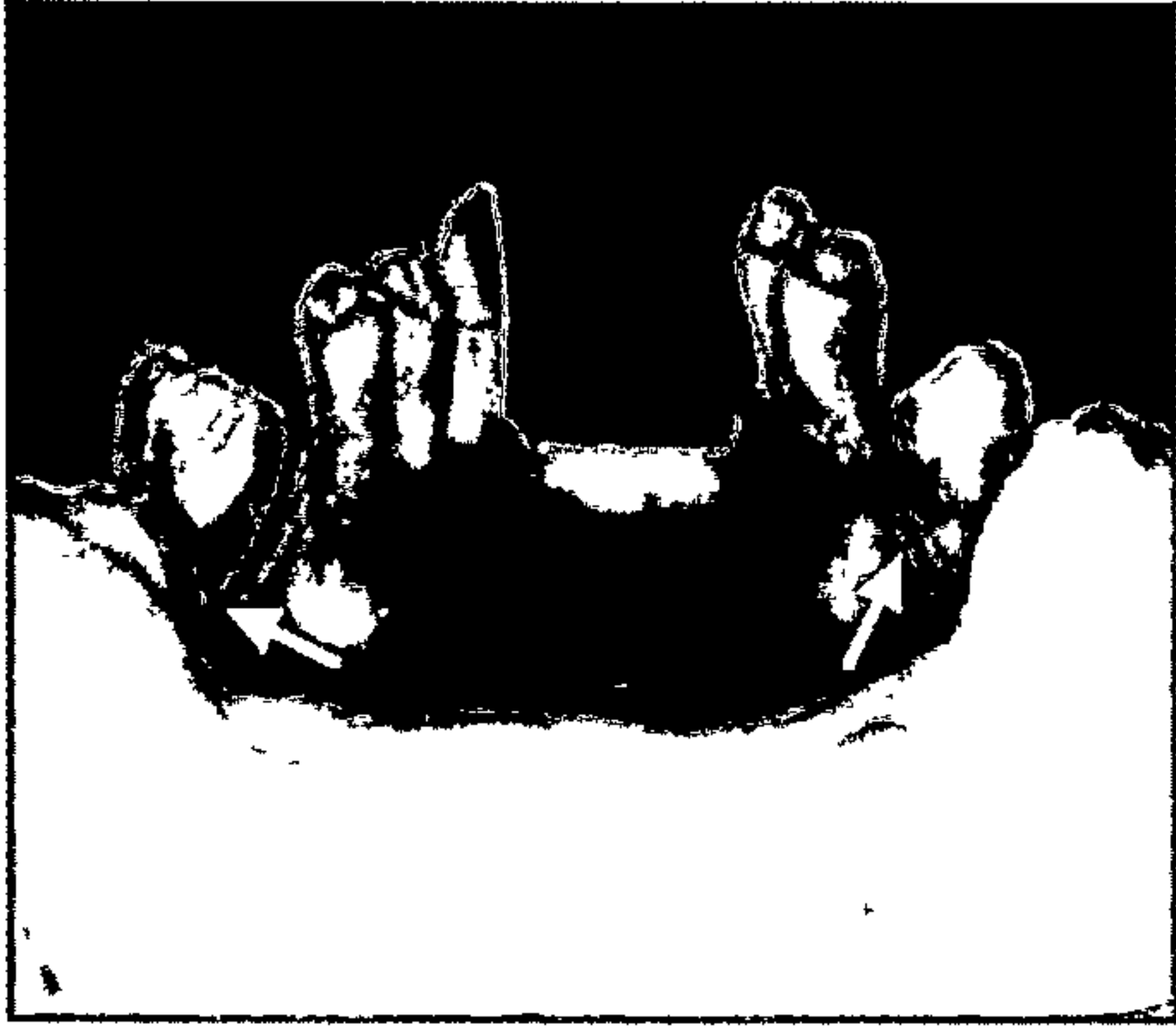


Figure 10



Figure 11



Figure 12

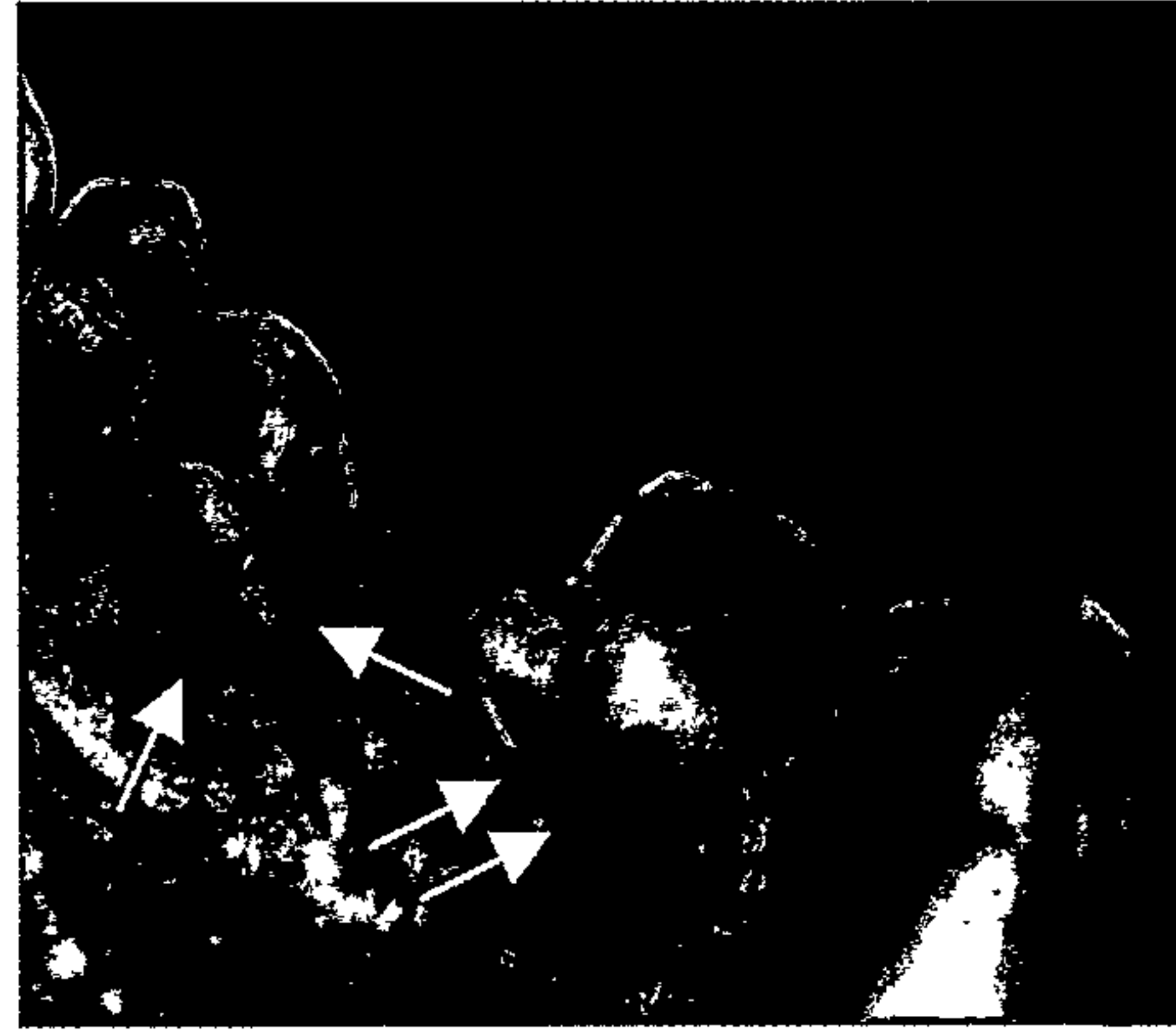


Figure 13



Figure 14



Figure 15

3.1.2 Surveying

Casts were secured to a surveyor by a specially designed clamp. A metal plate was used to ensure that the occlusal plane was parallel to the horizontal plane. Casts were secured in position and surveyed (Figures 16 and 17).

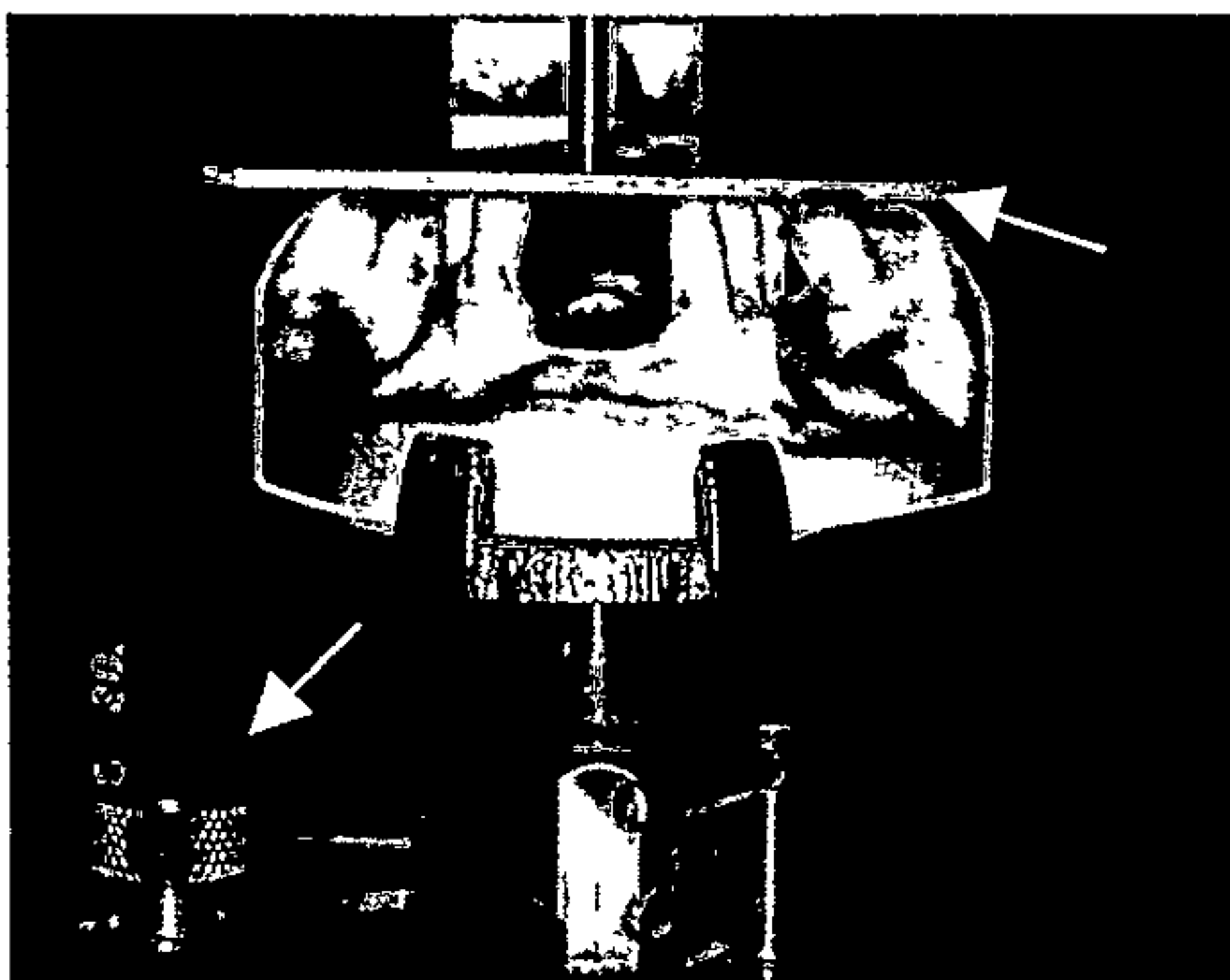


Figure 16

Top arrow: the metal plate
(parallelism check)

Bottom arrow: The designed clamp

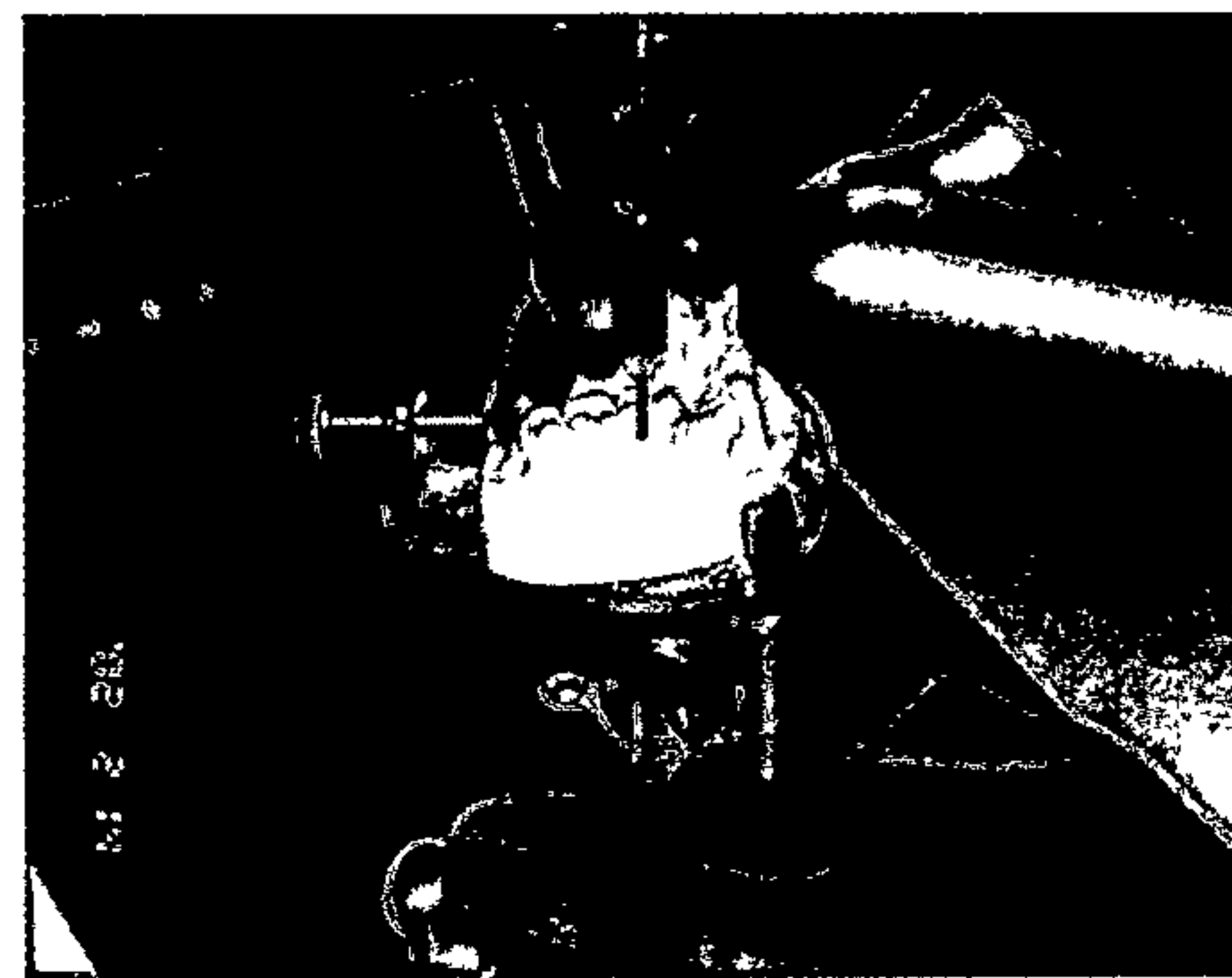


Figure 17

Surveying casts after securing in position

3.1.3 Methods of quantifying undercuts

Initially an attempt was made to measure tooth undercuts with a prototype with a millimetre scale and a locking screw, however, this was discontinued as it was too large to penetrate the full depth of an undercut and allow accurate measurements (Figure 18).

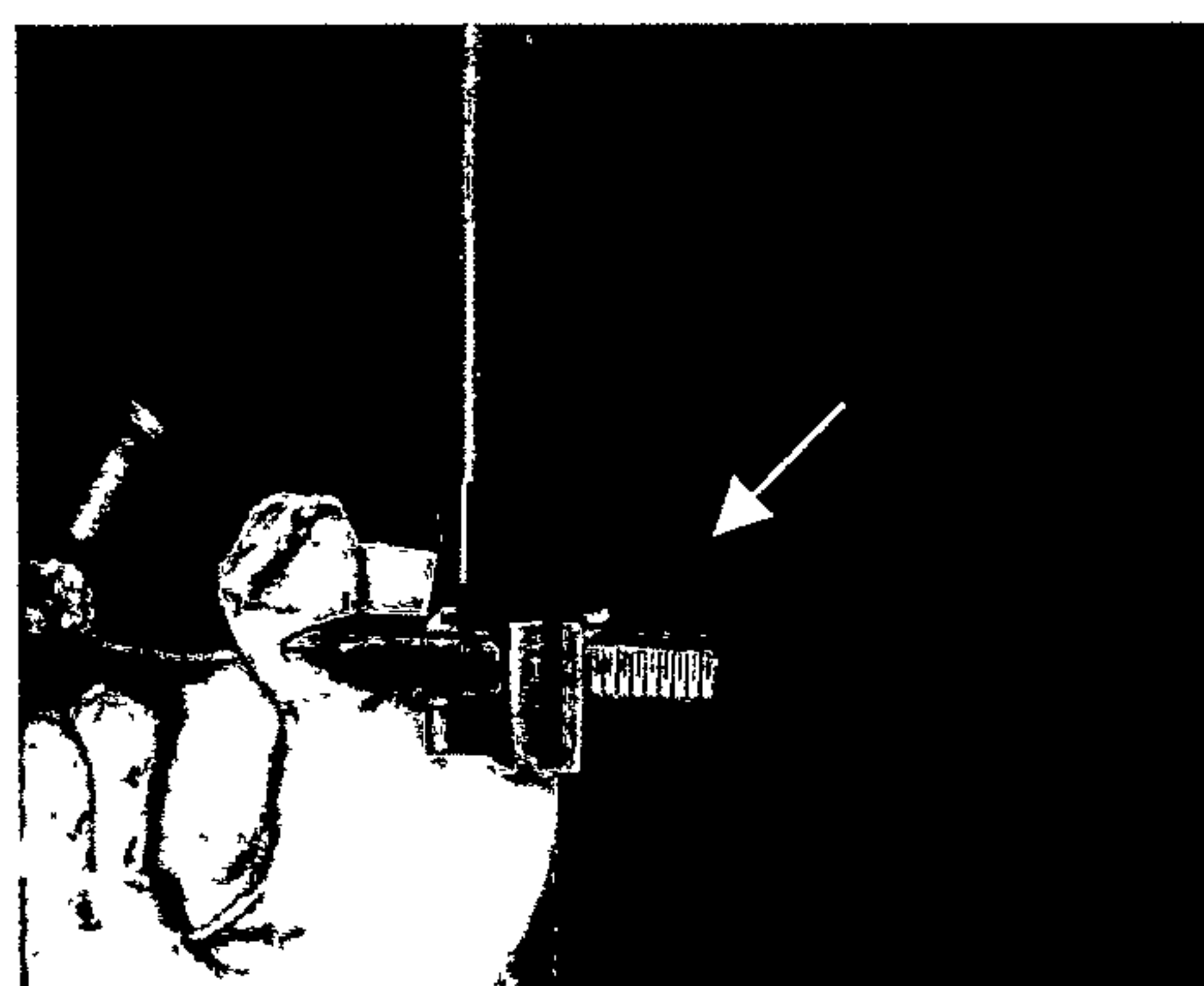


Figure 18

The designed prototype.

Arrow indicates the position of the locking screw

The following two techniques were used for undercut quantification and a similar protocol was followed for each.

A) The Microscribe 3DX technique (Method one)

The first technique was developed to measure undercuts used a 3D digitiser instrument (Microscribe 3DX-Immersion Corp.) (Figure 19) to trace complex contours, coupled with compatible software (Rhinceros) (Figure 23) to accurately represent curved shapes using a new computer-modelling technology. An attempt to measure tooth undercut depth using this technique failed, but the volume or the area of an undercut could be calculated. Further information is given on pages 66 and 67. Calculating the volume was complicated because it required selecting many reference points on the tooth surface in order to create triangles and to measure the spaces between them. It was therefore decided to measure triangular areas of relative undercuts, which represented the maximum convexity of the tooth on each surface, and in this application the Microscribe technique proved to be reliable.

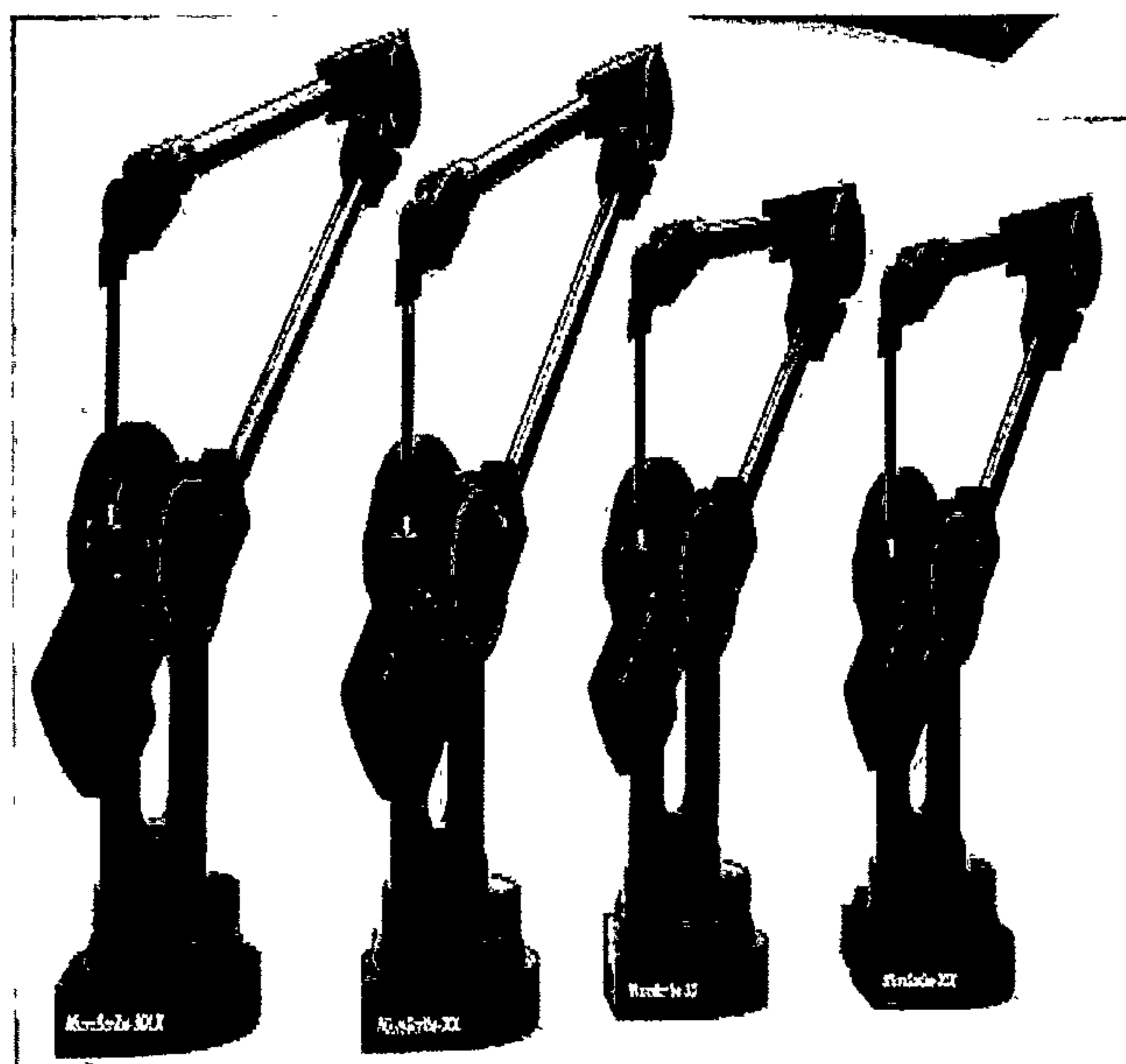


Figure 19
Different models of Microscribe. 3DX, second
from right was used in this study.

Three long shank tungsten carbide cutting burs were modified, resulting in three sizes (small, medium and large). The burs were modified with projections of 0.25, 0.50 and 0.75 mm corresponding to the three common sizes of undercut gauges described in literature (Figure 20). These burs were attached to the vertical arm of the surveyor to reach and measure as many undercuts as possible. A locking screw secured them in position. The vertical arm of the surveyor was adapted to be locked in any desired position with the aid of a screw after attaching the necessary accessory tool.

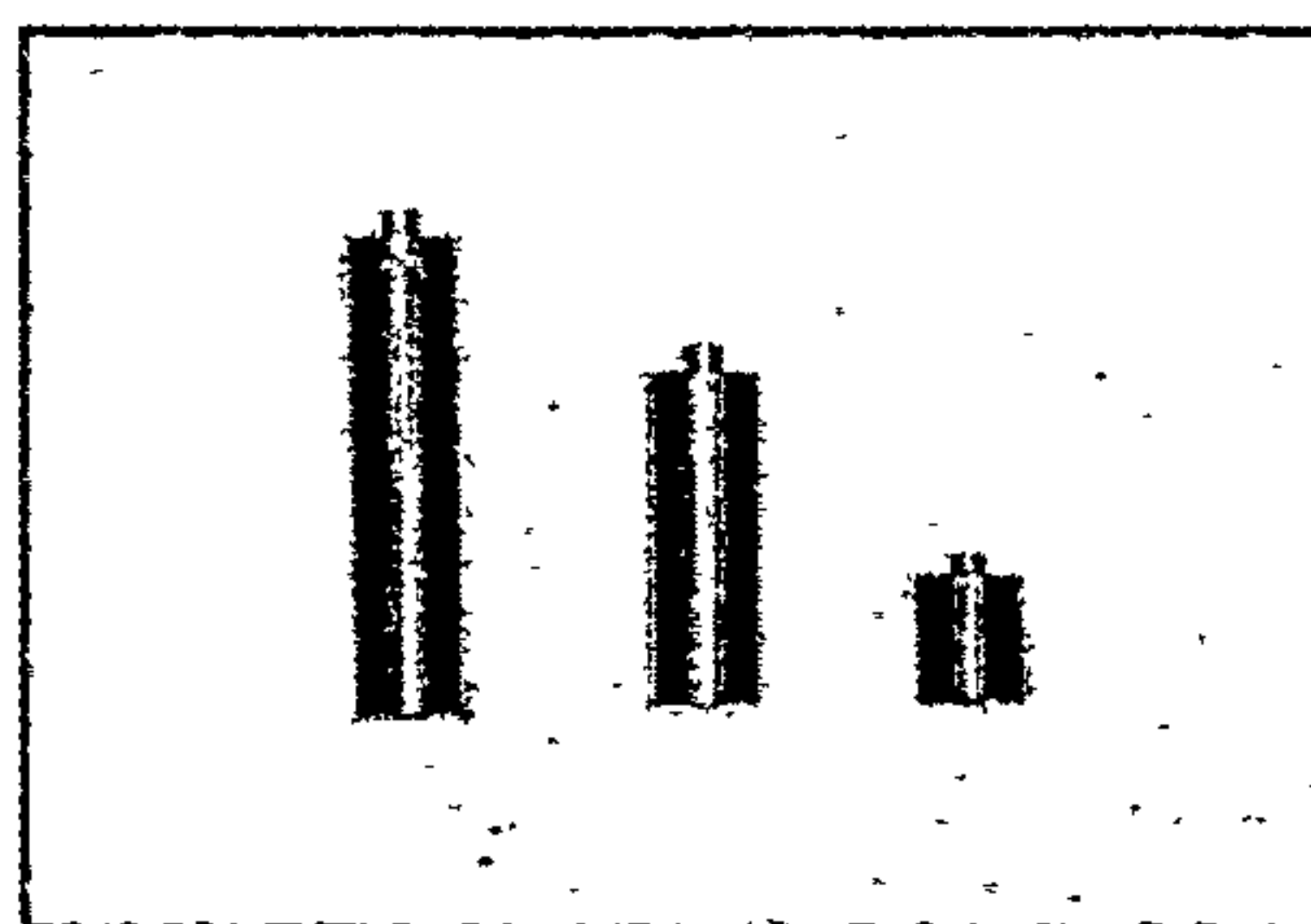


Figure 20
The modified burs

Two points of reference were selected at the maximum convexity of each surface of the teeth to be measured. The first point was at the level of the survey line and the second point was at the level of the cervical line. The third point of reference was a dimple created on the vertical arm of the surveyor. All points were marked on the teeth with a black marker (Figure 21).



Figure 21
Arrows show the adjustable locking screw and the third point of reference

The Microscribe 3D pen and its accessories were used to form a three-dimensional triangle. The areas of 399 undercuts in 327 teeth were calculated utilising the dedicated software (Figures 22 and 23). Three readings were taken for each area.

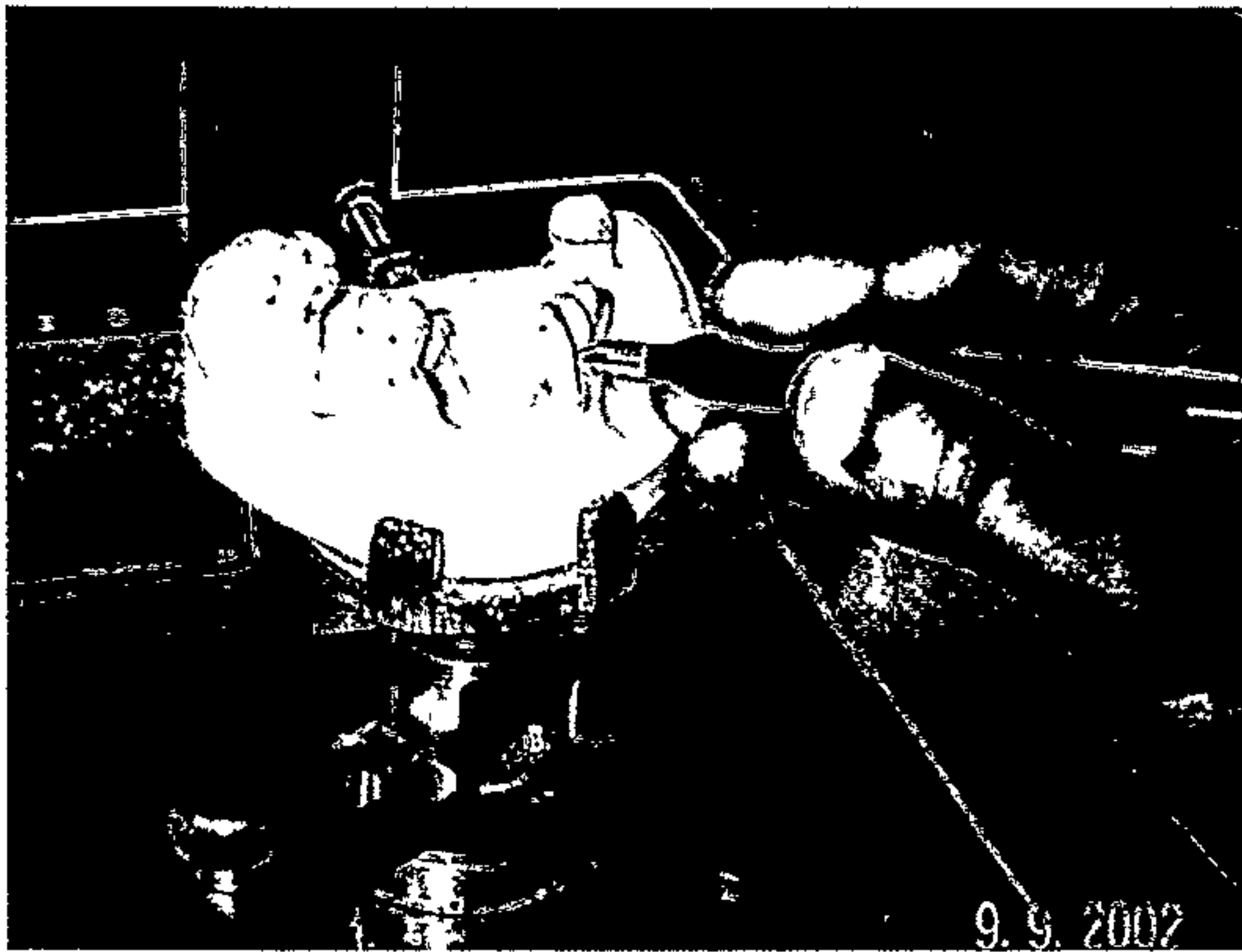


Figure 22

Microscribe pen and its accessories created triangles by clicking on the reference points .

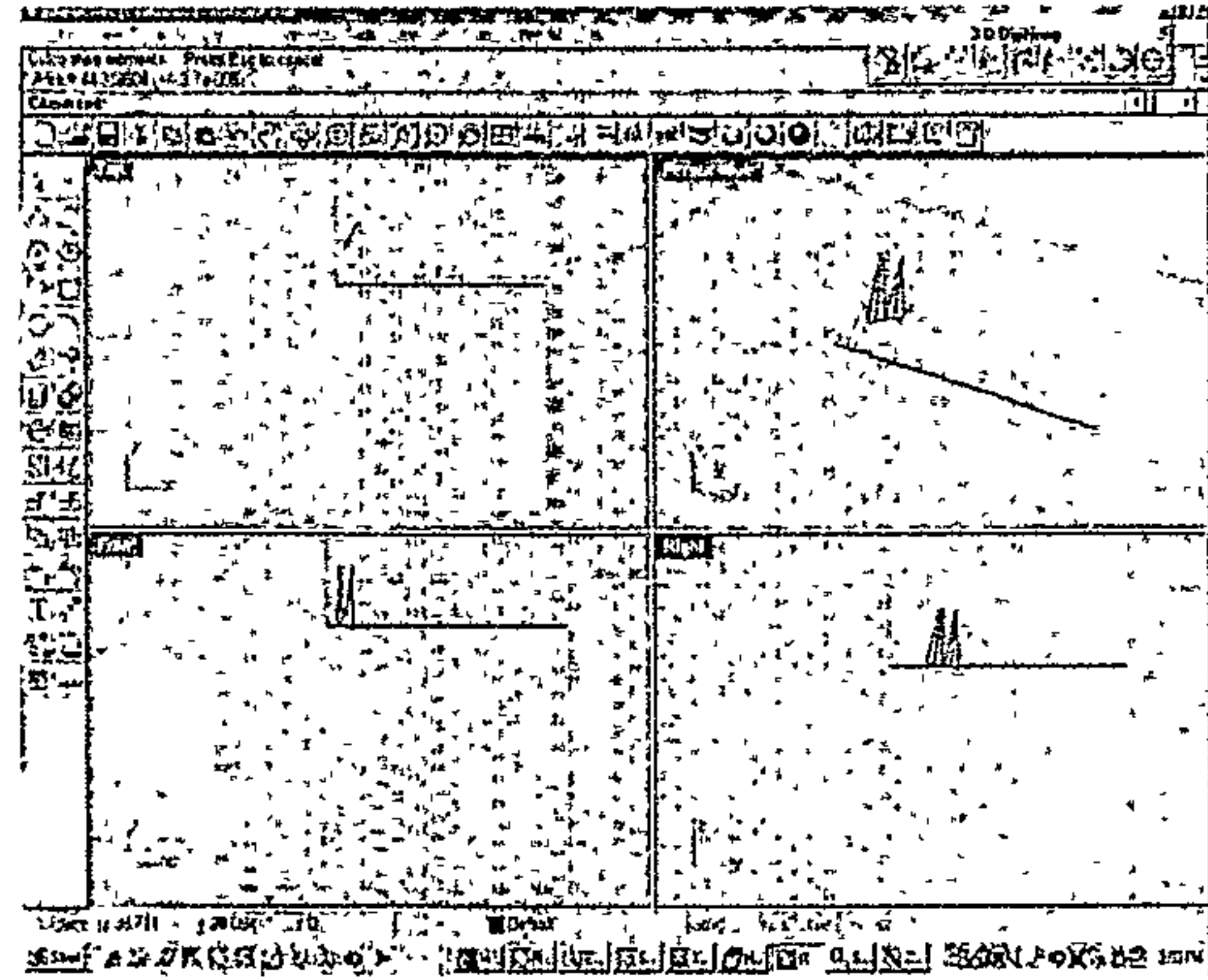


Figure 23

Rhinoceros soft ware showing undercut triangles formed

B) The Relative Undercut Measurement-RUM technique (Method two)

The second method was developed by modifying the vertical arm of the dental surveyor, using two micrometer heads of 0.01 (Mitutoyo 0-25mm, made in Japan) orientated vertically and horizontally, to measure all measurable undercuts (Figures 24 and 25). This method for measuring undercuts utilised a needle which was modified and attached to the horizontal micrometer. Two readings were taken to measure undercut depth. The first reading was taken by rotating the vertical micrometer downwards to the level of the second point of reference at the cervical line; the second reading was taken by rotating the horizontal micrometer towards the tooth till the operator felt resistance or the needle started to move. Magnifying loupes and a light source were sometimes used to assist in measuring. The difference between the two readings gave the depth of an undercut. To calculate the area, two additional readings from the vertical micrometer

were taken, one at the level of the survey line and the other at the level of cervical line. The difference between them was the length or the height of the coronal portion of the tooth on each surface. The formula $\text{area} = 1/2 \times \text{base} \times \text{height}$, defined the area of an undercut triangle, but this procedure was complicated and time consuming. The second method for measuring undercuts proved to be unreliable and details are discussed in Results (Figures 24 and 25 illustrate the micrometer heads and their use on undercuts).

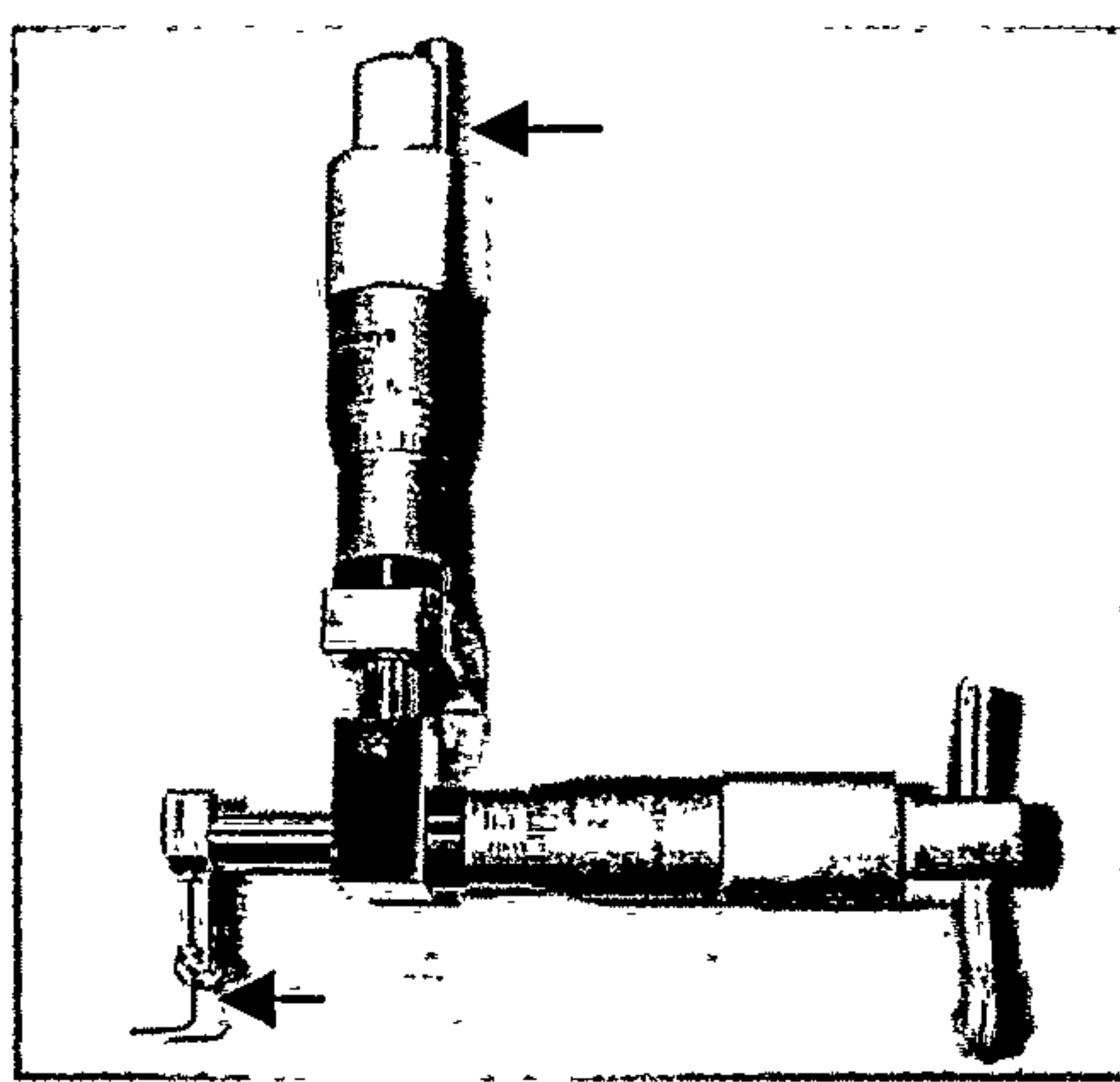


Figure 24
Top arrow: the position where apparatus
joined the surveyor. Bottom arrow: the
needle used in measurements

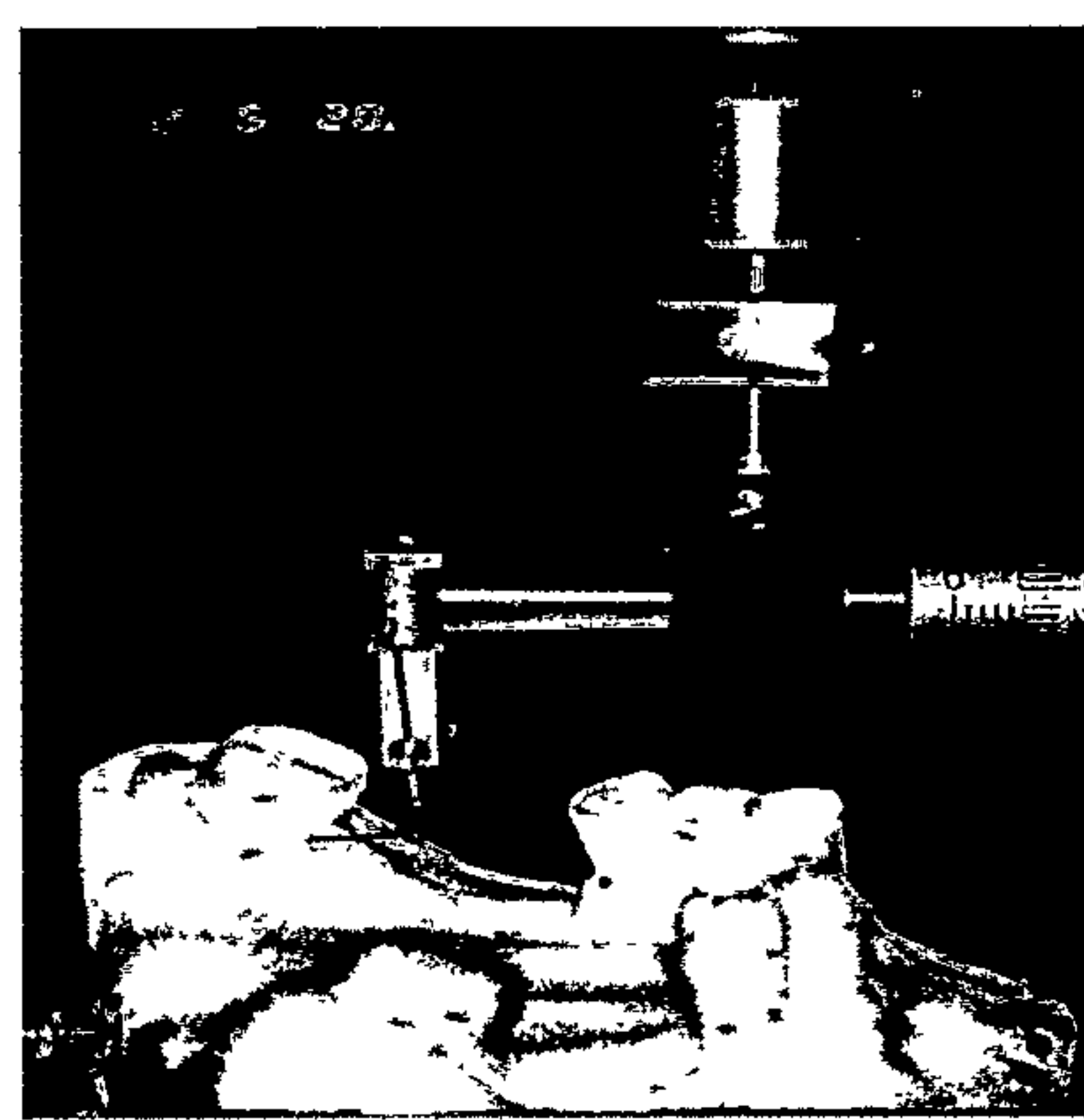


Figure 25

3.2 Part II

This part of the research was based at the Australian Technology Park (ATP) Redfern, Sydney, NSW, Australia. Table 6 lists the materials tested.

Table 6

Materials tested	Type	Brand name	Manufacturer	Batch number
Alginates	Powder and water	Liffin Green (Dust free-regular)	Nissin Dental Products INC Japan	CA 0501
		Aroma Fine DF III (Normal set)	G.C.Corporation Japan	0110121
		Hydrogum (Fast set)	Zhermack Italy	A1223B-A189B
		Palgat Plus Quick	ESPE Germany	ZP0010245 ZP0010300
		Kromopan 100 (Dust free-fast set)	LASCOD Italy	015229232.201
Polyvinyl siloxane	Two pastes (base & catalyst)	President (Regular)	Coltene Switzerland	LA489
	Syringeable	Imprint II Tray material high Viscosity	3M USA	20011228 20011114
	Syringeable	Imprint II Wash material low Viscosity	3M USA	20011228 20020411 20011114
	Syringeable	Imprint II Wash material regular Viscosity	3M USA	20011228 20020322 20011114
Polyether	Two pastes (base & catalyst)	Impregum-F	ESPE Germany	100701-115720

3.2.1 Tear energy experiment for alginates(Method 1: crescent-shaped mould)

Experiments were performed using a two-piece, plastic mould, with fabricated dimensions as specified in the Australian standards for alginate impression material AS 1282 1972, and similar to the one used in the American Standards for Testing and Materials ASTM D1004-94a. The mould was crescent-shaped on one side and had a 90° angle on the other side allowing specimens to rupture at this potential stress point (Figures 26 and 27).

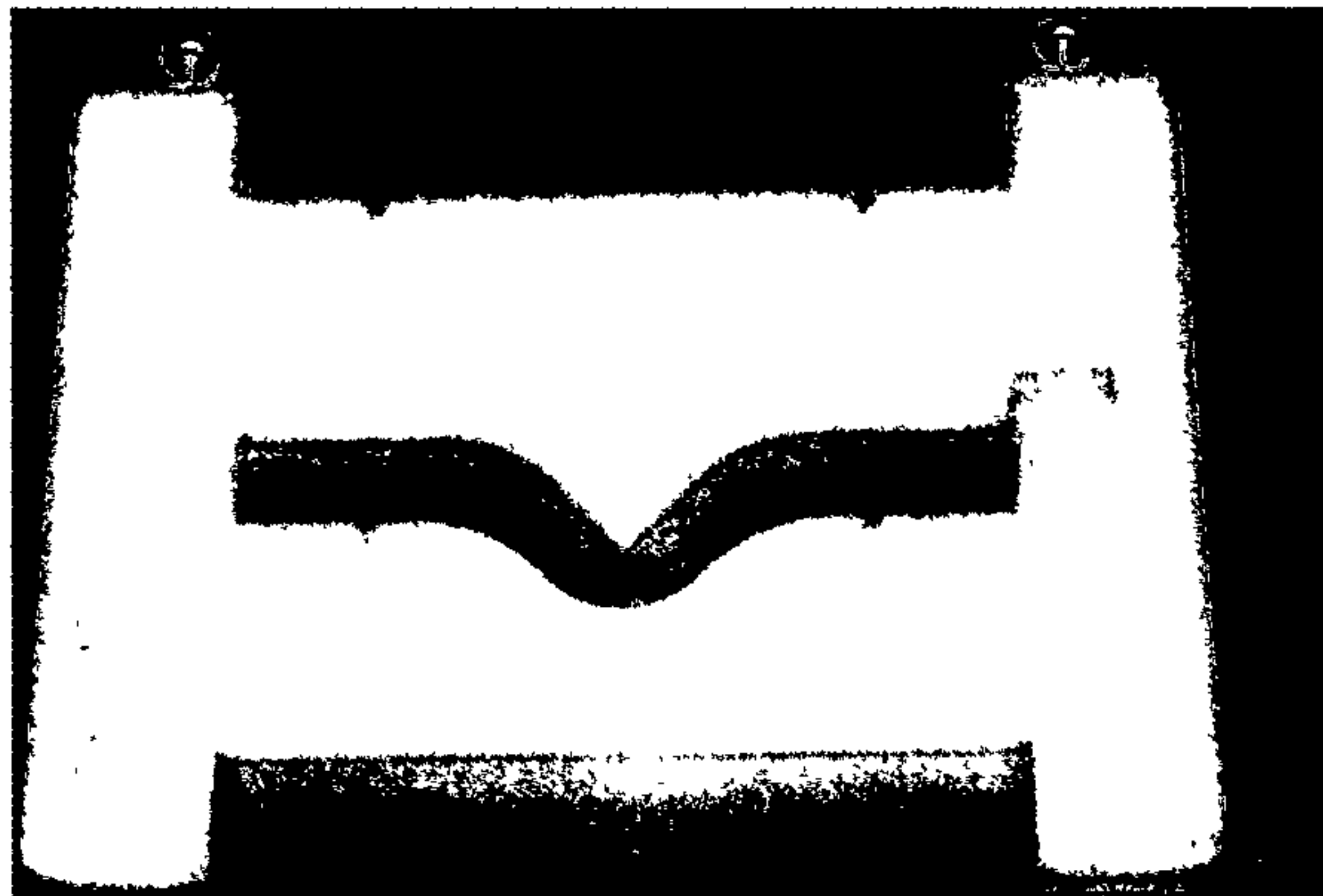
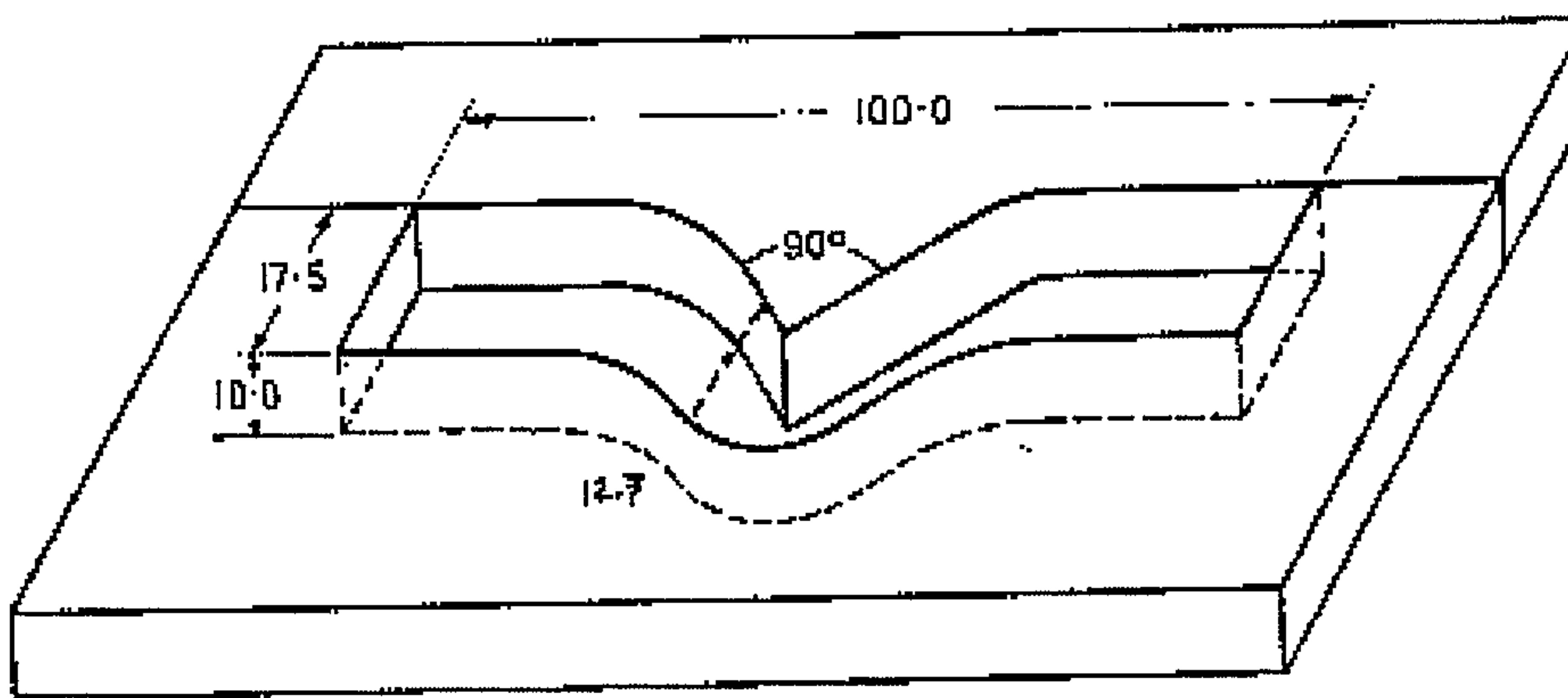


Figure 26

AS 1282 — 1972



Dimensions in millimetres

Figure 27

Five brands of alginate commonly used by staff and students in the Faculty of Dentistry, University of Sydney, and by private practitioners were selected. Five samples from each brand (see Table 6) were mixed according to manufacturers' instructions in an automatic mixing machine (which took approximately 1-1.5 minutes) to eliminate chances of bubble entrapment which might have compromised the results (Figure 28). Experiments were performed at $22^{\circ}\text{C} \pm 1$ and 70% relative humidity.



Figure 28

The plastic container into which the proportioned alginate was kept in the automatic mixing machine.

The mixed material was immediately removed from the container and placed in the mould, with the assistance of two glass slabs (200 mm x 50 mm each), one placed underneath and the other on the top to ensure that a uniform thickness of specimens was obtained. In addition, two escape channels were incorporated in the mould to allow for excess material to escape (Figures 29 and 30).



Figure 29

Loading the material in the mould.

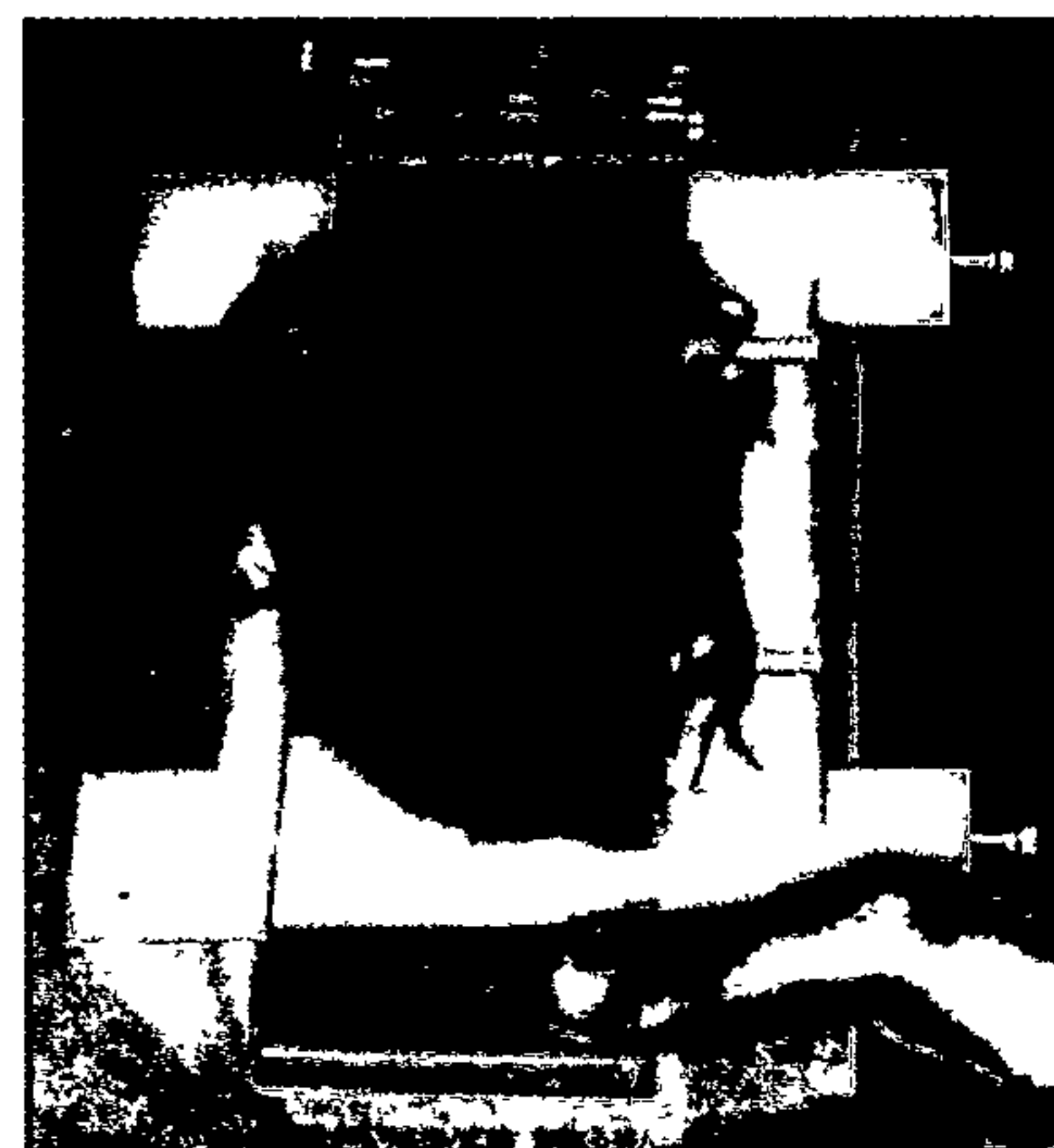


Figure 30

Two glass slabs with digital pressure ensured uniform samples.

Approximately 10 minutes from the start of mixing, specimens were placed into the tensile testing machine (Shimadzu, Japan) with the assistance of specially designed plastic clamps. Tests were performed at the rate of 500 mm/min until complete rupture (Figures 31 and 32).

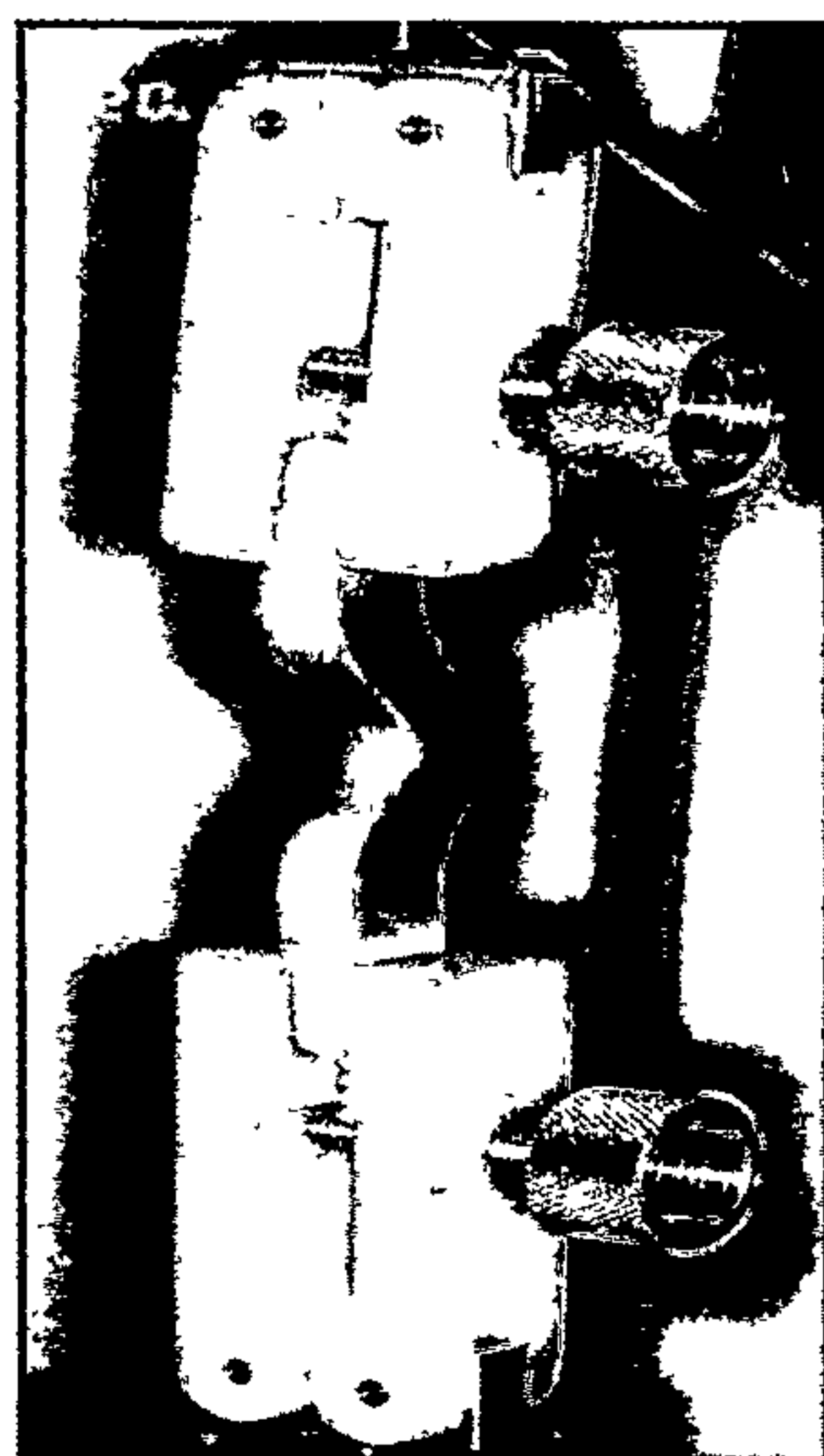


Figure 31
Specimen before rupture.



Figure 32
Specimen after rupture.

3.2.2 Tear energy experiments for alginates and elastomers (Method 2; trouser-shaped mould)

This method utilised a trouser-shaped mould as described by Webber and Ryge (1968). This technique was specified in standards such as the American Society of Testing and Materials ASTM D624-00, die T. This method was used to compare alginate and elastomeric impression materials listed in Table 6. The second aim was to compare results from "method one" with "method two" for alginates. A three-part mould was used to create specimens of 2 mm thick, 20 mm wide and 80 mm long. Specimens had a 1 mm v-shaped depth groove along the length to act as a "crack guide" and a 20 mm split at one end to facilitate specimen placement in the grips of the tensile testing machine (Figures 33, 34 and 39).



Figure 33
Apparatus for tear energy, method two
(trouser-shaped mould)

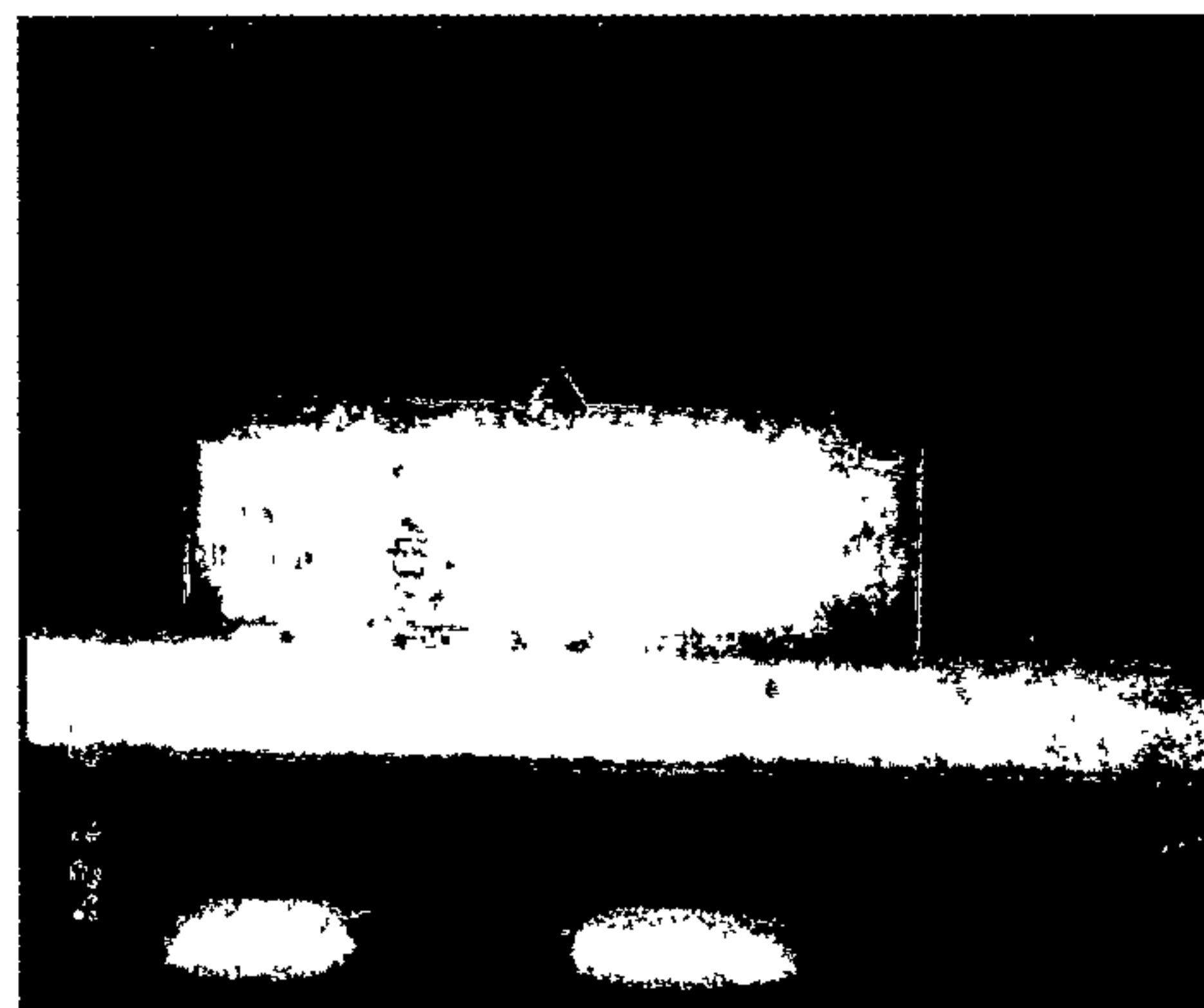


Figure 34
Cross section of the trouser mould
showing the v-shaped notch

Ten samples of each brand of the materials were tested. Alginates were mixed in a similar fashion to that in Method one, but they were kept at 100% relative humidity for 15 minutes, to allow for comparison with the elastomers. The latter were either dispensed or mixed according to manufacturers' instructions (Figures 35 and 36) and allowed to set for 15 minutes for polymerisation. This time was selected because the state of set material (for elastomers) was considered to be similar to that clinically found at the time of removal from the mouth. An 8-8 silicone spray (CRC Sydney-Australia) was used as separating medium and sprayed on a glass slab (200 mm x 50 mm) which was used with digital pressure to allow uniform sample thickness (with the assistance of the escape channels) and to avoid distortion of the samples. The spray helped in separation of the assembly because of the sticky nature of rubber materials. Mixing and handling of the materials into the mould are shown in Figures 35, 36, 37 and 38.

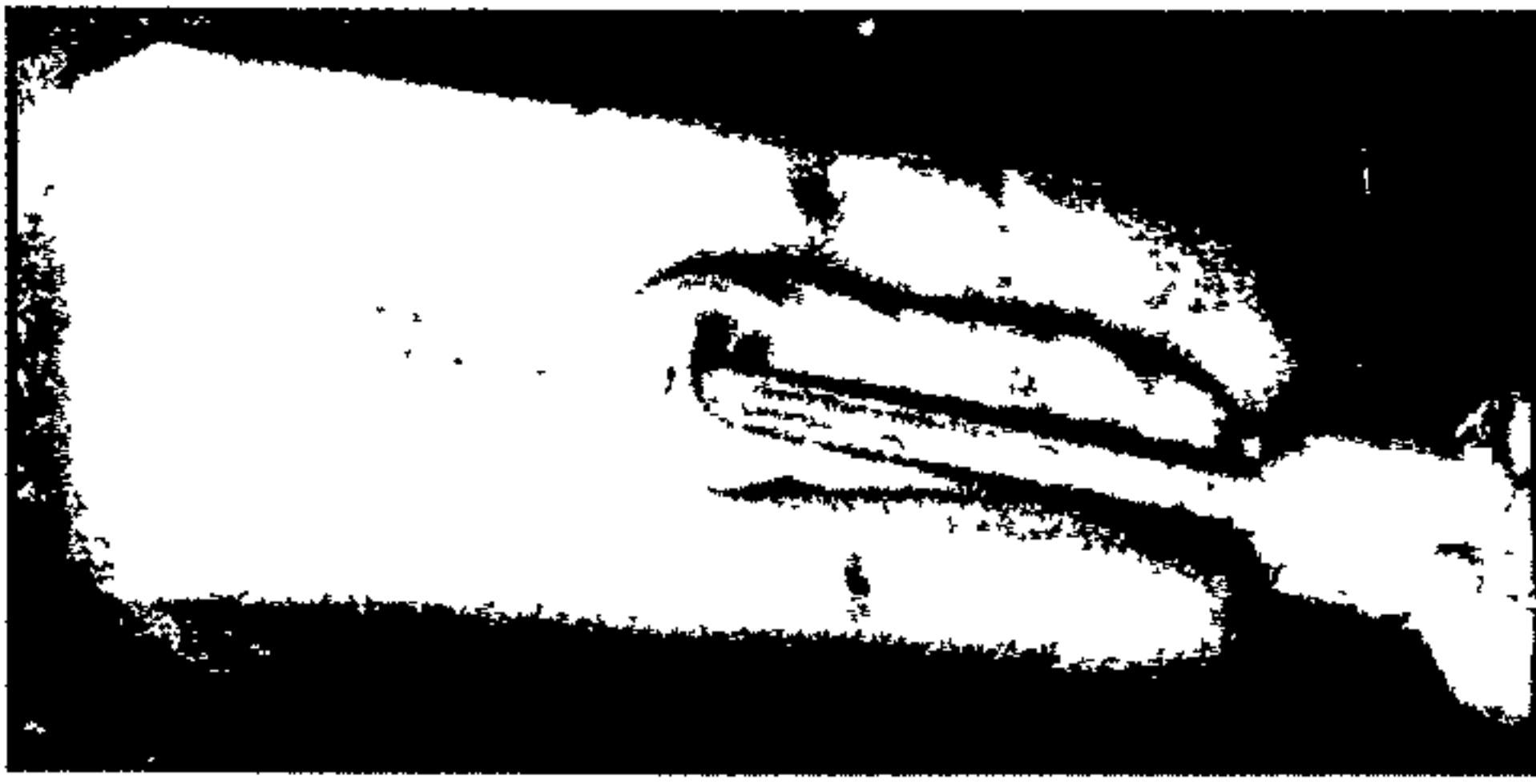


Figure 35
Dispensed material loaded
into the mould

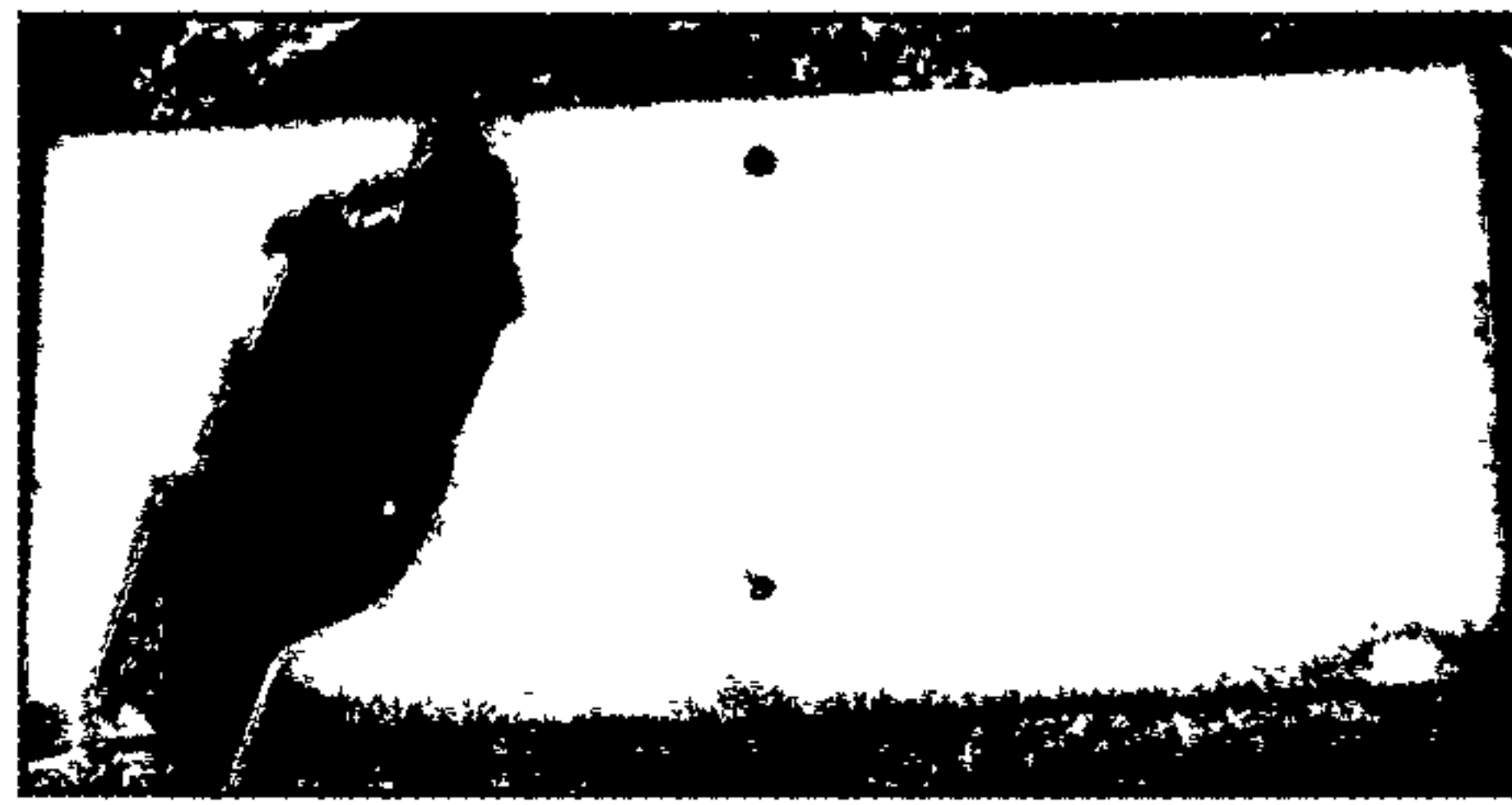


Figure 36
Mixed material loaded into
the mould

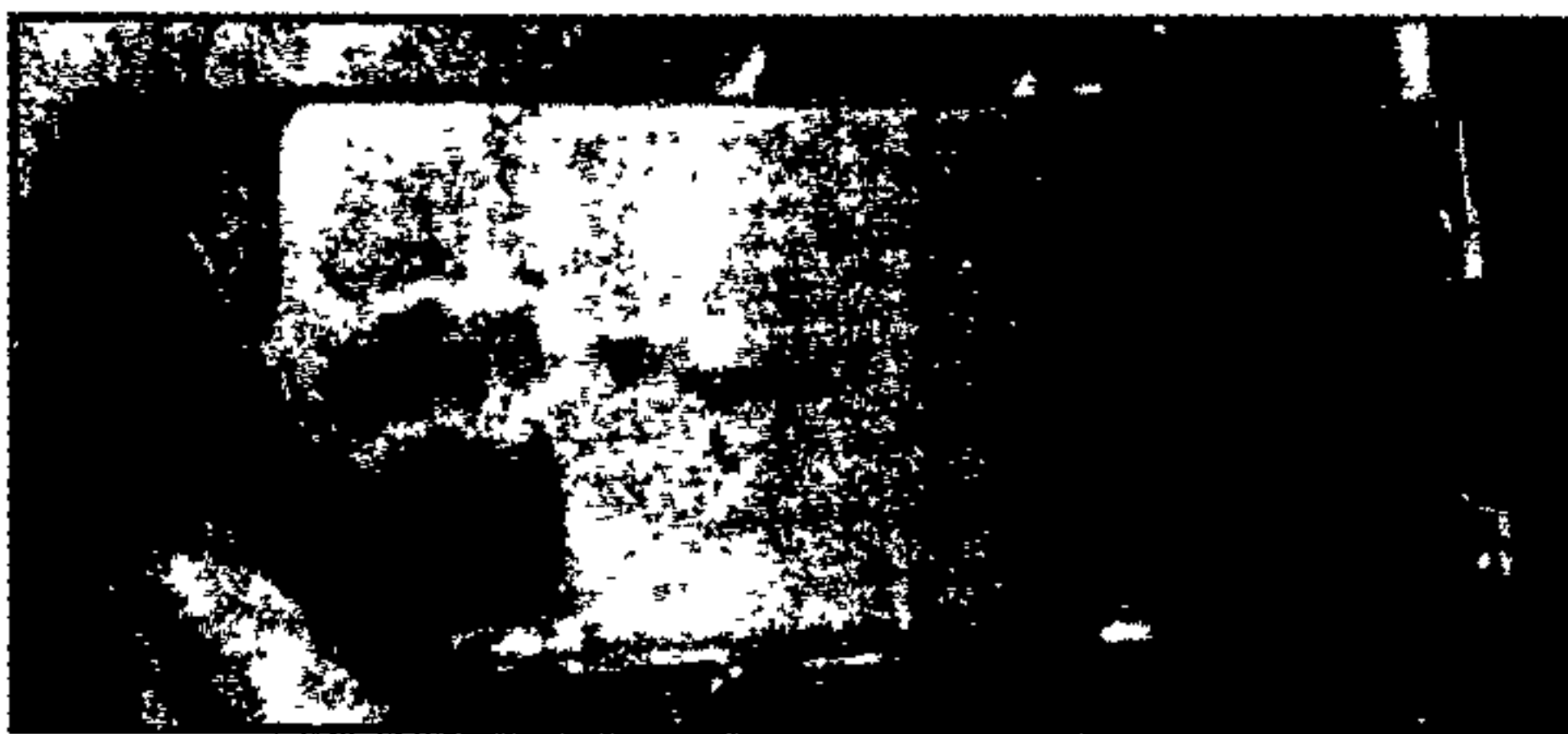


Figure 37
A glass slab ensured
a uniform sample thickness



Figure 38
Set material removed from
the mould

An initial incision was made with a blade to guide the tear into the v-shaped groove only. The specimens were placed in the tensile testing machine and tested at uniform rate of 50 mm/min until complete rupture (Figure 39).

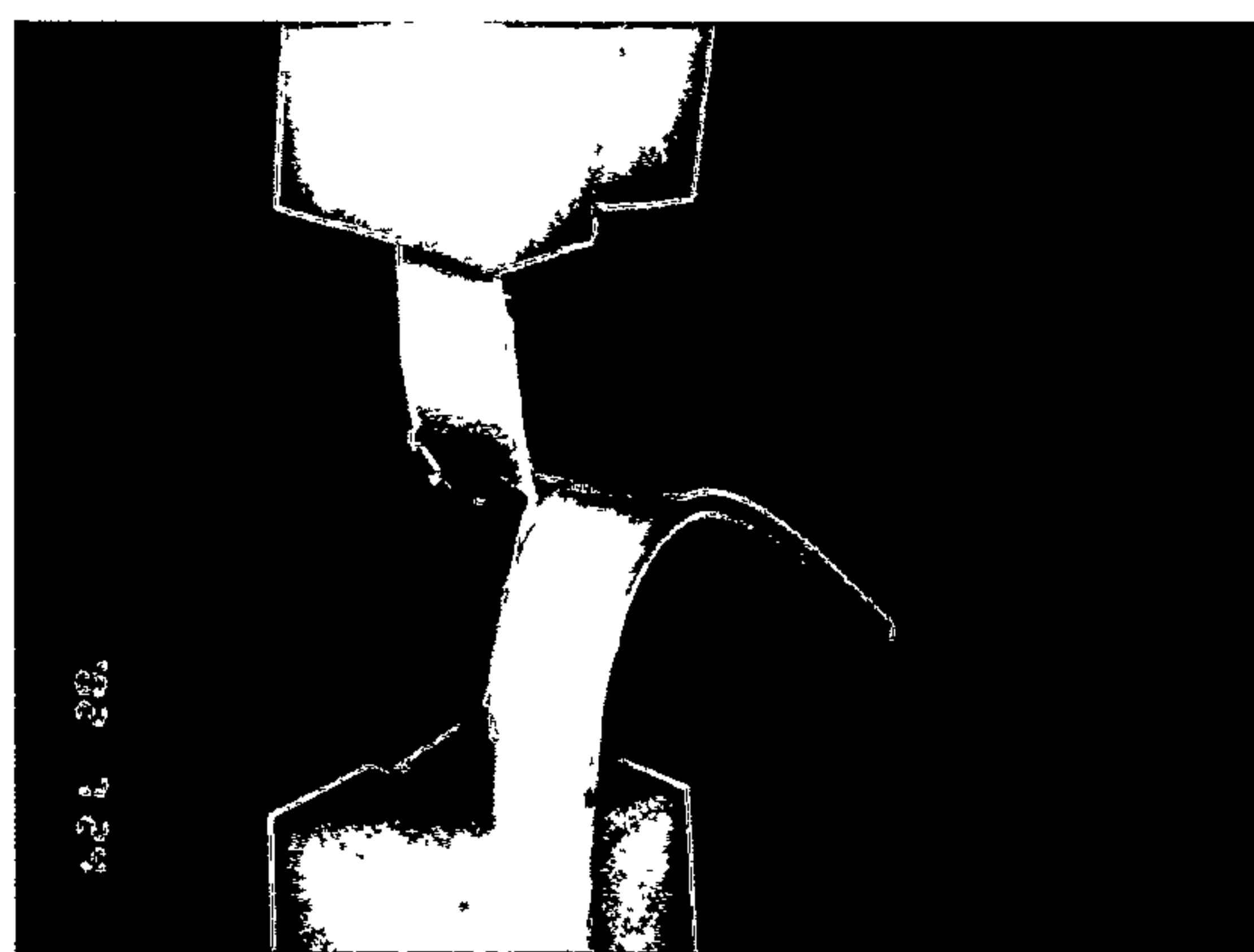


Figure 39
Specimen in the tensile testing machine
during tear

3.2.3 Tensile tests for alginates and elastomers (dumb-bell-shaped mould)

A Universal "dog- bone" shaped or "dumb-bell" shaped mould was used for this purpose (Cook et al. 1984). The mould consisted of two plastic parts assembled together by a cylindrical shaped ring (Figure 40). The mould had a gauge length of 30 mm and a

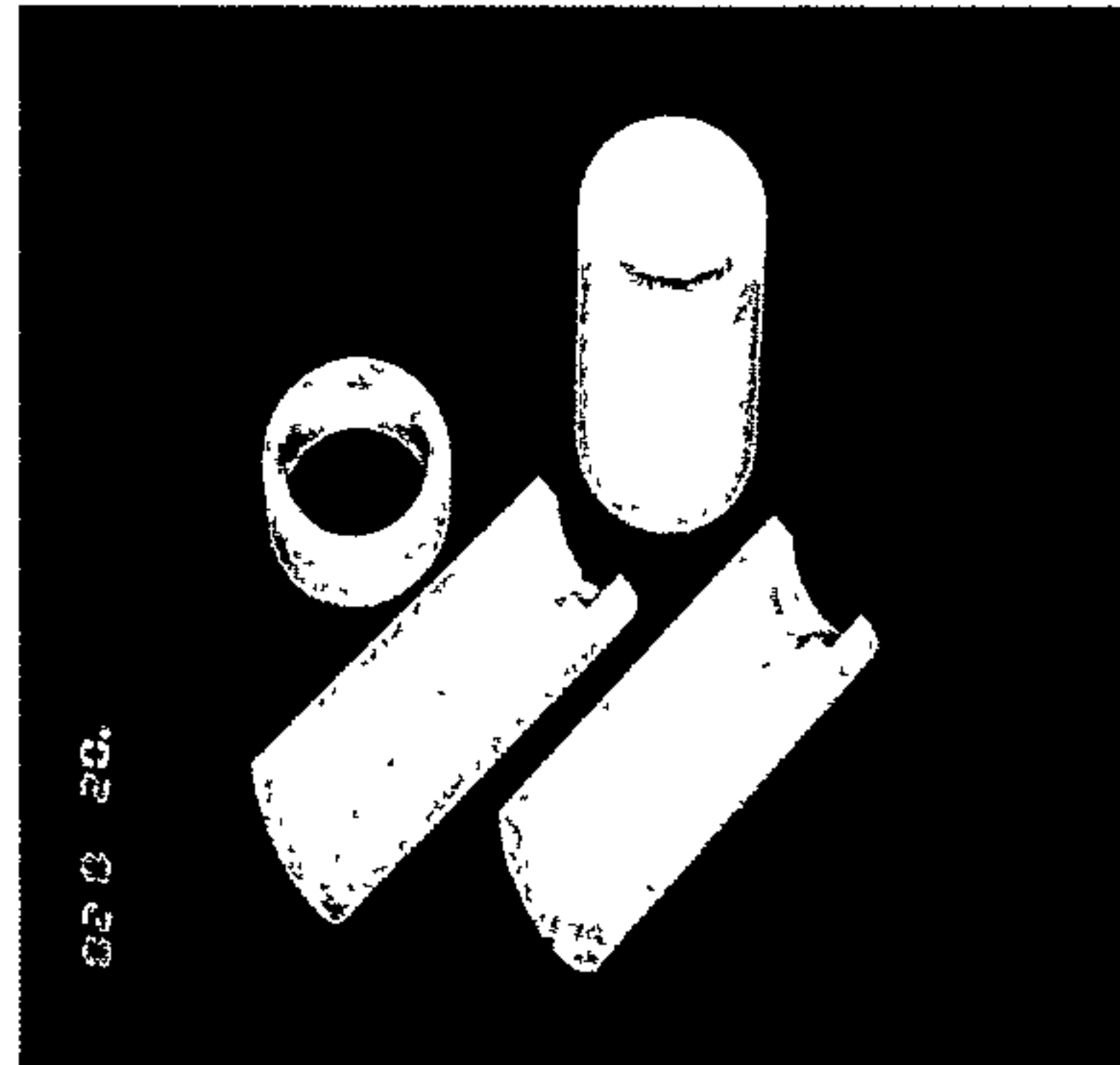


Figure 40
Different parts of the tensile test mould

diameter of 5 mm. These specimens were used for testing tensile strength, the elastic modulus and the yield stress and strain of selected impression materials.

Five samples of each brand of impression material were mixed according to manufacturers' instructions. Tests were carried out at $22^{\circ}\text{C} \pm 1$. Alginate specimens were kept at 100% relative humidity (in a jar). A 15-minute waiting period was allowed for the polymerization process of elastomers. Figures 41, 42 and 43 show mixing and handling of the materials. A plastic plate and a glass plate (200 mm x 50 mm) were used incorporating escape channels to ensure uniform sample size (Figure 43). A specially designed removal clamp helped in separation of the assembly after set (Figures 44 and 45). Specially designed metal holding clamps were used to hold the specimens in the tensile testing machine, where they were tested at a uniform rate of 50 mm/min until complete rupture (Figures 46 and 47).



Figure 41
Loading the material
into the mould

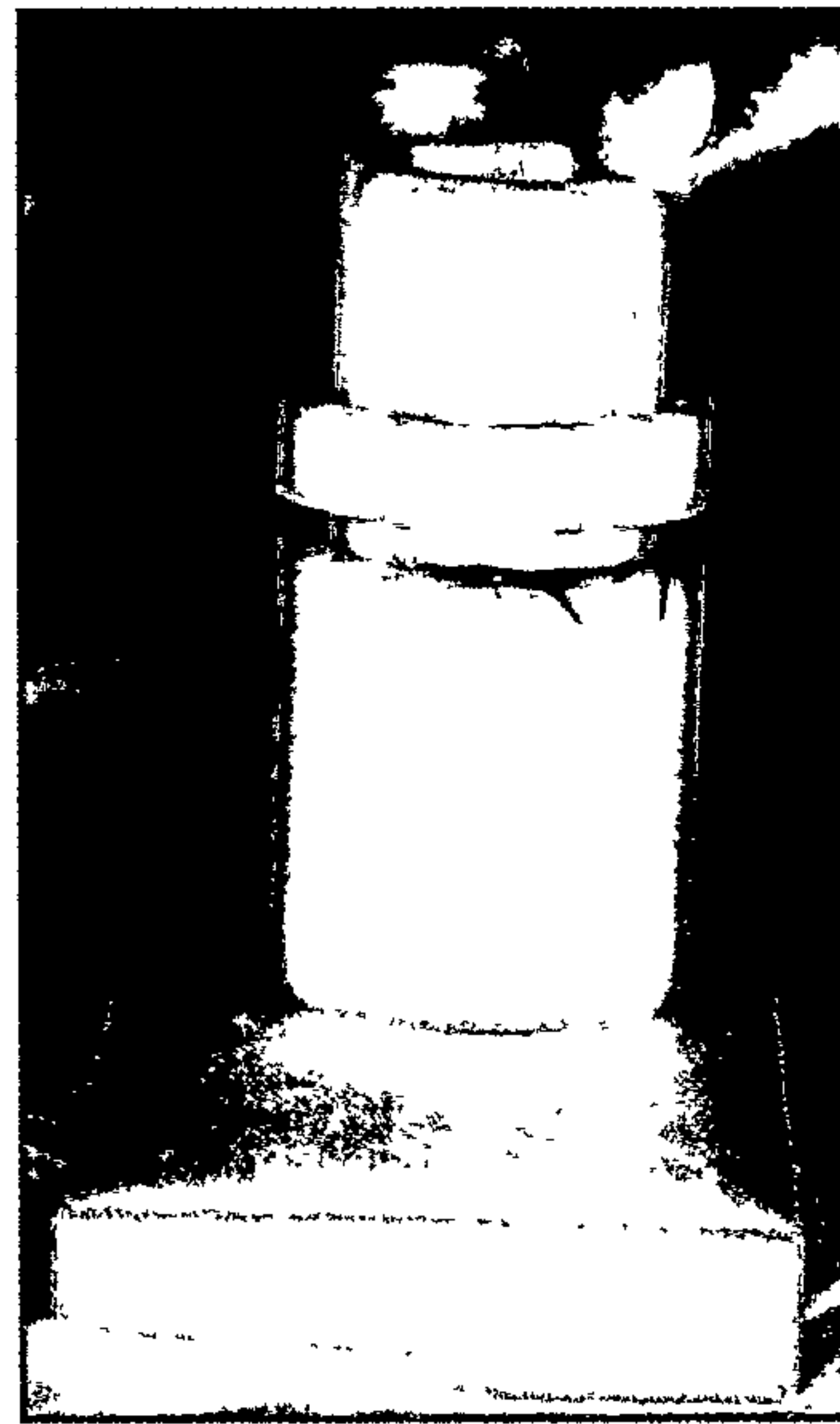


Figure 42
Assembling the parts
with digital pressure



Figure 43
Glass & plastic slabs ensured
uniform sample size.

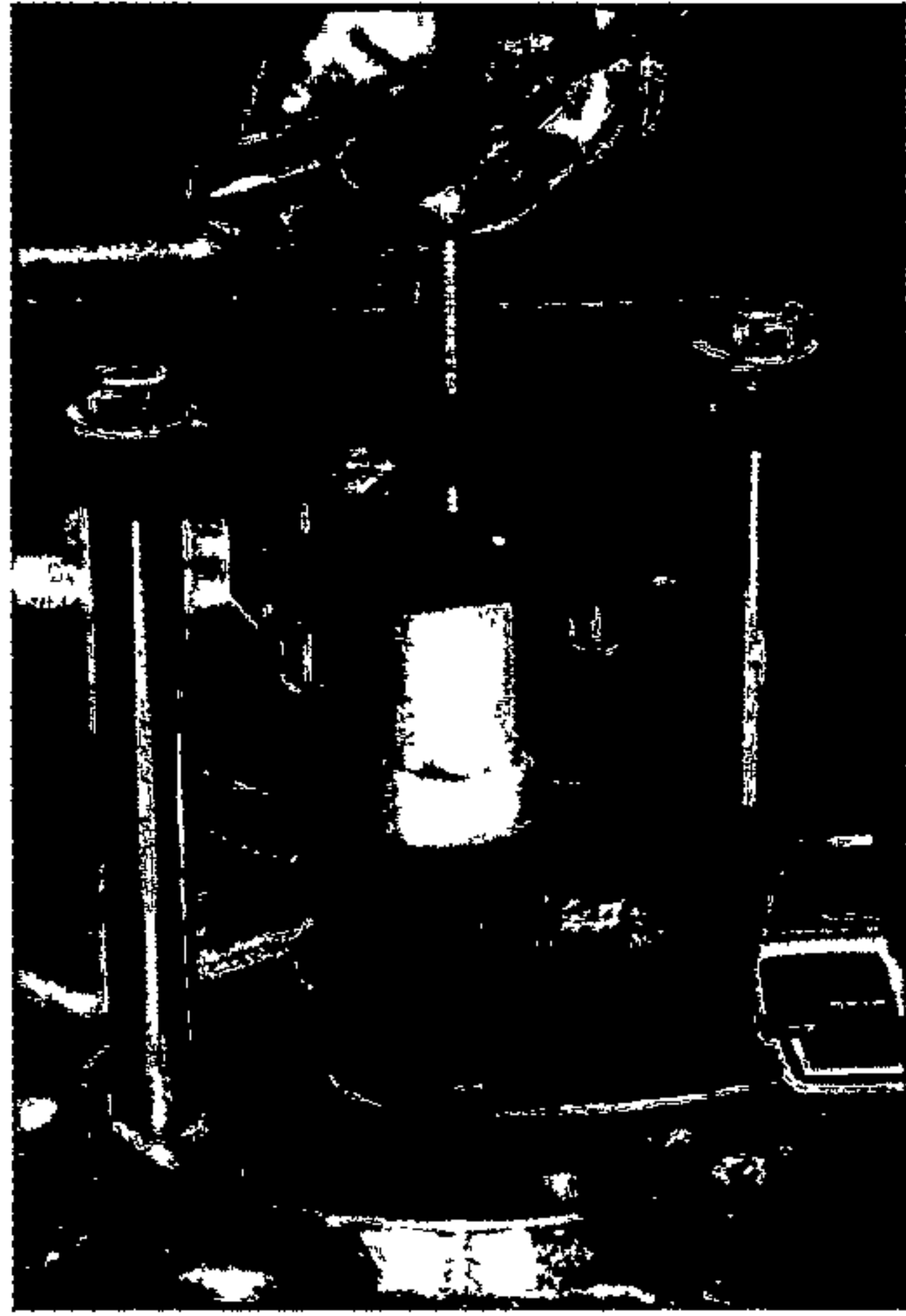


Figure 44
The removal clamp



Figure 45
Set material in the mould

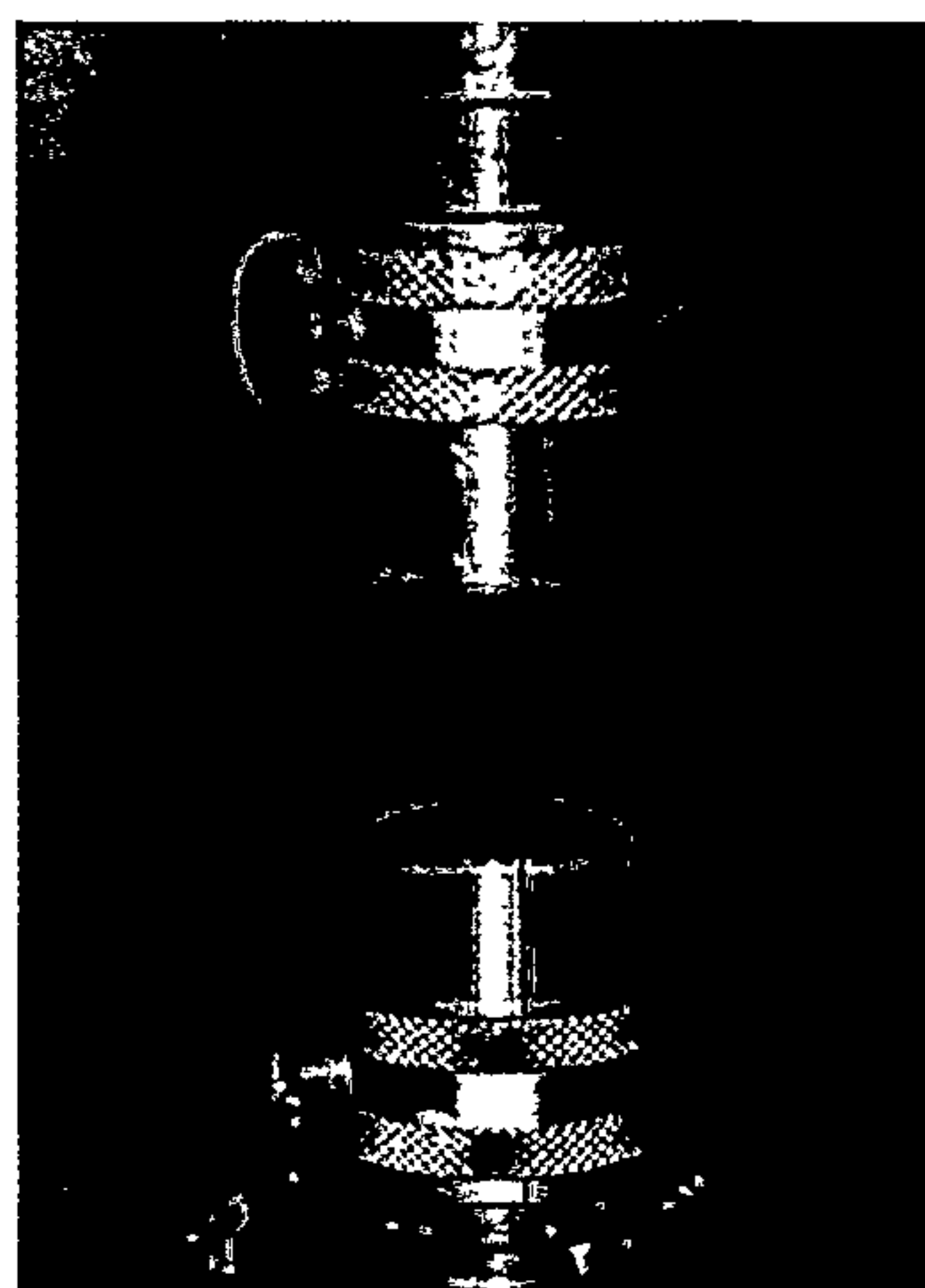


Figure 46
Specimen before rupture.
Arrows point to the metallic
holding clamps

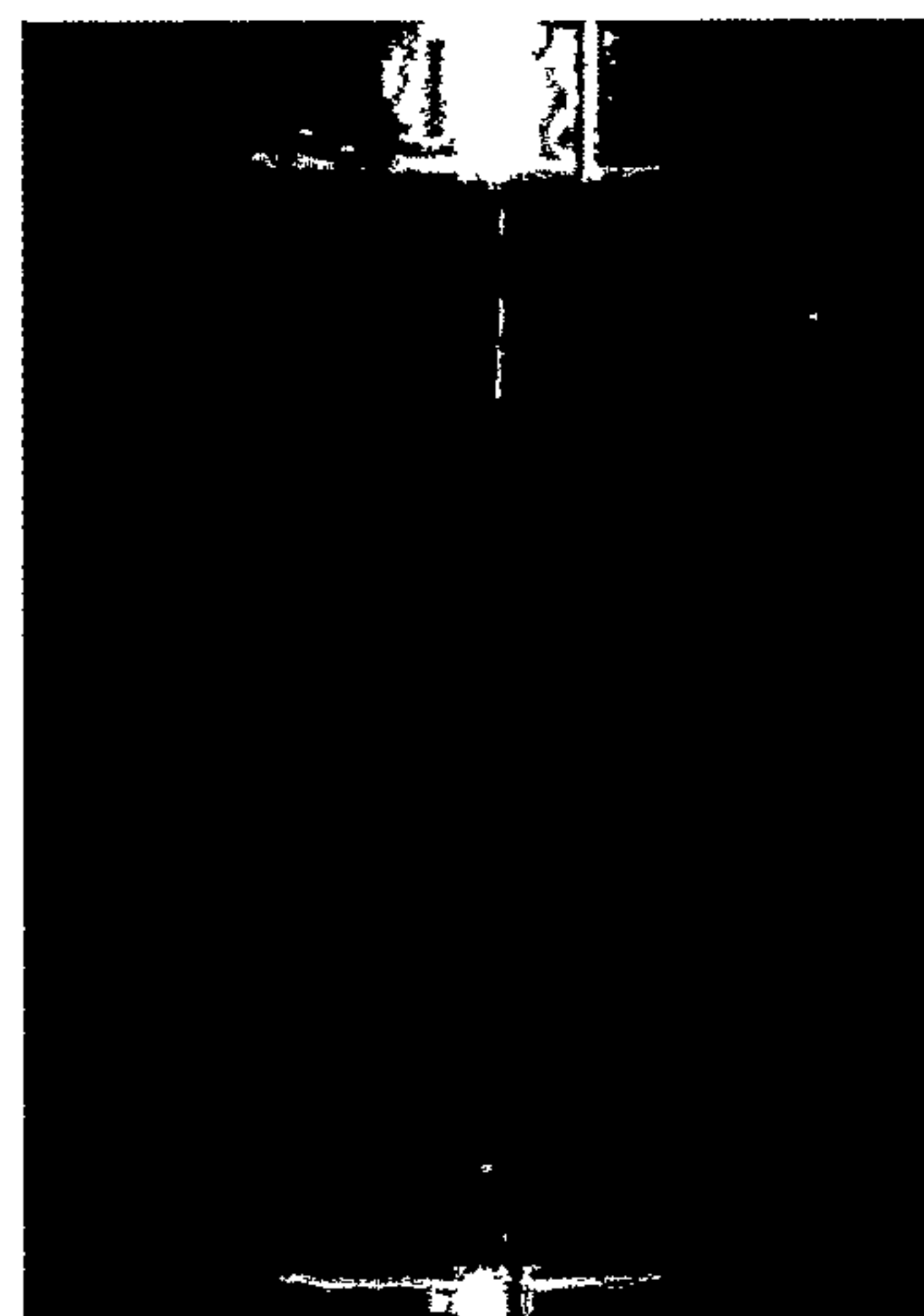


Figure 47
Specimen after rupture.

4. RESULTS

4.1 Statistical analysis of undercut measurements (Microscribe and RUM)

4.1.1 Severity of the undercut measurements

A) Average undercut (buccal, lingual, mesial and distal)

All undercut measures (i.e. each of the buccal, lingual, mesial or distal measures) were based on the average of three readings. The ‘average undercut’ analysed in this section was the average of the four possible areas measured. Out of 279 teeth measured:

41 were distal measures=15%

235 were buccal measures=84%

42 were mesial measures=15%

81 were lingual measures=29%

Note: The outcome of measures was significantly influenced by buccal measurements (235 teeth out of 279 total had buccal measures only).

Table 7 Means and standard deviations (SD) of average undercut measures for the five fitting categories

Did casting fit?	Mean (mm ²)	N (teeth)	SD (mm ²)
Did fit	8.87	37	6.62
Did not fit	11.36	42	5.67
Don't know	7.96	107	5.95
No missing teeth	6.33	71	5.90
Orthodontically treated cases	6.90	22	6.50
Total	8.10	279	6.20

A1 "Fit" compared with "did not fit" (N=79 teeth)

The distribution of undercut values was significantly skewed. However, this was rectified using a square root transformation. A *t* test showed that there was a "border line" significant difference in severity of undercut between "fit" and "did not fit" groups (*t* = -2.09, *df* =77, *p* =0.040).

A2 Maxilla compared with mandible (N=279)

The distribution of undercut values in this sample was also significantly skewed, but was rectified using a logarithmic transformation. There was no significant difference in terms of severity of undercut between maxilla and mandible (*t*=-0.87, *df* =277, *p*=0.388).

A3 Left compared with right (N=279)

The distribution of undercut values was significantly skewed, but was rectified by logarithmic transformation. There was no significant difference between left and right in terms of severity of undercut (*t*=0.67, *df*=277, *p*=0.503; Table 8).

Table 8 Means and SD of average undercut measures for right compared with left sided teeth

	Mean (mm ²)	N	SD (mm ²)
Right	8.37	136	6.35
Left	7.83	143	6.07

A4 Anteriors compared with posteriors (N=279)

The distribution of undercut values was significantly skewed, but was rectified by logarithmic transformation. There was a significant difference in the severity of the averaged undercut severity between anteriors and posteriors (*t*=10.84, *df* =267, *p*=0.000; Table 9).

Table 9 Means and SD of average undercut measures for anteriors and posteriors

	Mean (mm ²)	N	SD (mm ²)
Anteriors	11.69	132	6.66
Posteriors	4.87	147	3.37

B) Distal, buccal, mesial and lingual surfaces

B1 Cases compared with controls

There was a significant difference between cases and controls buccally and lingually (p<0.001 and p<0.01 respectively; see Tables 10 and 11).

Table 10 Statistical comparison of cases and controls on each of the four surfaces of teeth

Number of surfaces (N)	FIT (2 groups: cases compared with controls)		
	t or z	p values df	p ^a
Distal ^b (41)	-1.450	NA	0.159
Buccal ^c (235)	-3.72	233	0.000
Mesial ^d (42)	NA	NA	NA
Lingual ^b (81)	-3.44	NA	0.001

^a Shaded areas indicate significant analyses.
^b Significant skew but unable to transform (non-parametric procedure, Mann-Whitney test Uz).
^c Significant skew but rectified using logarithmic transformation.
^d Not applicable (no mesial measures).

Table 11 Means and SD of each of the measures (mm²) for cases and controls

Measure	Two group fit	Mean	N(teeth)	SD
Distal	Controls	3.00	4	1.95
	Cases	5.09	37	4.60
Buccal	Controls	7.29	78	6.21
	Cases	9.79	157	6.53
Mesial	Controls	-	0	-
	Cases	5.80	42	4.45
Lingual	Controls	2.60	23	1.64
	Cases	5.88	58	5.75

B2 "Fit" compared with "did not fit" groups analyses

There were significant differences in average undercut between the "fit" and "did not fit" groups for all surfaces except the buccal (Table 12).

Table 12 Number of teeth measured for different surfaces and their p values

Number of surfaces (N)	FIT (2 groups: fit compared with didn't fit)		
	p values		
	t	df ^a	p ^b
Distal ^c (41)	-4.14	9.4	0.002
Buccal ^d (235)	-0.92	67	0.360
Mesial ^d (42)	-3.07	11.1	0.011
Lingual ^c (81)	-3.63	19.5	0.002

^a unequal variance t test used for distal, mesial and lingual comparisons

^b Shaded areas indicate significant analyses (p<0.05).

^c Significant skew rectified using a square root transformation.

^d Significant skew rectified using a logarithmic transformation.

B3 Analyses of the cases only (N=186)

B3.1 Maxilla compared with mandible

Means and standard deviations for each of the different surfaces are presented in Table 13, grouped according to whether the teeth were maxillary or mandibular.

Distal: the distal surfaces data were significantly skewed, but unable to be normalised.

There were no significant differences in distal undercut between the maxillary and mandibular cases (Mann-Whitney U z = -1.07, p =0.297).

Buccal: the buccal data were skewed, but were rectified using logarithmic transformation. There were no significant differences between maxilla and mandible in the severity of the buccal undercuts (t= 1.22, df =155, p=0.223).

Mesial: the mesial data were skewed, but were rectified using logarithmic transformation. There were no significant differences between maxilla and mandible in the severity of the buccal undercuts (t= 0.87, df =22.6, p=0.391).

Lingual: as before; the data were skewed, but were rectified using logarithmic transformation. The average lingual undercuts did differ significantly between the maxillary and mandibular cases ($t= 2.96$, $df =56$, $p=0.005$), with the mandibular cases having the more severe lingual undercuts.

Table 13 Means and SD of different surfaces measured on maxillary and mandibular casts for the cases only (mm²).

Type of cast		Distal	Buccal	Mesial	Lingual
Mandibular	Mean	6.35	10.54	7.13	7.02
	N	20	64	17	41
	SD	5.88	6.54	6.28	6.44
Maxillary	Mean	3.61	9.28	4.90	3.14
	N	17	93	25	17
	SD	1.51	6.51	2.33	1.72

B3.2 Left compared with right

The distribution of each of the surfaces was significantly skewed. The distal measure was unable to be normalised. The remaining measures were successfully normalised with a logarithmic transformation. There were no significant differences between the undercuts of left and right sided teeth on any surface (see Table 14).

Distal: Mann-Whitney U $z = -1.68$, $p=0.097$

Buccal: $t=0.74$, $df =155$, $p=0.462$

Mesial: $t=0.93$, $df = 40$, $p=0.360$

Lingual: $t= -0.67$, $df =56$, $p=0.506$

Table 14 Means and SD of different surfaces measured on right and left sided teeth for the cases only (mm²).

Site		Distal	Buccal	Mesial	Lingual
Right	Mean	4.14	10.23	6.07	5.70
	N	17	78	25	32
	SD	4.36	6.80	3.57	5.76
Left	Mean	5.91	9.36	5.39	6.12
	N	20	79	17	26
	SD	4.75	6.27	5.60	5.85

B3.3 Anteriors compared with posteriors

The distribution of each of the surfaces was significantly skewed. The distal measure was unable to be normalised. The remaining measures were successfully normalised with a logarithmic transformation. There were no significant differences between the undercuts of anterior and posterior teeth on the distal, mesial or lingual surfaces (see Table 15 and below). However, the anterior buccal undercut was significantly greater than the posterior buccal undercut (see below).

Distal: $z = -0.47, p=0.658$

Buccal: $t=8.04, df=155, p=0.000$

Mesial: $t= -0.04, df = 40, p=0.965$

Lingual: $t=0.39, df =56, p=0.700$

Table 15 Means and SD of different surfaces measured on anterior and posterior teeth for the cases only (mm²).

Site		Distal	Buccal	Mesial	Lingual
Anteriors	Mean	5.56	13.39	5.51	8.15
	N	11	80	8	2
	SD	4.83	6.90	3.48	8.82
Posteriors	Mean	4.90	6.055	5.86	5.80
	N	26	77	34	56
	SD	4.59	3.23	4.69	5.72

B4 Analyses of controls (N=93)

B4.1 Maxilla compared with mandible

Comparisons were unable to be made between maxilla and mandible for the distal measure since there were no distal measures available either from mandibular control casts, or for the mesial measure since there were no mesial surfaces available from the control casts.

Buccal: these skewed data were rectified using a logarithmic transformation. There was no significant difference in buccal undercut between maxilla and mandible in controls ($t = -1.61$, $df = 76$, $p = 0.111$).

Lingual: these skewed data were rectified using a square root transformation. There was no significant difference in lingual undercut between maxilla and mandible in controls ($t = -0.92$, $df = 21$, $p = 0.366$).

Table 16 Means and SD of different surfaces measured on maxillary and mandibular control casts (mm²).

Type of cast		Distal	Buccal	Mesial	Lingual
Mandibular	Mean	Not applicable	5.67	Not applicable	2.48
	N		30		18
	SD		4.54		1.77
Maxillary	Mean	3.00	8.30	Not applicable	3.04
	N	4	48		5
	SD	1.95	6.90		1.08

B4.2 Left compared with right

There were no mesial surfaces available. Of the remaining surfaces, the distal measures were normally distributed, but the buccal and lingual were significantly skewed. The skew in the buccal measure was able to be rectified using a logarithmic transformation and the lingual measure with a square root transformation. There were no significant differences on any surface between left and right sided teeth from control casts (see Table 17 and below).

Distal: $t = -0.87$, $df = 1.14$, $p = 0.528$

Buccal: $t = 0.11$, $df = 76$, $p = 0.912$

Mesial: it was not applicable because no mesial measures were available.

Lingual: $t = -0.40$, $df = 21$, $p = 0.969$

Table 17 Means and SD of different surfaces measured on right and left sided control teeth (mm²).

Site		Distal	Buccal	Mesial	Lingual
Right	Mean	2.11	7.34	Not applicable	2.38
	N	2	38		10
	SD	0.74	6.27		1.16
Left	Mean	3.89	7.24	Not applicable	2.78
	N	2	40		13
	SD	2.78	6.23		1.97

B4.3 Anteriors compared with posteriors

There were no posterior teeth with a distal or lingual surface, so comparisons were unable to be made. There were no mesial measures in the control casts. The buccal data were significantly skewed, but this was rectified using a logarithmic transformation. There was a significant difference between posteriors and anteriors for the buccal measures ($t = 8.55$, $df = 72.5$, $p = 0.000$; see Table 18).

Table 18 Means and SD of different surfaces measured on anterior and posterior teeth for the controls only (mm²).

Site		Distal	Buccal	Mesial	Lingual
Anteriors	Mean	Not Applicable	10.51	Not applicable	Not applicable
	N		44		
	SD		6.58		
Posteriors	Mean	3.00	3.13	Not applicable	2.60
	N	4	34		23
	SD	2.04	1.32		1.64

4.1.2 Reliability of method 1 (Microscribe-3DX)

A) Inter-observer (2 raters)

Prior to examining the reliability of the microscribe method, a pilot inter-observer study was completed. The lingual surface of one tooth (number 38 from the study group, cast 1) was measured using an average of three readings on seven different occasions by each of two raters (3 times for area 1(lingual), and once for each of the remaining 4 areas).

The inter-observer reliability was analysed with intraclass correlation coefficients (ICC) using a two-way mixed effect model (the single measure ICC is reported). An ICC > 0.80 indicates excellent agreement between raters. The microscribe method demonstrated high inter-observer consistency (ICC = 0.986 (95% CI: 0.921 – 0.998); F (6, 6) = 141.50, p = 0.000), albeit in a small pilot sample of measurements. It was concluded to be of significant reliability to warrant an investigation of the intra-observer reliability. Table 19 shows minimum and maximum values obtained by two raters, Ammar Razek (AR) and Graham Thomas (GT). Table 20 shows means obtained from five areas measured by the two raters (in mm²).

Table 19 Minimum and maximum undercut measurements of pilot study (mm²).

	N	Minimum	Maximum	Mean	SD
Rater 1 (AR)	7	24.03	37.96	30.24	6.38
Rater 2 (GT)	7	24.68	37.95	30.06	5.99

Table 20 Mean undercut measurements by the raters for the five areas measured in pilot study

Which area?	Which rater?	Mean (mm ²)
1	Rater 1	24.38
	Rater 2	24.77
2	Rater 1	28.13
	Rater 2	27.99
3	Rater 1	34.73
	Rater 2	32.40
4	Rater 1	37.96
	Rater 2	37.95
5	Rater 1	37.74
	Rater 2	37.74

B) Intra-observer (1 rater, 3 readings)

The second part of the pilot study investigated intra-observer reliability of rater AR on three different occasions. Intraclass correlation coefficient (ICC) using a two-way mixed effects model showed excellent intra-observer reliability:

for distal ICC = 0.996 (95% CI: 0.994 to 0.998; F(40, 80) = 263.92, p = 0.000),
for buccal ICC = 0.998 (95% CI: 0.997 to 0.998; F(234, 468) = 449.31, p = 0.000),
for mesial ICC = 0.997 (95% CI: 0.994 to 0.998; F(41, 82) = 289.89, p = 0.000),
for lingual ICC = 0.995 (95% CI: 0.993 to 0.997; F(80, 160) = 197.41, p = 0.000).

Table 21 Descriptive statistics for all the surfaces measured (mm²)

	N (teeth)	Minimum	Maximum	Mean	SD
Distal range	41	0.14	2.90	0.75	0.53
Buccal range	235	0.05	6.27	0.76	0.67
Mesial range	42	0.15	2.67	0.68	0.52
Lingual range	81	0.03	8.76	0.75	1.00

4.1.3 Defining a severe undercut (Microscribe-3DX)

The definition of a severe undercut was explored by ascertaining the proportion of surfaces greater than one and then greater than two standard deviations above the average surface undercut.

Distal (N = 41 teeth, Table 22, Figure 48)

Table 22 Proportion of distal surfaces greater than one or two standard deviations above the mean

Distal	Did fit	Did not fit	Don't know	No missing teeth	Orthodontically treated cases
N	7	9	21	4	0
1 SD or more	0	44.4%	0	0	-
2 SD or more	0	44.4%	0	0	-

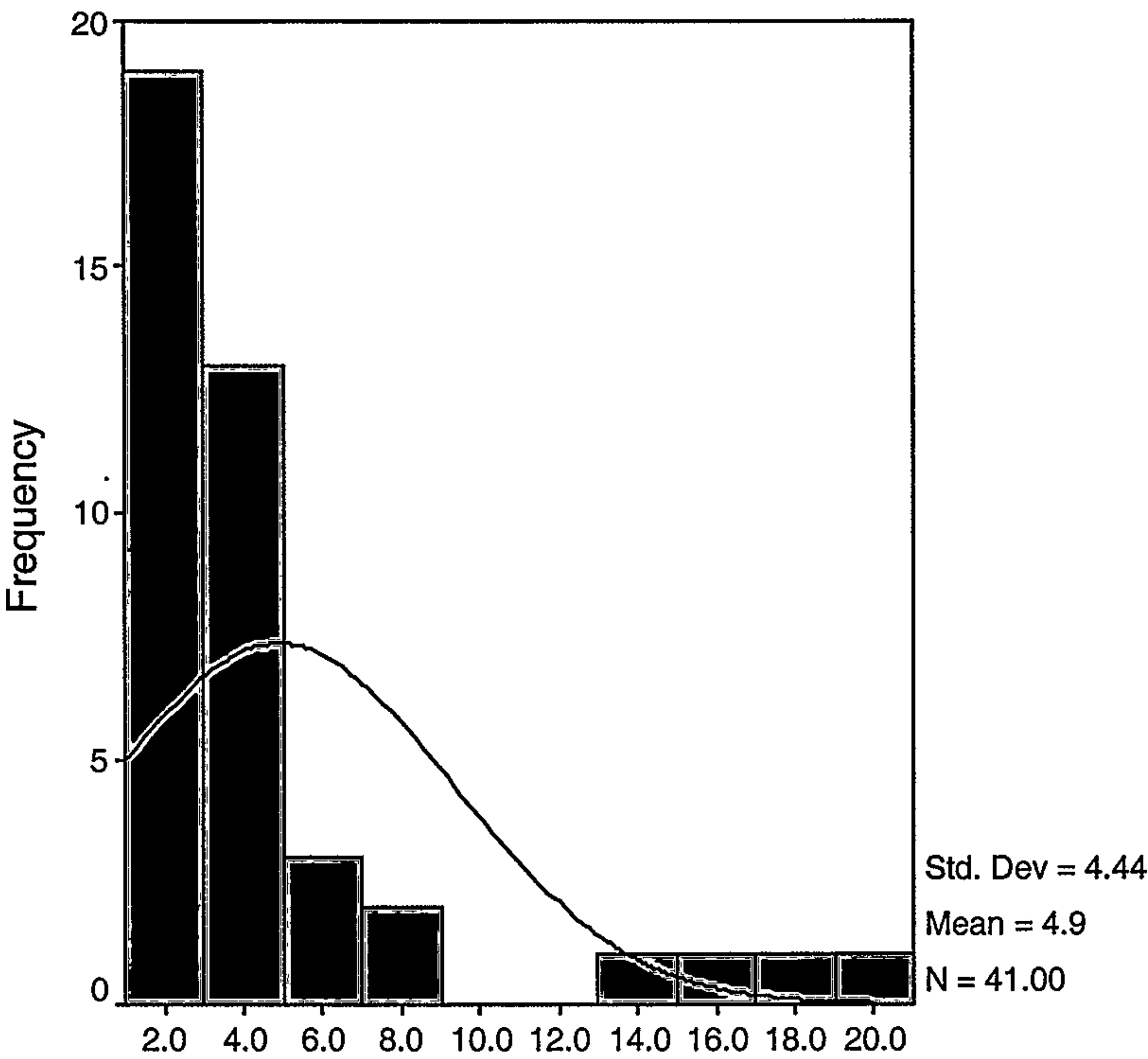


Figure 48 Frequency distribution of microscribe distal measurements (mm²)

Thus, in total 9.8% of the 41 distal measures were one standard deviation above the mean. This proportion did not change when a definition of two standard deviations

above the mean was applied (i.e. one or two standard deviations cut off the same sub-sample).

Buccal (N = 235 teeth; Table 23, Figure 49)

Table 23 Proportion of buccal surfaces greater than one or two standard deviations above the mean.

Buccal	Did fit	Did not fit	Don't know	No missing teeth	Orthodontically treated cases
N	35	34	88	59	19
1 SD or more	14.3%	29.4%	23.9%	15.3%	15.8%
2 SD or more	8.6%	0	6.8%	3.4%	5.3%

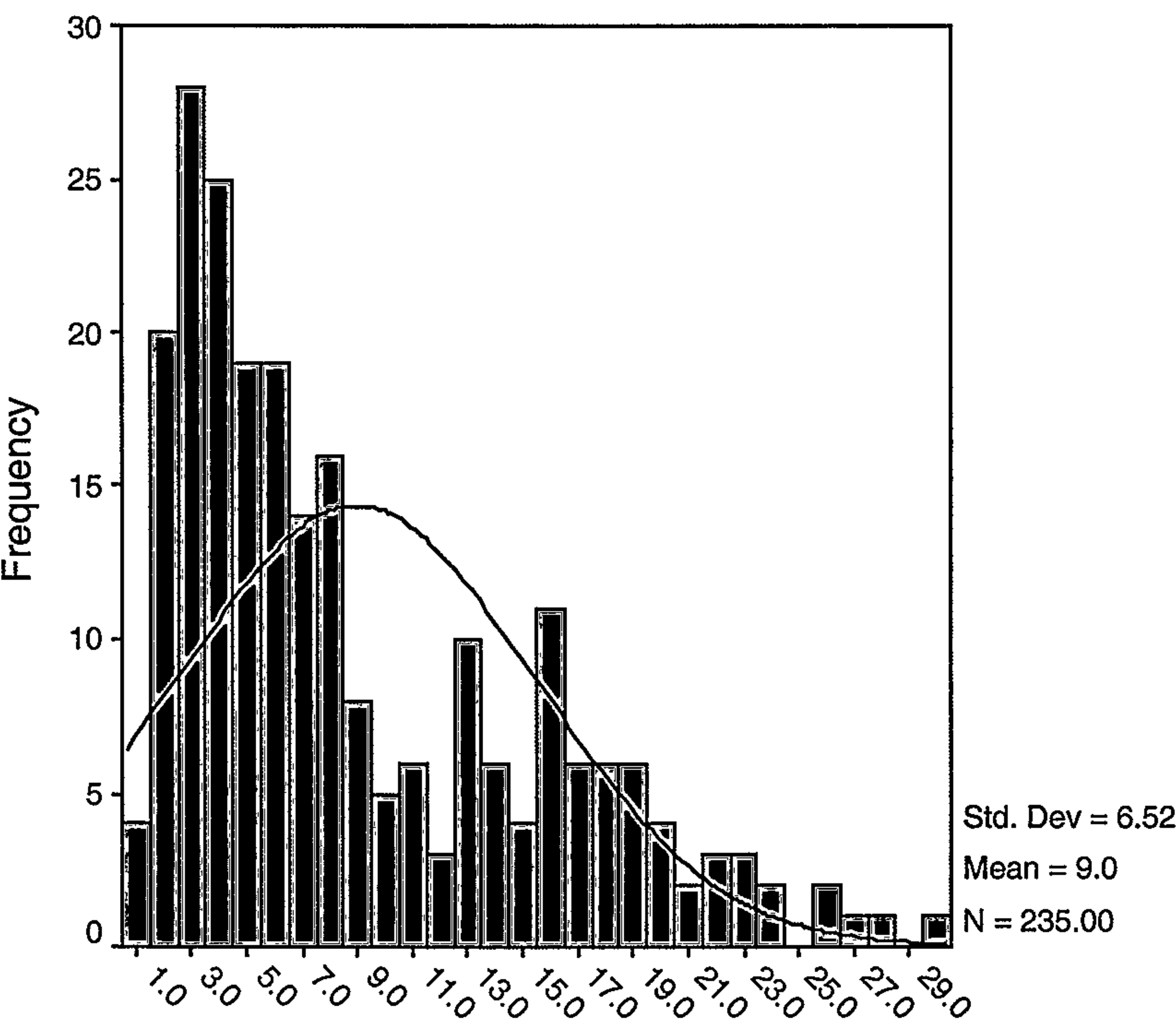


Figure 49 Frequency distribution of microscribe buccal measurements (mm²)

In total, 20.4% of the 235 buccal measures were one standard deviation or greater above the mean, compared with 5.1% two standard deviations or more above the mean.

Mesial (N = 42 teeth; Figure 50, Table 24)

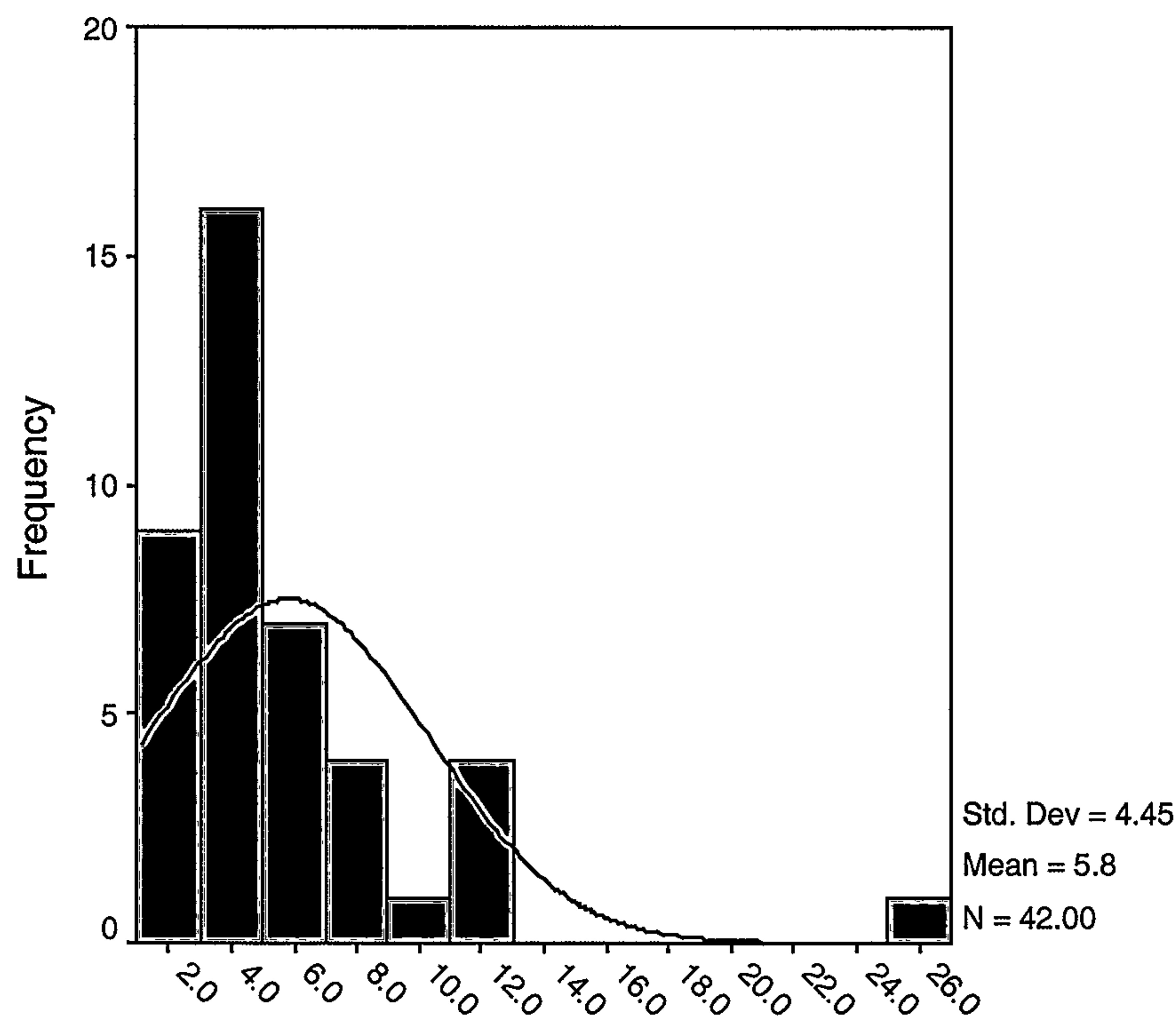


Figure 50 Frequency distribution of microscribe mesial measurements (mm²)

Table 24 Proportion of mesial surfaces greater than one or two standard deviations above the mean.

Mesial	Did fit	Did not fit	Don't know	No missing teeth	Orthodontically treated cases
N	10	9	23	0	0
1 SD or more	0%	44.4%	8.7%	-	-
2 SD or more	0	11.1%	0	-	-

In total, 14.3% of the 42 mesial measures were one standard deviation or greater above the mean, compared with 2.4% two standard deviations or more above the mean.

Lingual (N = 81 teeth, Figure 51, Table 25)

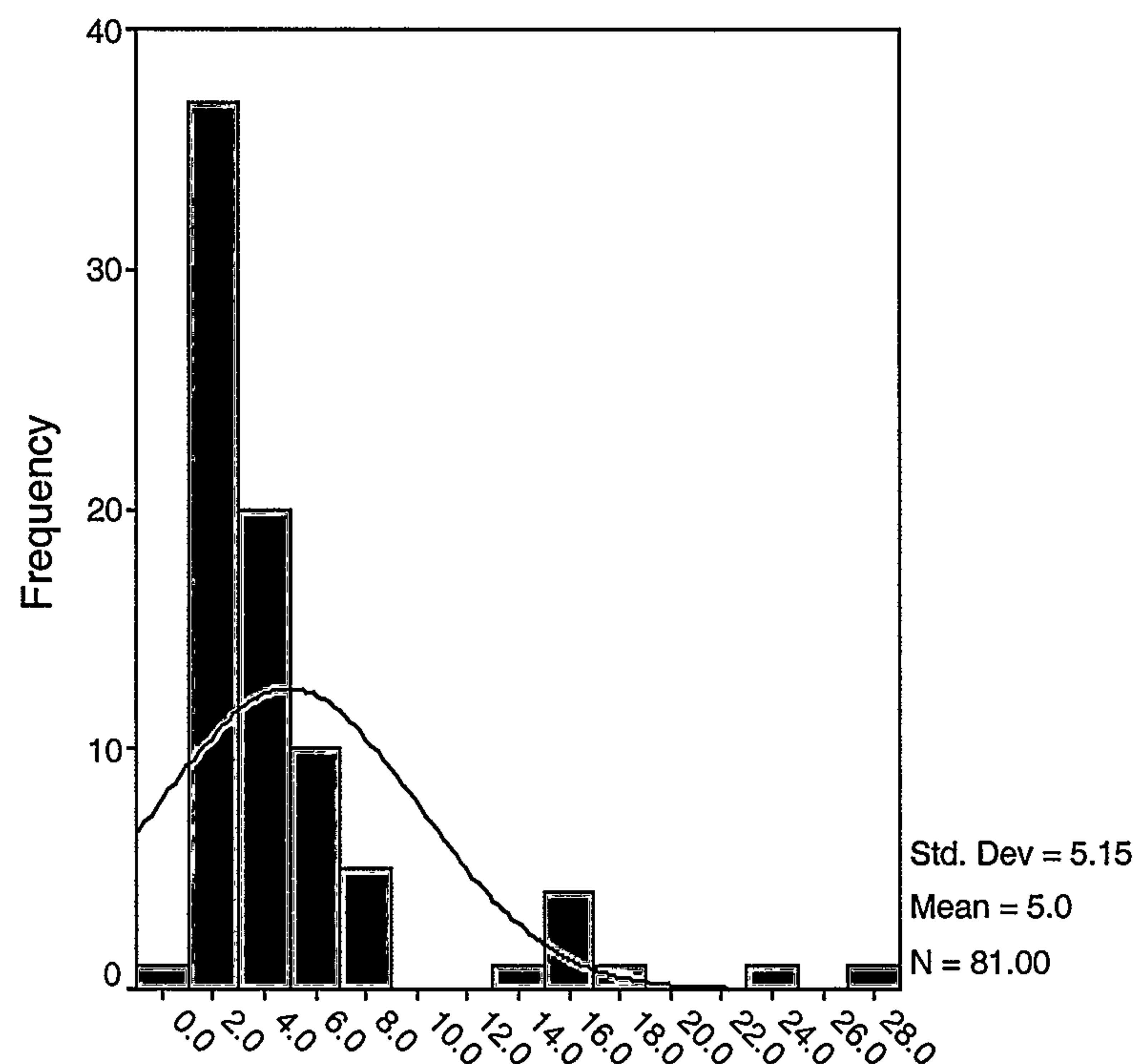


Figure 51 Frequency distribution of microscribe lingual measurements (mm²)

Table 25 Proportion of lingual surfaces greater than one or two standard deviations above the mean.

Lingual	Did fit	Did not fit	Don't know	No missing teeth	Orthodontically treated cases
N	7	15	36	19	4
1 SD or more	0%	53.3%	0%	0%	0%
2 SD or more	0%	46.7%	0%	0%	0%

In total, 9.9% of the 81 lingual measures were one standard deviation or greater above the mean, compared with 8.6% two standard deviations or more above the mean. It is suggested that an undercut of one standard deviation or more above the mean should serve as the definition of a severe undercut because too few cases met the criteria for a severe undercut when the harsher cut-off of two standard deviations was imposed.

4.1.4 The association between severe undercut (one standard deviation) and case or control

Chi square analyses explored whether there was a significant association between two variables, whether cases or controls were associated with the severity of undercut. In other words, was the proportion of teeth with a severe undercut significantly different between cases and controls? In summary, the only surface with sufficient data to facilitate a valid statistical analysis was the buccal surface, and there was no statistically significant relationship between case or control and severity of undercut ($\chi^2= 1.39$, $df=1$, $p=0.238$). In spite of the fact that Chi square analyses were not valid for the other surfaces (distal, mesial and lingual) since the minimum expected value was less than five, a pattern emerged for all the different surfaces, including severe buccal undercuts which were more common in the cases than in the controls.

Distal: Findings are summarised in Table 26 and Figure 52.

Table 26 Proportion of teeth with small compared with severe undercut distally

Distal	Cases	Controls
Small	33 (89.2%)	4 (100%)
Severe Undercut	4 (10.8%)	0

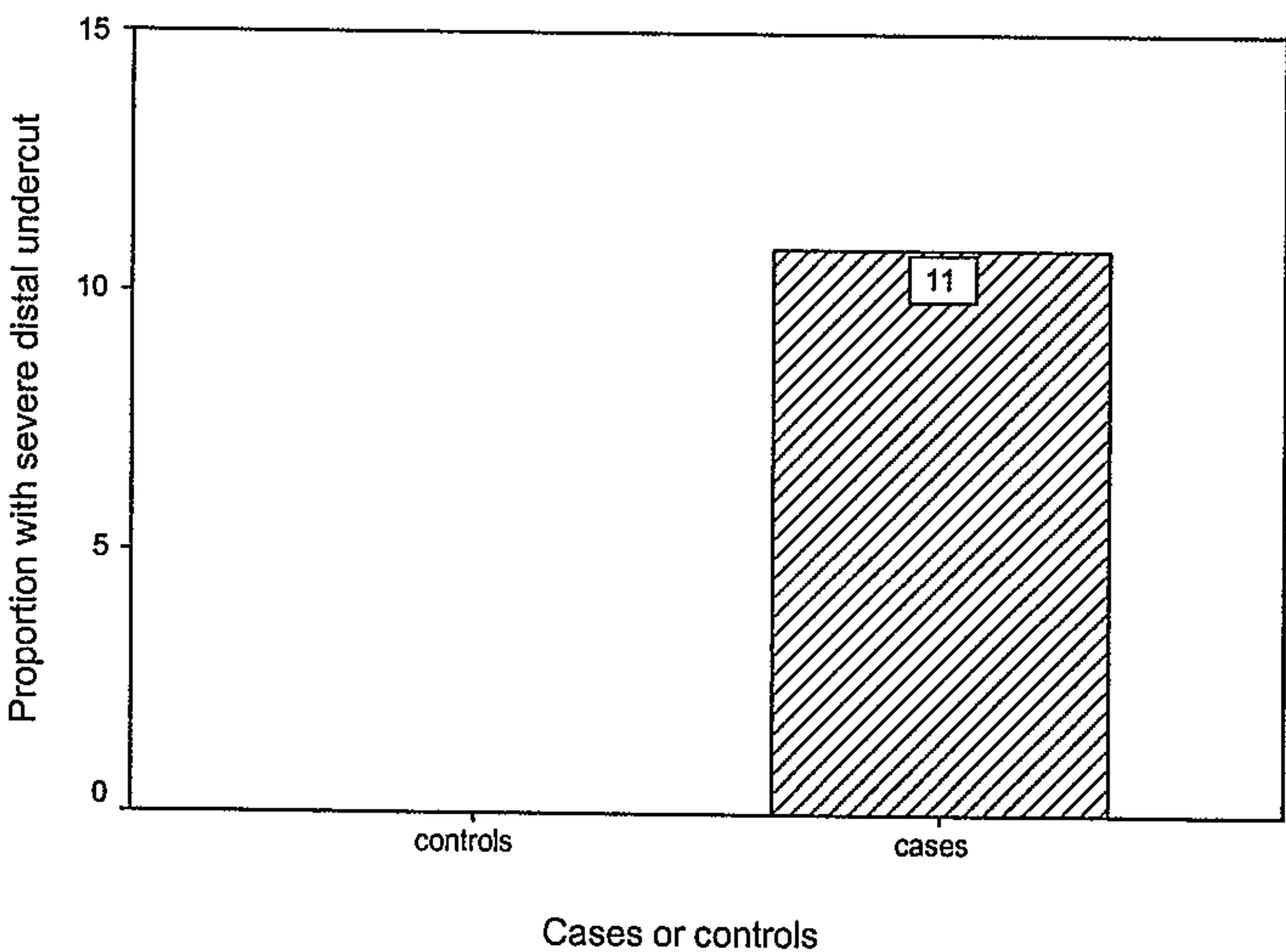


Figure 52 Histogram of proportions of teeth with severe distal undercuts

Buccal: Findings are summarised in Table 27 and Figure 53.

Table 27 Proportion of teeth with normal compared with severe undercut buccally

Buccal	Cases	Controls
Normal	121 (77.1%)	66 (84.6%)
Severe Undercut	36 (22.9%)	12 (15.4%)

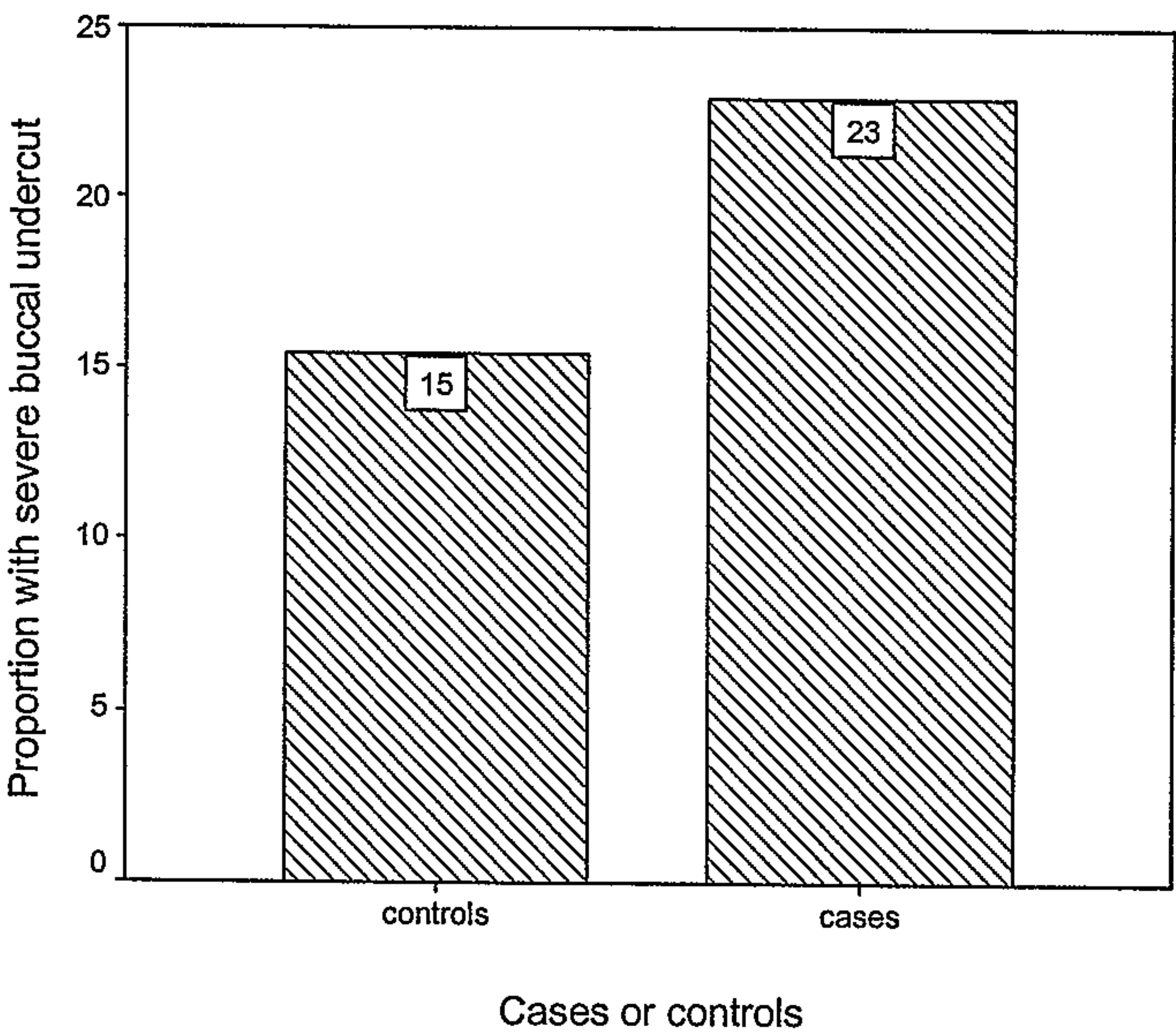


Figure 53 Histogram of proportions of teeth with severe buccal undercuts

Mesially: Chi square analysis was not valid since no control tooth had a mesial surface measured and therefore a bar chart could not be produced. Table 28 summarised mesial findings.

Table 28 Proportion of teeth with normal compared with severe undercut mesially.

Mesial	Case	Control
Normal	36 (85.7%)	-
Severe undercut	6 (14.3%)	-

Lingual: Findings are summarised in Table 29 and Figure 54.

Table 29 Proportion of teeth with normal compared with severe undercuts lingually.

Lingual	Case	Control
Normal	50 (86.2%)	23 (100%)
Severe Undercut	8 (13.8%)	0

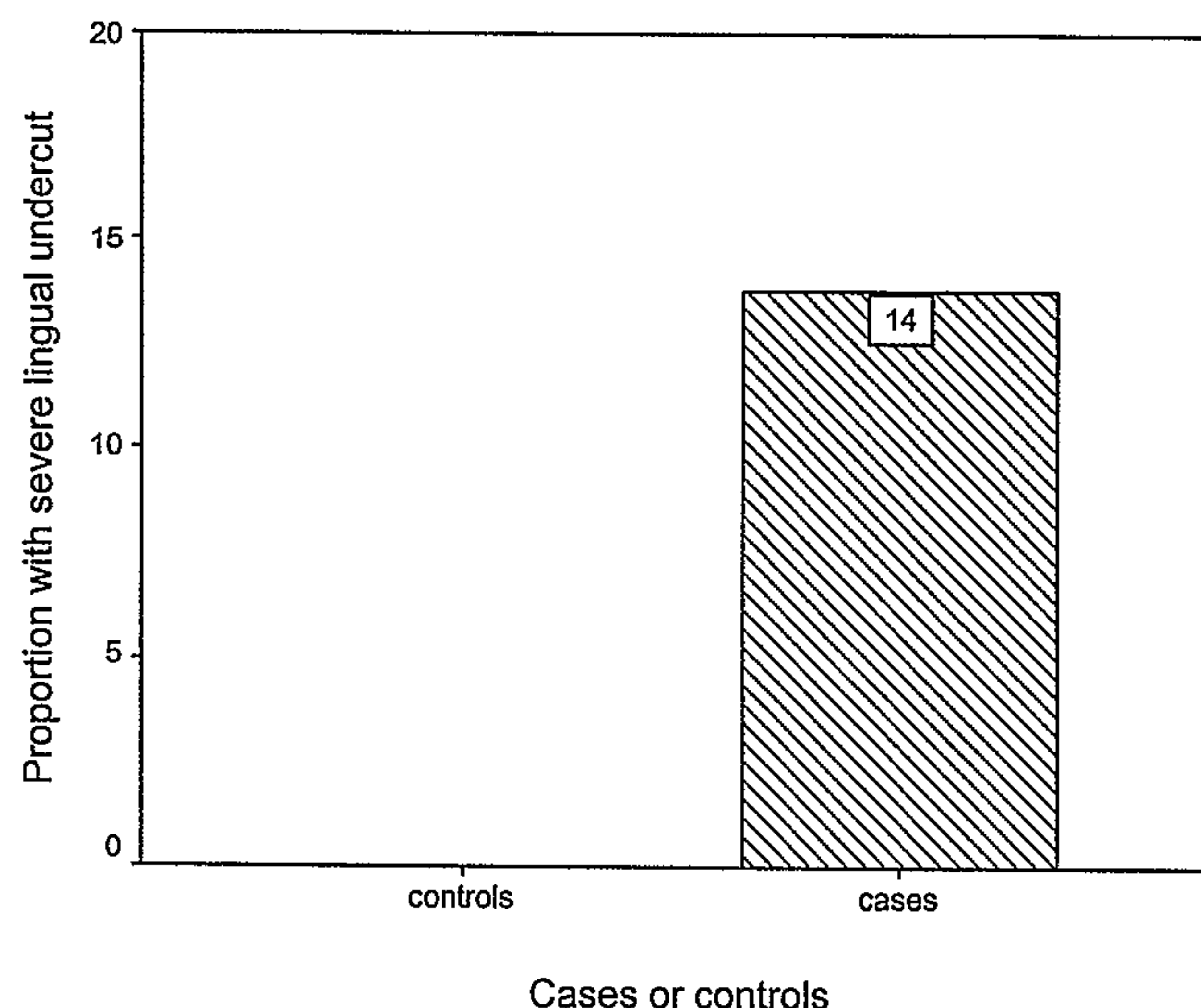


Figure 54 Histogram of proportions of teeth with severe lingual undercuts

4.1.5 The association between severe undercut (one standard deviation) and casting fit ("fit" compared with "did not fit")

Chi square analyses were used to explore whether there was a significant association between two variables-in this section whether the fit (or lack of fit) of a prosthesis (or a casting framework) was associated with the severity of undercut, or was the proportion of teeth with severe undercuts significantly different between the two “cast fit” groups? As before, the only surface with sufficient data to facilitate a valid statistical analysis was the buccal surface, and there was no statistically significant relationship between case or control and undercut severity of ($\chi^2= 1.52$, $df =1$, $p=0.218$). In spite of the fact that Chi square analyses were not valid for the other surfaces (distal, mesial and lingual) since the minimum expected value was less than five, a similar pattern was observed for the different surfaces, including severe buccal undercuts being more common on casts having a prosthesis of poor fit, than on casts having a prosthesis of good fit.

Distal: Findings are summarised in Table 30 and Figure 55.

Table 30 Proportion of teeth with small compared with severe undercuts (distal)

Distal	Casting did fit	Casting did not fit
Small	7 (100%)	5 (55.6%)
Severe undercut	0	4 (44.4%)

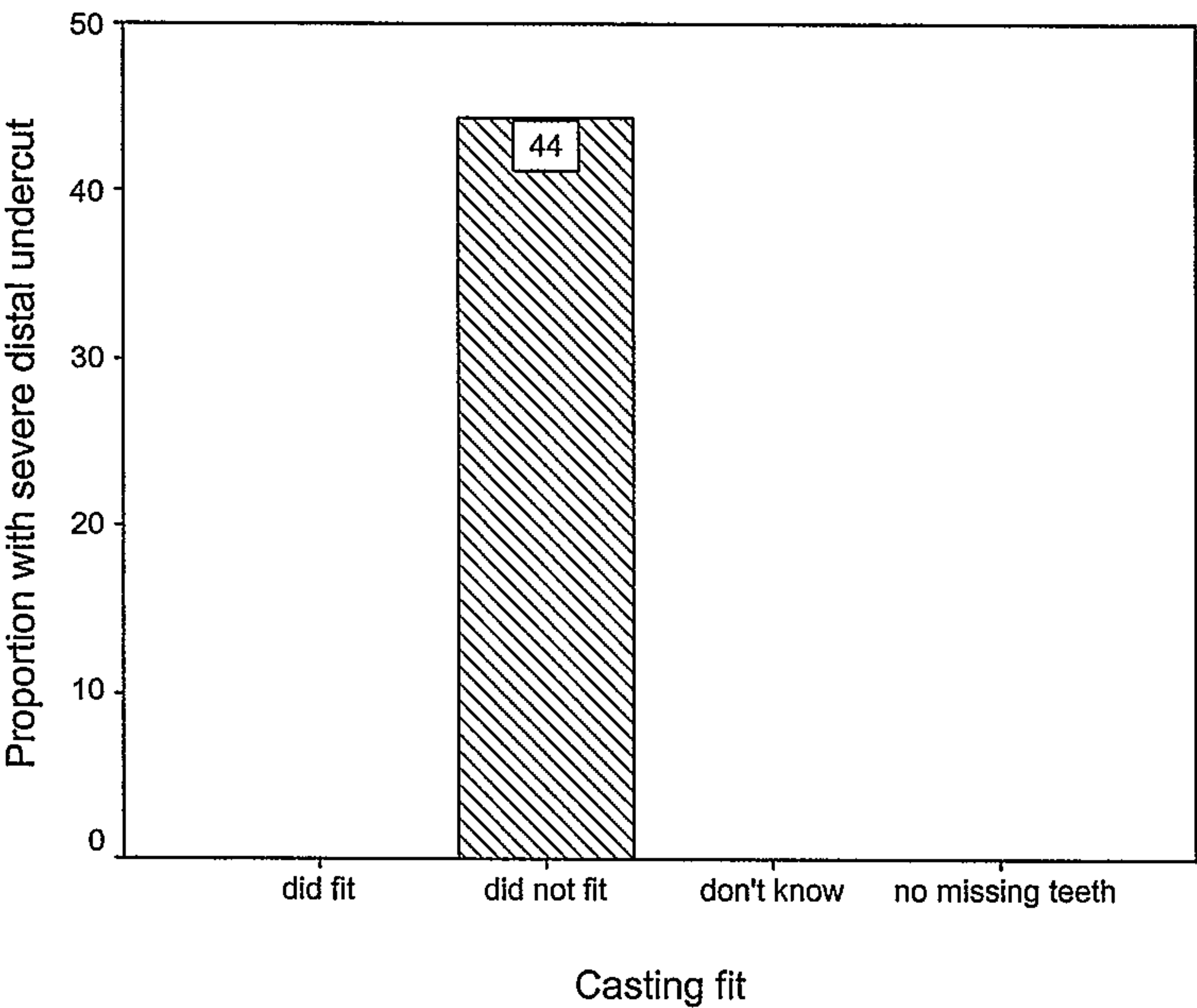


Figure 55 Histogram of proportions of teeth with severe distal undercuts

Buccal: Summarised results are in Table 31 and Figure 56.

Table 31 Proportion of teeth with small compared with severe undercuts (buccal)

Buccal	Casting did fit	Casting did not fit
Small	30 (85.7%)	24 (70.6%)
Severe undercut	5 (14.3%)	10 (29.4%)

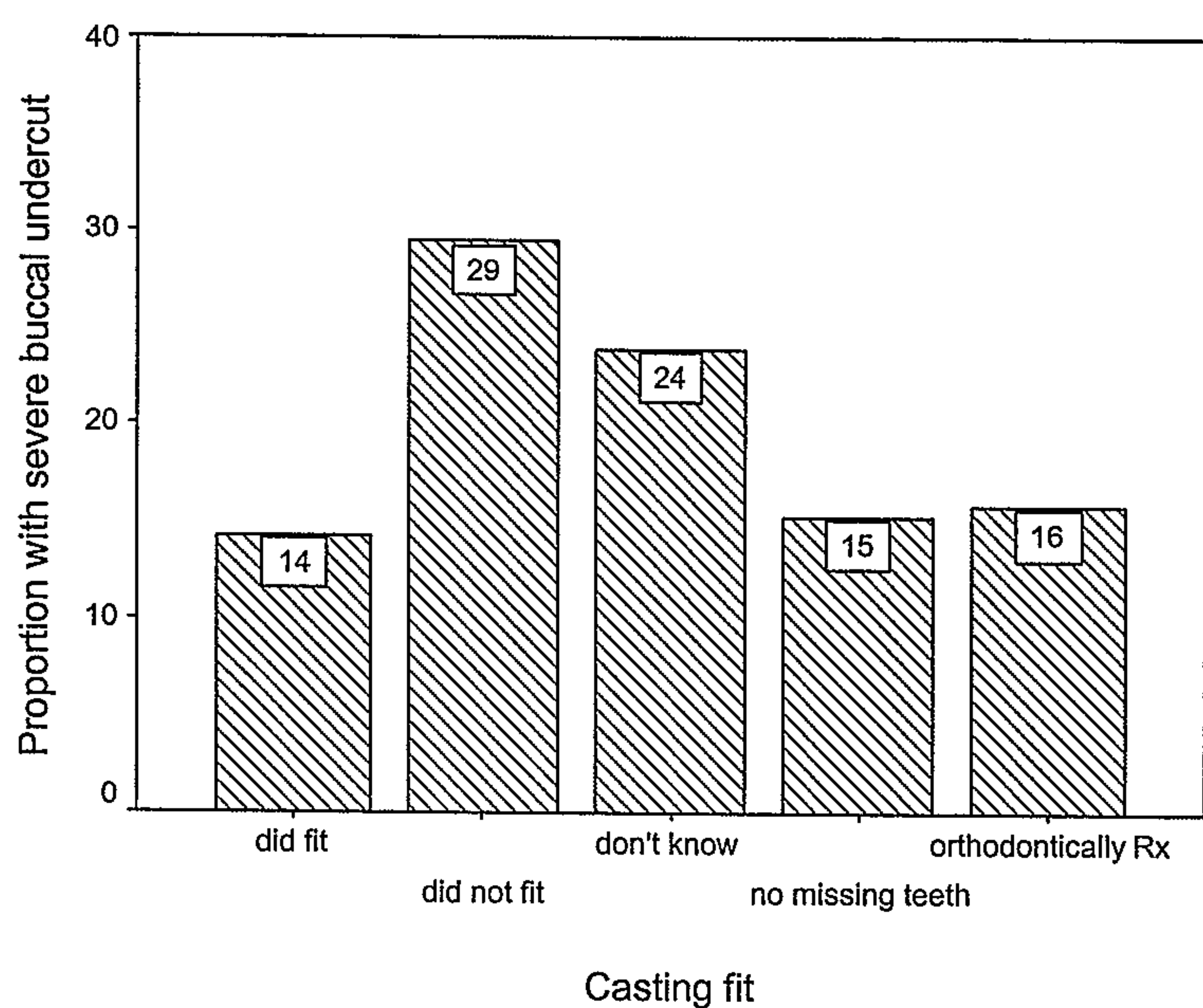


Figure 56 Histogram of proportions of teeth with severe buccal undercuts

Mesial: Summarised results are in Table 32 and Figure 57.

Table 32 Proportion of teeth with small compared with severe undercuts (mesial)

Mesial	Casting did fit	Casting did not fit
Normal	10 (100%)	5 (55.6%)
Severe undercut	0	4 (44.4%)

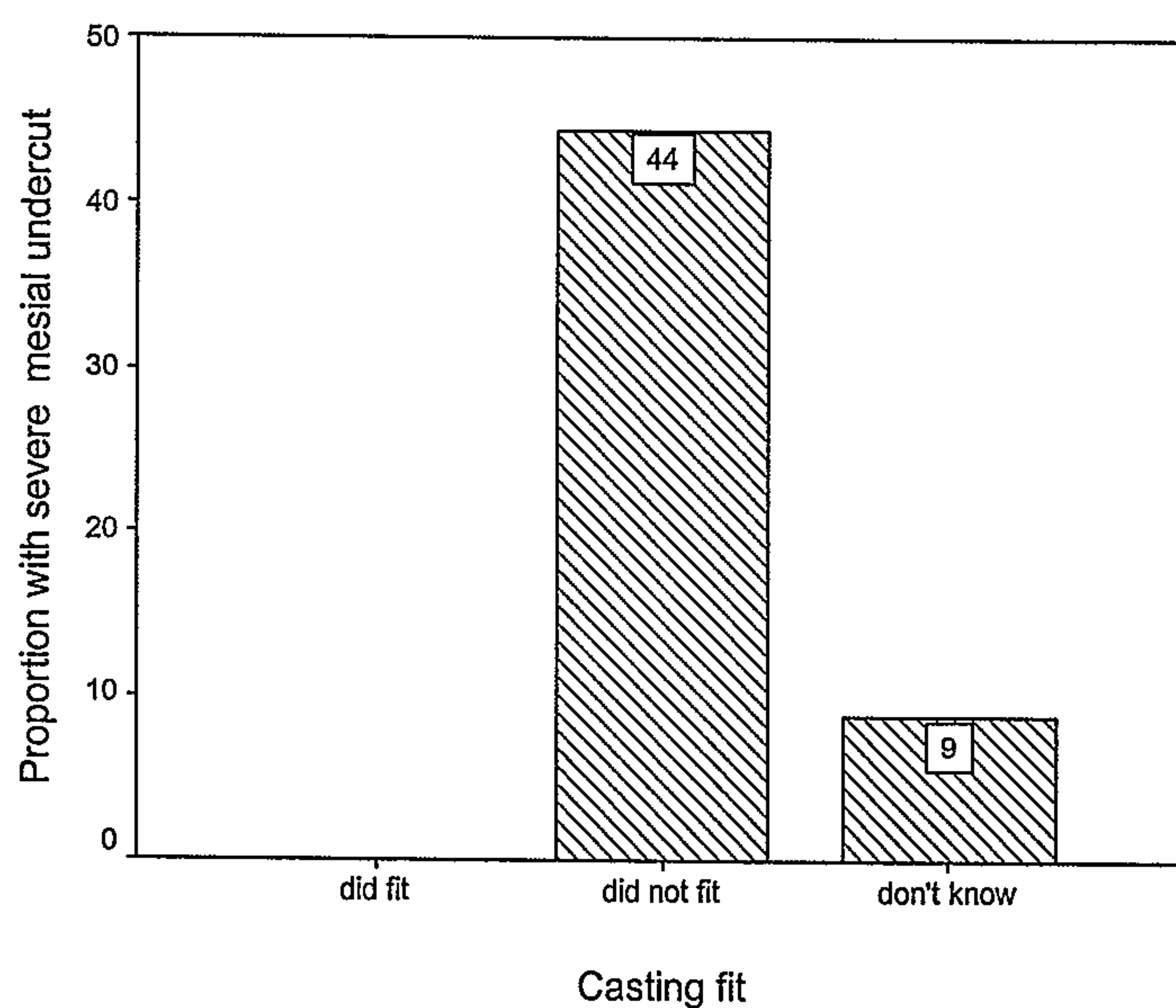


Figure 57 Histogram of proportions of teeth with severe mesial undercuts

Lingual: Summarised results are in Table 33 and Figure 58.

Table 33 Proportion of teeth with small compared with severe undercuts (lingual)

Lingual	Casting did fit	Casting did not fit
Normal	7 (100%)	7 (46.7%)
Severe Undercut	0	8 (53.3%)

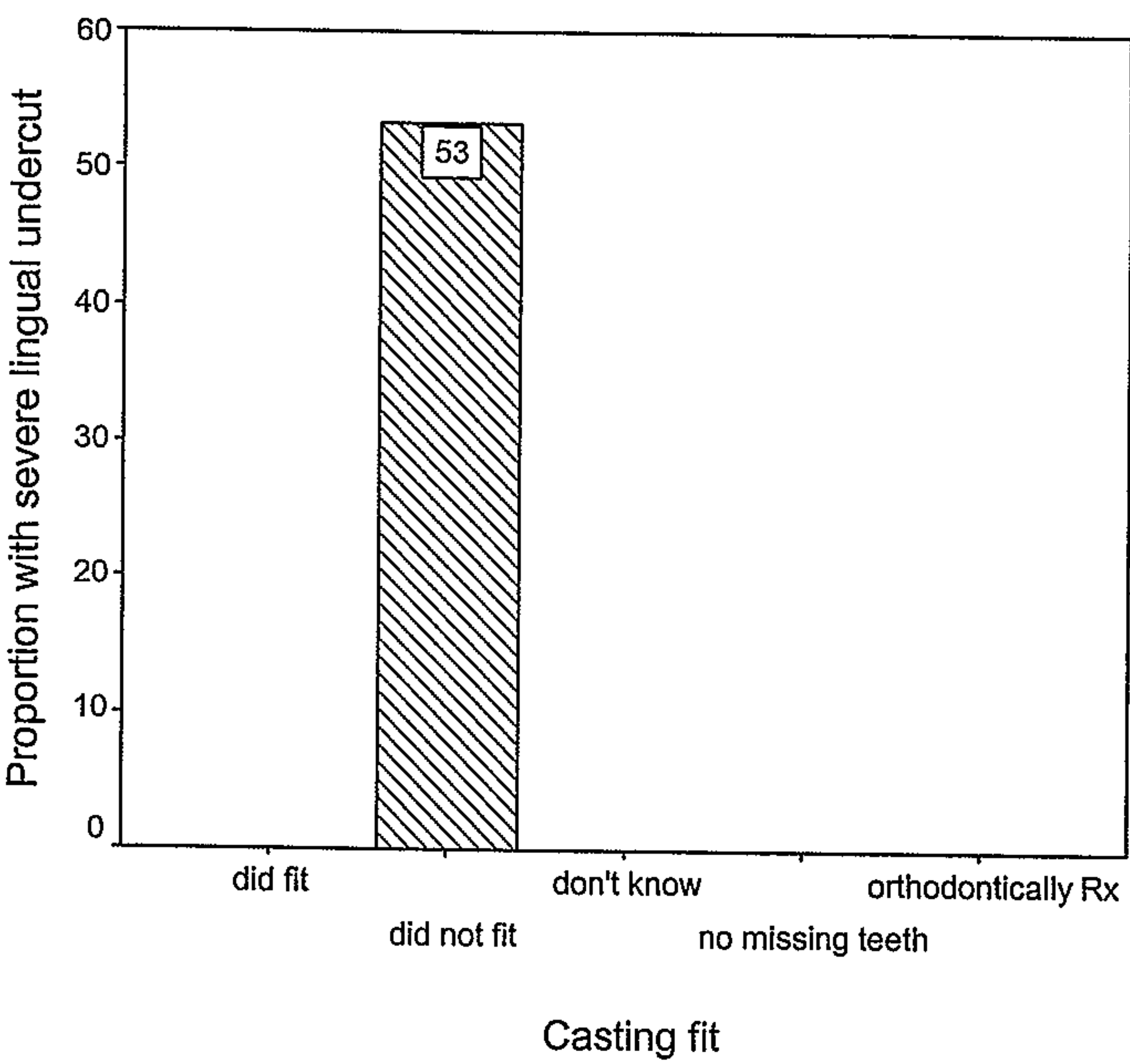


Figure 58 Histogram of proportions of teeth with severe lingual undercuts

4.1.6 Reliability of method two, the Relative Undercut Measurements technique (RUM)

A pilot study was completed to test reliability in which two teeth from one cast, which was part of the study group, were used (tooth 38 and tooth 35 which had severe lingual and mesial undercuts). The two-way mixed effects ICC model was used to assess the reliability of this method and as discussed earlier an ICC of 0.75 or 0.80 would be considered as excellent agreement between raters.

Distal (N = 2): was not significant, probably due to low target number (ICC = -0.20 (95% CI: -0.49-0.99); F (1, 2) =0.50, p=0.554).

Buccal (N=7) was significant but border-line (ICC=0.77 (95% CI 0.40-0.95); F (6, 12) =11.28, p=0.000). Mesial (N=3) showed excellent agreement, and it was significant (ICC=0.99 (95% CI 0.93-1.00); F (2, 4) =411.09, p=0.000). Lingual (N=7) showed excellent agreement, and it was significant (ICC=0.99 (95% CI 0.97-1.00); F (6, 12) =410.63, p=0.000). In summary, intercorrelation coefficients showed acceptable reliability except distal (but only two teeth were measured). This technique was less reliable than the microscribe technique, as indicated by the smaller coefficients.

4.2 Statistical analysis of tear energy (Method one and Method two)

4.2.1 Tear energy (Method one: crescent-shaped mould)

The cross sectional area of the specimen at the torn surface defined the tear energy, and the latter was derived from calculating the area under the load-displacement curve (Greensmith 1960 and Figure 59). Five specimens of each brand were tested and the means of tear energies were calculated. Figure 55 shows the typical tear pattern of the highest tear energy obtained by method one (Liffin Green, 727 J/m²).

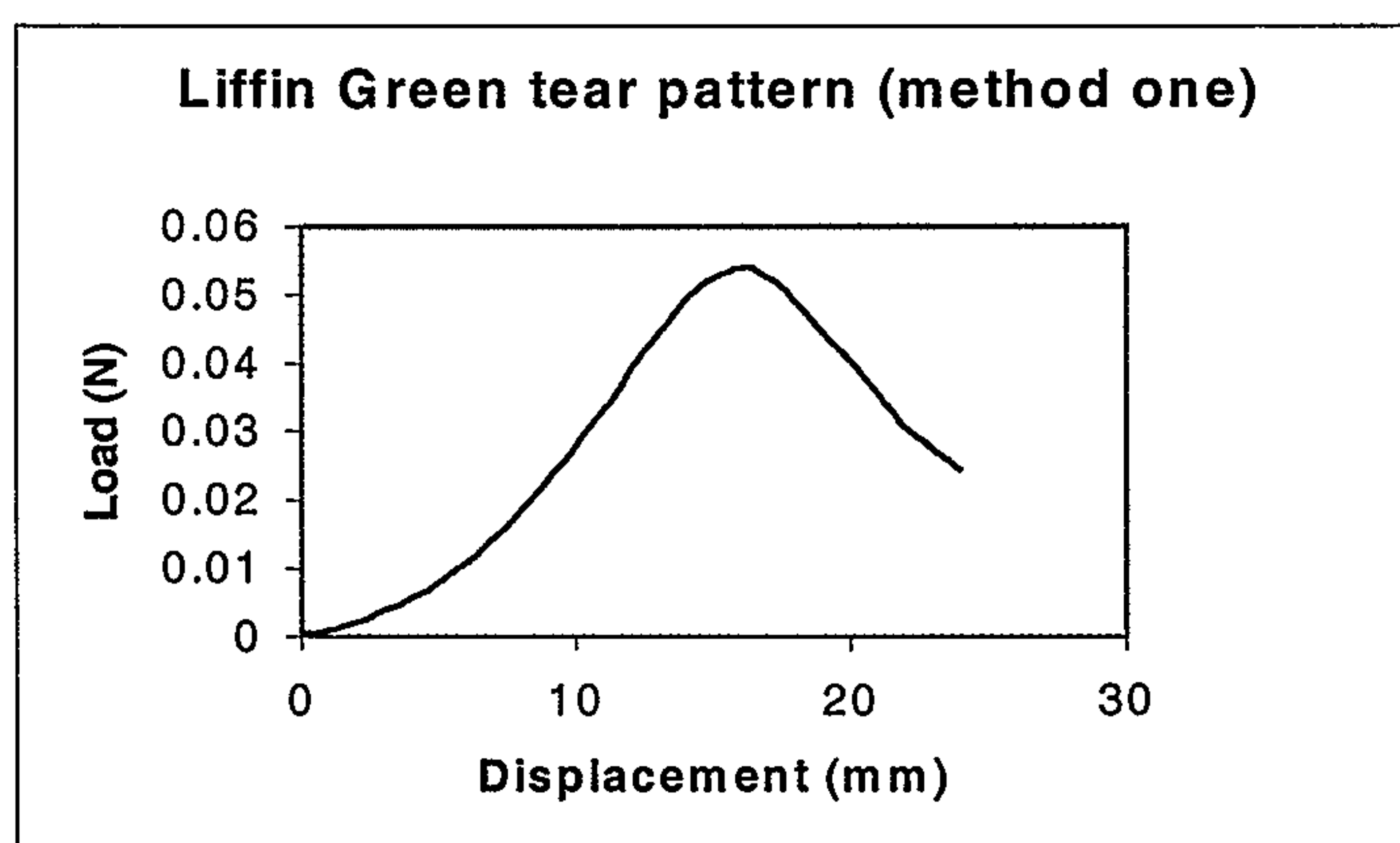


Figure 59

Means and standard deviations of tear energies of the studied alginate brands (J/m²) are shown in Table 34.

Table 34		
Material (10 mm thickness)	Method one Tear Energy (J/m ²)	
	Mean	SD
<i>Alginates:</i>		
Kromopan 100*	441	65.20
Palgat Plus	712.30	47.20
Liffin Green	727.06	63.10
Aroma Fine	414	12.13
Hydrogum	655.15	55.05

4.2.2 Tear energy (Method two: trouser-shaped mould)

In this test, ten samples of each alginate and elastomeric impression material were tested because of the scattered results obtained by this method, particularly by the elastomers. Tear energy was calculated using the formula obtained from Webber and Ryge (1968): $T = F (\lambda + 1) / t$, where T is the tear energy, F is the force to propagate the tear, t is the sample thickness and λ is the extension ratio of the material during tear. The means and standard deviations of the average loads and the tear energies (J/m²) are shown in Table 35.

Table 35				
Material (1 mm thickness)	Average Load (N)		Method two Tear Energy (J/m ²)	
	Mean	SD	Mean	SD
<i>Alginates:</i>				
Kromopan 100	0.28	0.07	856.07	224.17
Palgat Plus	0.34	0.05	1032	163
Liffin Green	0.26	0.07	778	216
Aroma Fine	0.25	0.05	770.02	169
Hydrogum	0.33	0.09	991.32	284.07
<i>Elastomers:</i>				
Imprint – High	0.68	0.21	1981	608
Imprint – Regular	0.42	0.12	1245.16	366
Imprint – Low	0.43	0.11	1289	342.33
Impregum-F	0.95	0.35	2933	1085.18
President regular	0.42	0.20	1235	610

All means based on 10 samples.

The highest value of tear energy was obtained from Palgat Plus (1032 J/m²).
 Tear pattern curve of Palgat Plus is shown in Figure 60 (trouser technique).

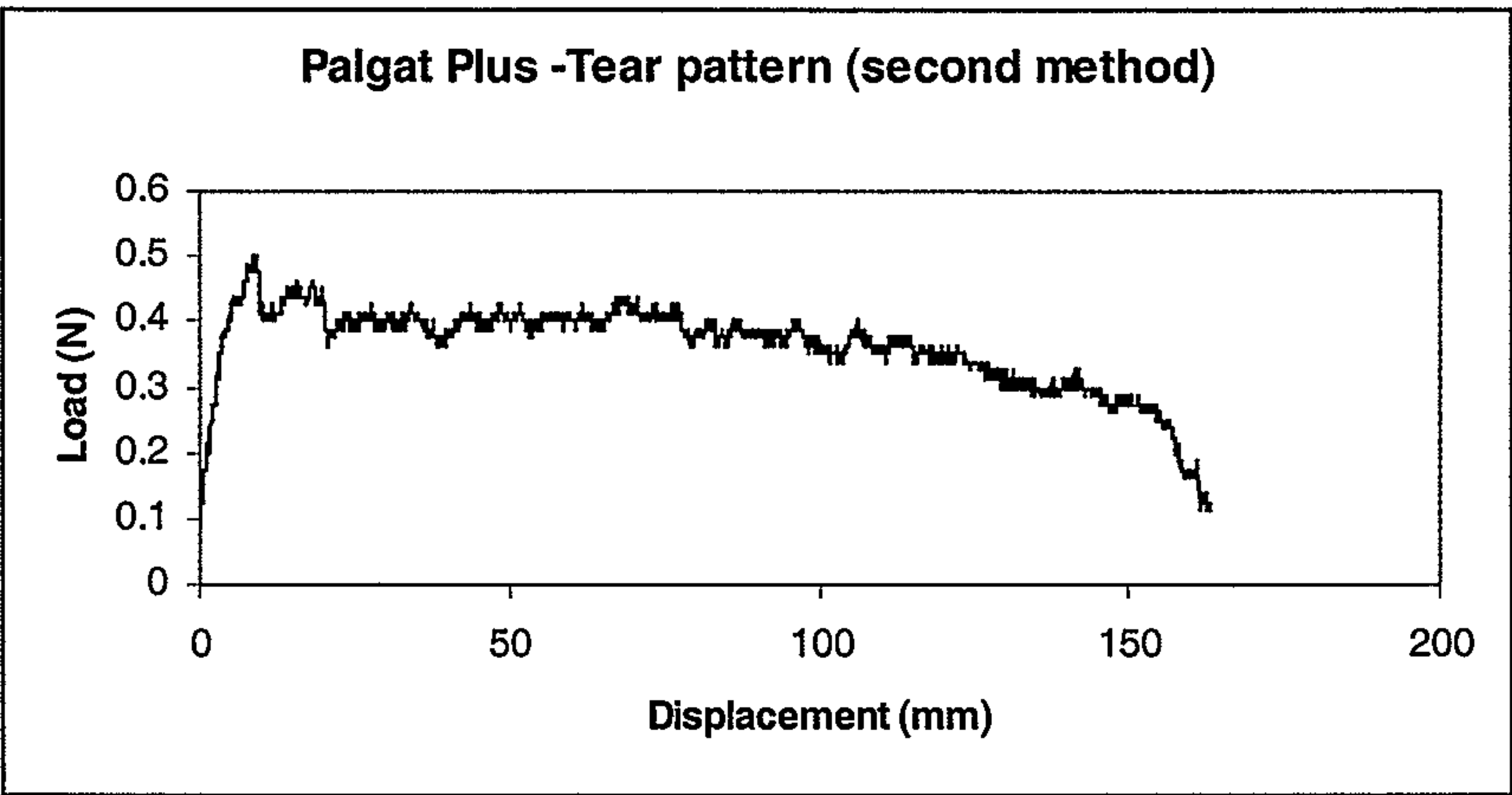


Figure 60

The distribution of tear energy across the ten impression materials was significantly skewed which was rectified by using a logarithmic transformation. In general, elastomeric impression materials have significantly greater tear energy than alginate impression materials ($t = -7.18$, $df = 76.9$, $p = 0.000$ or $p < 0.001$, unequal variance t test) (Table 36).

Table 36 Means and standard deviations comparisons between alginates and elastomers

Material	Mean (J/m ²)	N	SD (J/m ²)
Alginates	885.39	50	2337.11
Elastomers	1736.41	50	9188.29

The distribution of tear energy within the alginate group was normal, however there was no significant difference in tear energy within the five alginate materials ($F (4, 49) = 3.14$, $p = 0.023$ or $p < 0.05$); but there was a trend for a difference. The distribution of tear energy within the elastomers group was significantly skewed, but rectified using logarithmic transformation. There was a significant difference in tear energy within the

five elastomeric impression materials ($F(4, 49) = 11.01, p = 0.000$ or $p < 0.001$). Aroma Fine had the lowest tear energy amongst the alginate group with method two (770 J/m^2) while Palgat Plus had the highest tear energy (1032 J/m^2). President Regular had the lowest tear energy amongst the elastomers (1235 J/m^2), while Impregum-F had the highest tear energy (2933 J/m^2). Figure 61 shows the ascending order of tear energy of alginates and elastomers.

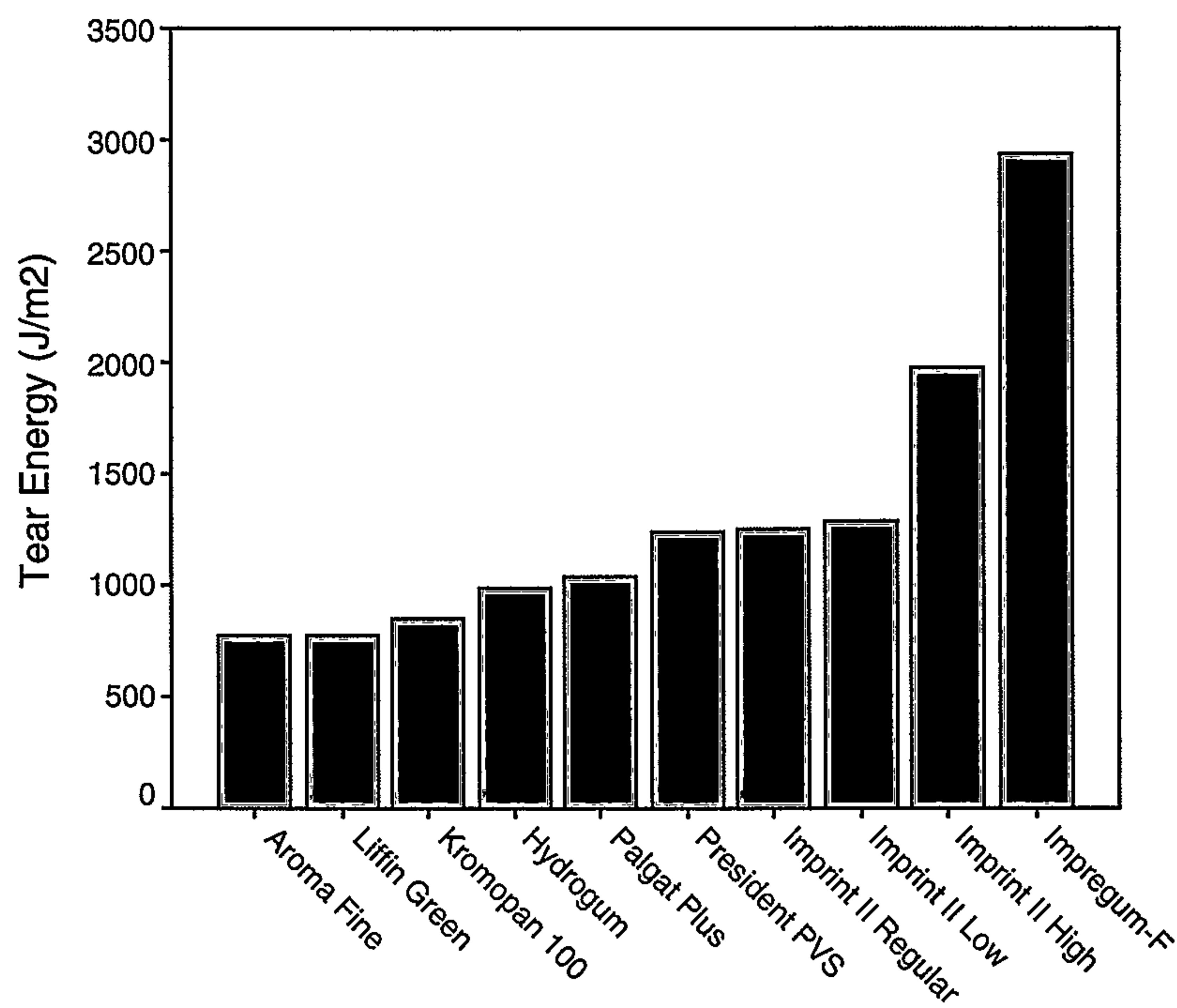


Figure 61 Ascending order for tear energy for the materials tested.

4.2.3 The association between the thickness of alginate impression material and tear energy (10 mm compared with 1 mm)

The results of tear energy of method one were compared with those of method two for alginate impression material, in order to determine whether thickness plays a role in the tear energies. Results were compared in Table 37 and 38.

Overall tear energy was normally distributed. Tear energy was significantly greater in the material of 1 mm thickness (tear 2) than 10 mm thickness (tear 1) ($t = 5.77$, $df = 73$, $p = 0.000$ or $p < 0.001$).

Table 37 Means and standard deviations of alginates of 1 mm compared with 10 mm

Alginate thickness	Mean (J/m ²)	N	SD (J/m ²)
1 mm (Trouser)	885.39	50	234
10 mm (Crescent)	590	25	146.08

Table 38 Means and standard deviation of alginate brands of method one compared with method two.

Material	Method one Tear Energy (J/m ²) (10 mm thickness)		Method two Tear Energy (J/m ²) (1 mm thickness)	
	Mean	SD	Mean	SD
<i>Alginates:</i>				
Kromopan 100*	441	65.20	856.07	224.17
Palgat Plus	712.30	47.20	1032	162.80
Liffin Green	727.06	63.10	778	216
Aroma Fine	414	12.13	770.02	169
Hydrogum	655.15	55.05	991.32	284.07

All tear 1 energies based on 5 samples and all tear 2 energies based on 10 samples.

Kromopan 100

Results of Kromopan 100 were normally distributed. There was a significant difference in tear energy between tear one and two ($t = 3.99$, $df = 13$, $p = 0.002$ or $p < 0.01$).

Palgat Plus

Results were normally distributed. There was a significant difference between the two methods ($t = 5.70$, $df = 11.8$, $p = 0.000$ or $p < 0.001$, unequal variance t test was used).

Liffin Green

Results were normally distributed, however there was no significant difference between the two methods ($t = 0.51$, $df = 13$, $p = 0.621$).

Aroma Fine

Results were normally distributed. There was a significant difference between the two methods ($t = 6.65$, $df = 9.2$, $p = 0.000$ or $p < 0.001$, unequal variance t test was used).

Hydrogum

Results were significantly skewed but rectified using a logarithmic transformation. There was a significant difference between the two methods ($t = 3.12$, $df = 13$, $p = 0.008$ or $p < 0.01$).

4.3 Statistical analysis of tensile properties of impression materials

True stress and true strain were used instead of engineering stress and engineering strain, because true stress and strain considered the cross sectional area, which decreased rapidly within the specimen when deformation occurred. The following formulae were used to convert engineering stress and strain to true stress and strain:

a) $\sigma_T = \sigma(1+\epsilon)$;

b) $\epsilon_T = \ln(1+\epsilon)$

Note: σ_T is the true stress, σ is the stress, ϵ is engineering strain, ϵ_T is the true strain, $\ln$ is the logarithm and ϵ is the engineering strain.

Figures 62 and 63 show the true stress-strain curve pattern for President which had the highest tensile strength amongst the elastomers (5.72 MPa) and Palgat Plus which had the highest tensile strength amongst the alginates (0.80 MPa).

It was not possible to obtain a clear yield point for the elastomeric impression materials; as a result no data on yield point were included in the elastomers section.

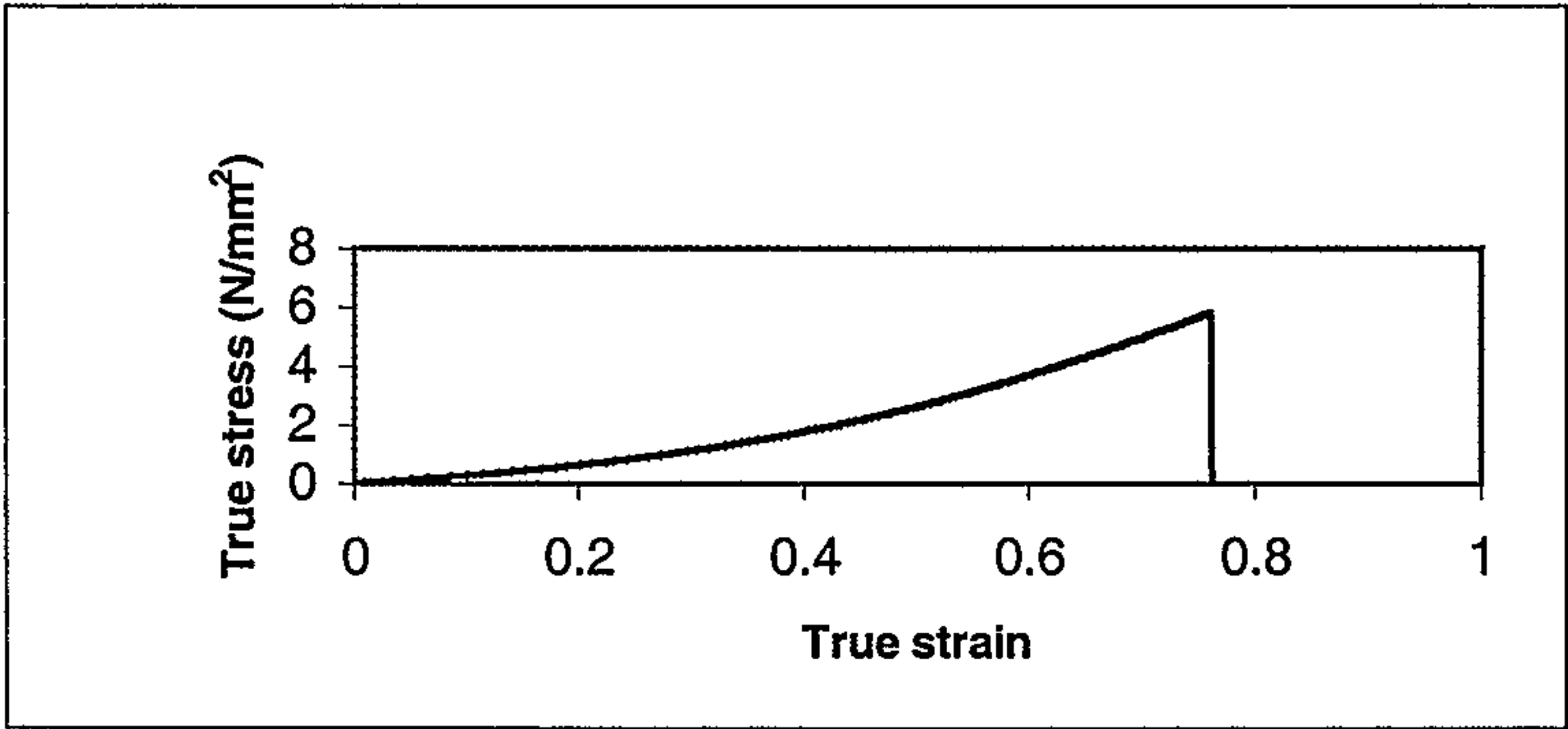


Figure 62 True stress-strain curve for President

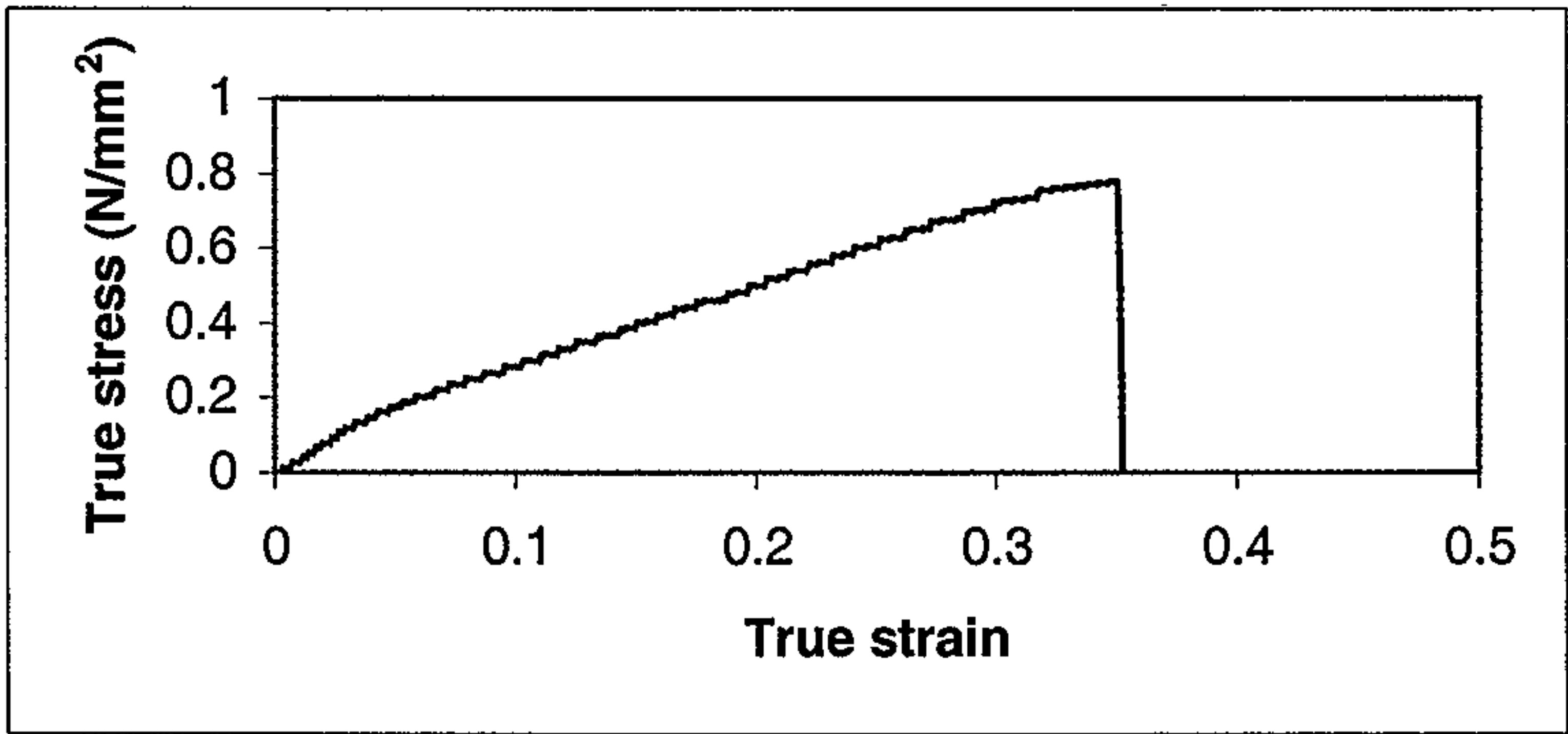


Figure 63 True stress-strain curve for Palgat Plus

Means and standard deviations of tensile strength and strain at failure for alginates and elastomers are shown in Table 39.

Table 39 Tensile strength and strain at failure data for the different materials.

Material	Tensile strength or stress (MPa)		Strain at failure	
	Mean	SD	Mean	SD
<i>Alginates:</i>				
Kromopan 100*	0.53	0.15	0.31	0.05
Palgat Plus	0.80	0.14	0.30	0.05
Liffin Green	0.40	0.02	0.48	0.05
Aroma Fine	0.44	0.08	0.30	0.05
Hydrogum	0.73	0.07	0.31	0.01
<i>Elastomers:</i>				
Imprint – High	4.77	0.68	0.71	0.09
Imprint – Regular	3.55	0.53	0.85	0.11
Imprint – Low	3.41	0.51	0.81	0.08
Impregum-F	5.60	1.40	1.05	0.19
President PVS	5.72	0.85	0.72	0.05

4.3.1 Comparison between the 10 materials

Tensile strength (stress)

Tensile strength was normally distributed for the ten materials. Significant difference was observed between the ten materials. $F(9, 40) = 67.879, p = 0.000$ or $p < 0.001$.

Strain at failure

Strain at failure was normally distributed for the ten materials. Significant difference was observed between the ten materials. $F(9, 40) = 51.756, p = 0.000$ or $p < 0.001$.

Modulus of elasticity

Modulus of elasticity was normally distributed for the ten materials; however there were significant differences between the ten materials. ANOVA: $F(9, 49) = 8.08, p < 0.001$

Maximum displacement (mm) before rupture

Data were significantly skewed for the ten materials, but were rectified using a logarithmic transformation. There were significant differences in maximum displacement between the ten materials. $F(9, 40) = 74.633, p = 0.000$ or $p < 0.001$

Comparison of means and standard deviations for modulus of elasticity and maximum displacement for the ten materials is shown in Table 40.

Table 40 Data for modulus of elasticity and maximum displacement for the different materials

Material	Modulus of Elasticity (MPa)		Maximum Displacement (mm)	
	Mean	SD	Mean	SD
<i>Alginates:</i>				
Kromopan 100*	2.10	0.67	9.77	1.39
Palgat Plus	4.23	1.64	9.69	1.85
Liffin Green	1.19	0.32	17	2.22
Aroma Fine	2.60	1.22	9.36	2.05
Hydrogum	4.30	0.47	9.85	0.44
<i>Elastomers:</i>				
Imprint – High	4.09	0.61	30.28	6.52
Imprint – Regular	3.07	0.12	40.20	7.21
Imprint – Low	2.57	0.23	37.33	5.10
Impregum-F	3	0.84	56.31	16.04
President PVS	3.36	0.21	31.81	3.20

4.3.2 **Comparison of the five elastomers with the five alginates**

Tensile strength

Data were normally distributed for the ten materials; elastomers had significantly higher tensile strength ($t = -15.721$, $df = 25$, $p = 0.000$ or $p < 0.001$ -unequal variance t test was used).

Table 41 Means and standard deviations comparison of tensile properties between alginates and elastomers

Property	Alginates (N=25)		Elastomers (N=25)	
	Mean	SD	Mean	SD
Tensile strength (MPa)	0.58	0.19	4.61	1.27
Strain at failure	.34	.08	.83	.16
Modulus of elasticity (MPa)	2.88	0.87	3.20	0.40

Strain at failure

Data were normally distributed for the ten materials; elastomers had significantly higher strain at failure ($t = -13.366$, $df = 35.9$, $p = 0.000$ or $p < 0.001$).

Modulus of elasticity

Data were normally distributed for the ten materials; however no significant difference between the five elastomers and the five alginates was observed ($t = -0.96$, $df = 33.2$, $p = 0.346$).

4.3.3 **Comparison amongst elastomers**

Tensile strength

Results were normally distributed for the five elastomers. Significant differences between the five elastomeric materials were observed ($F (4, 20) = 8.146$, $p = 0.000$ or $p < 0.001$).

Strain at failure

Data were significantly skewed for the five elastomers; however they were rectified using a logarithmic transformation. Significant differences between the five elastomeric materials were observed ($F(4,20) = 6.937$, $p = 0.001$ or $p < 0.01$).

Modulus of elasticity

Data were normally distributed for the five elastomers; however significant differences between the five elastomeric materials were observed ($F(4, 24) = 6.78$, $p < 0.01$).

4.3.4 Comparison amongst alginates

Tensile strength

Data were normally distributed for the five alginates. Significant differences between the alginates were observed ($F(4, 20) = 13.968$, $p = 0.000$ or $p < 0.001$).

Strain at failure

Data were significantly skewed for the five alginates, but were rectified using a logarithmic transformation. Significant differences between the five alginate materials were observed ($F(4, 20) = 12.206$, $p = 0.000$ or $p < 0.001$).

Modulus of elasticity

Data were normally distributed for the five alginates. Significant differences between the five alginate materials were observed. $F(4, 24) = 9.32$, $p < 0.001$.

Yield stress/strength at 1% strain

Data were normally distributed for the five alginate materials (data were not obtained for three samples). Significant differences between the five alginate materials were observed ($F(4, 17) = 7.92$, $p = 0.001$ or $p < 0.01$).

Table 42 Means and standard deviation of yield point stress at 1%, for alginate impression materials

Alginates	Mean (MPa)	N	SD (MPa)
Kromopan 100	0.24	3	0.05
Palgat Plus	0.33	5	0.07
Liffin Green	0.15	4	0.03
Aroma Fine	0.20	5	0.06
Hydrogum	0.25	5	0.03

Yield strain (%)

This was normally distributed for the five alginate materials (data were not obtained for three samples). Significant differences between the five alginate materials were observed ($F(4, 17) = 13.82, p = 0.000$ or $p < 0.001$). This data is listed in Table 43.

Table 43 Means and standard deviations of yield point strain of the different brands of alginate

Alginates	Mean	N	SD
Kromopan 100	0.12	3	0.04
Palgat Plus	0.10	5	0.02
Liffin Green	0.16	4	0.02
Aroma Fine	0.09	5	0.02
Hydrogum	0.06	5	0.02

5. Discussion

Tipping and drifting of teeth often accentuates the magnitude of undercuts, particularly on posterior teeth, and increases the volume of impression material having to be used in the impression. The effect of an undercut on the accuracy of impression materials has been well documented, but there appears to be no satisfactory method reported in the literature to describe tooth undercut severity.

Different devices have been used for measuring tooth dimensions and positions on dental casts such as rulers, calipers, vernier gauges, dividers, symmetrographs, scales, radiographs, photographs, prints and television images. The most commonly used instruments for measuring undercut depth are undercut gauges (Ney and Jelenko), using three sizes: 0.25, 0.5 and 0.75 mm. Such tooth measurements may be important when assessing the capability of an impression to record undercuts in order to fabricate an accurately fitting prosthesis.

The exact undercut for positioning the retentive clasp arm in removable partial dentures must be measured and marked on the master cast (McGivney and Carr-2000). Two techniques were used for undercut quantification, the first method used the Microscribe and the second method used two micrometers (horizontal and vertical) attached to a surveyor. This latter method utilised a fine needle which was modified and attached to the horizontal micrometer so that it could reach the full depth of an undercut. It was considered that it would be feasible for dentists, dental students and dental technicians to use this method as it would be simple and available whereas the Microscribe technique requires the operator to have advanced computer skills, and in addition the machine is costly.

As it eventuated, this technique proved to be unreliable and had limitations such as the attached needle being too flexible and moving, and creating pressure on contacting the tooth surface and further, possibly penetrating the surface of the cast if the operator was not careful; a die hardener would be required. Another limitation was that the operator routinely needed magnifying loupes and a light source in order to ensure that the needle just contacted the tooth surface and no excess pressure was exerted. In addition, the vertical arm, which was designed to connect the vertical micrometer with the surveyor, was also flexible. For these reasons this method was discontinued and further research is required to modify it for more accurate results.

A definition of a severe undercut was established as one standard deviation from the mean. Analysis of the results was divided into cases and controls, cases included casts with missing teeth, casts from poor fitting, good fitting and unknown fitting cobalt-chrome castings. Controls included casts with no missing teeth. Comparisons were carried out between undercuts on individual tooth surfaces (buccal, lingual, mesial and distal), between anteriors and posteriors, between maxilla and mandible and between right and left. There were significant differences in the undercuts between cases and controls buccally and lingually, while on the other hand there were significant differences between "fit" and "did not fit" groups for all the surfaces except the buccal.

The average undercut mean for "fit" group was 8.87 mm^2 , for "did not fit" group was 11.36 mm^2 , for unknown casting status was 7.96 mm^2 , for casts with no missing teeth was 6.33 mm^2 , and for casts from orthodontically treated cases was 6.90 mm^2 . There was no significant difference in severity of undercuts between maxillary and mandibular teeth and similarly, there was no significant difference between left sided and right sided teeth; however there was a significant difference in severity of the averaged

undercut between anteriors and posteriors. Anteriors had a mean of 11.69 mm² and posteriors had a mean of 4.87 mm². This might be explained by the orientation of anterior teeth, which are tilted labially. These teeth had an influence on the outcome of measurements in this study, as most anterior teeth had labial or buccal measurements only; in addition posterior teeth had either minimum or small buccal measurements due to their tilt mesially, distally or lingually. Cases always presented with more severe undercuts than controls, and undercuts were greater where castings did not fit than where the casting fit was good.

There is general agreement in the literature that the ability of an elastic impression material to be withdrawn from severe undercuts without distortion is an important property to determine the success or failure of an impression. A criterion of rupture was first described for amorphous solids by Griffith (1920) as cited by Greensmith (1960).

Greensmith (1960) Thomas and Rivlin (1953) and Thomas (1960) described a tearing criterion for rubber, which was modified to test tear energy of impression materials by Braden (1963) and Webber and Ryge (1968).

Tear energy or the energy required to sustain a tear through a material is traditionally measured by testing a trouser shaped specimen as described by Webber and Ryge (1968), or a crescent shaped specimen according to Chong, Chong and Docking (1971).

None of the reviewed articles compared the results from the two methods. Our study has compared tear energy of alginate impression materials, tested by the two methods in an attempt to investigate the role of material thickness and the rate of separation on tear energy.

Clinically, alginate impression materials are compressed about 10% in undercut areas during removal. The magnitude depends on the extent of the undercuts and the space between the tray and the teeth. The American Dental Association (ADA) specification requires that recovery from deformation will be more than 95% when the material is compressed 20% for 5 seconds at the time it will be normally removed from the mouth. We hypothesised that the greater the thickness of alginate around the undercuts, the greater the tear energy. This contradicted our findings, which showed that tear energy values obtained by the trouser technique (tear 2 method) were greater than that obtained from the crescent technique (tear 1 method). We expected to record higher values from method one, due to the sample thickness (10 mm compared with 1 mm) and the speed of separation (500 mm/min compared with 50 mm/min) as would be expected clinically when an alginate impression is removed with a snap. Method two showed a mean of 885.39 J/m², while method one showed a mean of 590 J/m².

Previous studies compared the rate of loading and temperature on tear energy and found that the greater the load, the greater is the tear energy and the same relation was implied for temperature (Braden 1963; Thomas 1960; Macpherson, Craig and Peyton 1966; Cook et al. 1984; Vrijhoef, Lourens and Leydekkersgovers 1986; Vrijhoef and Battistuzzi 1986; Klooster, Logan and Tijan 1991). However these studies investigated the role of temperature and rate of loading on tear energy, using the same mould or the same technique. In our study the two moulds have different geometries, and testing was conducted under different conditions. As well, the crescent shaped mould (method one) testing was performed under tension while the trouser mould (method two) testing was performed in shear. Further, method one took approximately five seconds while method two took approximately three minutes. This might explain the difference in ranking of

alginate between the two techniques. Tear one method showed that Aroma Fine had the lowest tear energy of 414 J/m^2 , and the highest value was for Liffin Green (727 J/m^2). Method two showed that Aroma Fine had the lowest tear energy, but higher than that obtained from method one (770 J/m^2), and Palgat Plus showed the highest value of 1032 J/m^2 .

The trouser tear technique was used to compare alginates with elastomers. A compromise had to be made however in regard to setting time for the elastomers, because of the difference setting time between the clinical (intraoral) and the laboratory (bench setting) conditions, a 15-minute waiting period being considered as sufficient for the completion of polymerisation. For comparison, alginate specimens were kept in a glass jar at 100% humidity in order to eliminate any chances of syneresis and imbibition and evaporation. As the time is critical in changing the polymer network of the elastomers, this might explain the scattered tear energy values obtained by the trouser method. The mean tear energy of elastomers was 1736 J/m^2 which was higher than the alginates. The lowest value for tear energy of elastomers was President Regular (Polyvinyl siloxane), and the highest tear energy value was for Impregum-F (Polyether). A universal dumb-bell-shaped specimen was used to compare alginates and elastomers for tensile strength, modulus of elasticity, yield point stress and strain, and extension ratio before breakage.

Addition silicones of low viscosity have an elastic recovery about 60%-95%, medium viscosity have about 70%-90%, high viscosity have about 70%-90% and very high viscosity has about 50%-80%. Polyethers have a range of elastic recovery from 98%-99% (Craig and Powers 2001). In general, our study showed that elastomeric materials

had significantly higher values for tensile strength (4.61 MPa compared with 0.58 MPa for alginates), higher strain at failure (83% compared with 34% for alginates) and higher modulus of elasticity (3.20 MPa compared with 2.88 MPa for alginates). The lowest tensile strength value amongst alginates was for Liffin Green (0.40 MPa), while the highest value was for Palgat Plus (0.80 MPa). The lowest value amongst elastomers was for Imprint-Low Viscosity (Polyvinyl siloxane) (3.41 MPa) and the highest value was for President Regular (Polyvinyl siloxane) (5.72 MPa).

Palgat Plus and Hydrogum alginate impression materials showed higher modulus of elasticity than the Imprint-High Viscosity (Polyvinyl siloxane), which had the highest values amongst the elastomers (4.23 MPa, 4.30 MPa and 4.09 MPa respectively).

The lowest value for maximum displacement before rupture of alginates was for Aroma Fine (9.36 mm) while the highest value was for Liffin Green (17 mm). The lowest value amongst elastomers was for Imprint-High Viscosity (30.28 mm), while the highest value was for Impregum-F (56.31 mm).

Our study did not obtain a yield point for elastomeric impression materials, possibly because of the chemical nature of “rubber”, which do not show a clear yield point. A yield point of 1% was found to be acceptable for alginates, because they have a low yield point and choosing 1% allowed more accurate reading of the yield point.

Some elastomeric impression materials such as Impregum had showed about 100% extension before breakage (in this case 83%). That is the reason behind choosing true stress and true strain instead of engineering stress and engineering strain. The use of

true stress and true strain considered the continuous change in the cross sectional area during testing (Callister 1991).

Yield stress (strength) determined the ability of the impression materials to withstand stress without permanent deformation, so the more rigid the material, the higher the yield strength. The strain at yield point indicated the amount of tissue undercut that the impression material could overcome without permanent deformation. Significant differences between the five alginate brands were observed. Liffin Green had the lowest strength at 1% strain (0.15 MPa), while Palgat Plus had the highest value (0.33 MPa). The yield point strain data showed that Hydrogum had the lowest value of 6% and Liffin Green has the highest value of 16%.

6. Conclusions

- A definition of a severe undercut was established.
- Subjects with missing teeth (cases) had more severe undercuts than subjects with no missing teeth (controls).
- Severe undercuts were more associated with poor fitting prostheses.
- There was a significant difference in the buccal and lingual undercuts between cases and controls.
- There were significant differences between "fit" and "did not fit" groups for all the surfaces of teeth measured except the buccal.
- There was no significant difference in the undercut severity between maxillary and mandibular casts and between left sided and right sided teeth.
- The severity of the averaged undercut of anterior teeth was more than that of the posterior teeth.
- Tear energy for alginate with the crescent mould technique ranked the different brands in ascending order as follows; Aroma Fine < Kromopan100 < Hydrogum < Palgat Plus < Liffin Green.
- Higher tear energy was found for alginates when the trouser technique (1 mm) was used compared with the crescent technique (10 mm).
- Tear energy for alginates and elastomeric impression materials with the trouser technique ranked them as follows; Aroma Fine < Liffin Green < Kromopan 100 < Hydrogum < Palgat Plus < President Regular (PVS) < Imprint Regular (PVS) < Imprint Low (PVS) < Imprint High (PVS) < Impregum-F (polyether).
- Modulus of elasticity ranked the materials as follows; Liffin Green < Kromopan 100 < Imprint Low (PVS) < Aroma Fine < Impregum-F (polyether) < Imprint

Regular (PVS) < President Regular (PVS) < Imprint High (PVS) < Palgat Plus < Hydrogum.

- It is necessary to select the most appropriate impression material to guarantee sufficient tear energy in different clinical situations.
- When dentists need a strong impression material in an area of stress or significant undercuts, they would be advised to consider the following;
 - (a) A material with adequate tear energy and high elastic modulus such as Imprint-High Viscosity or President Regular Viscosity (both are Polyvinyl siloxane) in fixed prosthodontics; in removable prosthodontics, it is recommended to use alginates such as Palgat Plus or Hydrogum.
 - (b) Blocking out severe undercuts with soft wax or temporary cement intraorally before taking the primary impression or blocking them in the laboratory with wax or plaster before constructing the special tray.
 - (c) Choosing a metal stock tray with sufficient mechanical retentive perforations for alginates.
 - (d) Designing a special tray which excludes severe unwanted undercuts if possible or by using thicker spacers for elastomers.
 - (e) Using an adhesive on the inner surface of the tray and 2-3 mm of the outer borders and allowing it to dry for at least 3 min.
 - (f) Designing the denture framework so as not to include an area with large or severe undercut.

7. REFERENCES

- Applegate OC. Use of the paralleling surveyor in modern partial denture construction. *J Am Dent Assoc* 1940; 27:1397-1407.
- Asgar K. Elastic impression materials. *Dental Clinics of North America* 1971; 15: 81-98.
- Baker PS, Beatty RG. A simplified technique for intraoral undercut blockout before impression procedures. *J Prosthet Dent* 1989; 62: 116-117.
- Bergman B, Olsson C-O. Further laboratory studies on reproduction of undercuts by means of alginate. *Sven Tandlak Tidskr* 1966; 59: 497-511.
- Bindra B, Heath JR. Adhesion of elastomeric impression materials to trays. *J Oral Rehabil* 1997; 24: 63-69.
- Bjorndal AM, Henderson WG, Skidmore AE, Kellner FH. Anatomic measurements of human teeth extracted from males between the ages of 17 and 21 years. *Oral Surg Oral Med Oral Pathol* 1974; 38: 791-803.
- Blatterfein L. A study of partial denture clasping. *J Am Dent Assoc* 1951; 43:169-185.
- Blomberg PAH, Mahmood S, Smales RJ, Makinson OF. Some parameters for testing deformation of elastomeric impression materials. *Aust Dent J* 1992; 37: 271-276.
- Braden M. Characterization of the rupture properties of impression materials. *The Dent Pract and Dent Rec* 1963; 14:67-71.
- Breeding LC, Dixon DL. Accuracy of casts generated from dual-arch impressions. *J Prosthet Dent* 2000; 84:403-407.
- Brown T, Margetts B, Townsend GC. Comparison of mesiodistal crown diameters of the deciduous and permanent teeth in Australian aboriginals. *Aust Dent J* 1980; 25: 28-33.
- Callister, Jr WD. *Materials Science and Engineering. An Introduction*. 2nd edition. John Wiley & Sons, Inc, 1991:117-134.
- Campbell SW, Zimmerman GJ, Tomlinson JL. A correlation of tooth circumferences. *Am J Orthod* 1978; 74: 656-662.
- Carrotte PV, Johnson A, Winstanley RB. The influence of the impression tray on the accuracy of impressions for crown and bridge work-an investigation and review. *Br Dent J* 1998;185: 580-585.
- Chai J, Takahashi Y, Lautenschlager EP. Clinically relevant mechanical properties of elastomeric impression materials. *Int J Prosthodont* 1998; 11: 219-223.

Chai JY, Jameson LM, Moser JB, Hesby RA. Adhesive properties of several impression material systems: Part II. J Prosthet Dent 1991; 66: 287-292.

Cho GC, Donovan TE, Chee WWL, White SN. Tensile bond strength of polyvinyl siloxane impressions bonded to a custom tray as a function of drying time: Part I. J Prosthet Dent 1995; 73: 419-423.

Chong MP, Chong JA, Docking AR. The tear test as a means of evaluating the resistance to rupture of alginate impression materials. Aust Dent J 1971; 16:145-151.

Civjan S, Huget EF, de Simon LB. Surface characteristics of alginate impressions. J Prosthet Dent 1972; 28:373-378.

Cohen BI, Pagnillo M, Deutsch AS, Musikant BL. Dimensional accuracy of three different alginate impression materials. J Prosthodont 1995; 4:195-199.

Cohen BI, Pagnillo MK, Musikant BL, Deutsch AS. Tear strength of four irreversible hydrocolloid impression materials. J Prosthodont 1998; 7:111-113.

Collard EW, Caputo AA, Standlee JP, Trabert KC. Dynamic stresses encountered in impression removal. J Prosthet Dent 1973; 29: 498-506.

Cook W. Alginate dental impression materials: chemistry, structure, and properties. J Biomed Mater Res 1986;20:1-24.

Cook WD, Liem F, Russo P, Scheiner M, Simkiss G, Woodruff P. Tear and rupture of elastomeric dental impression materials. Biomaterials 1984; 5:275-280.

Craig RG, Peyton RA. Restorative Dental Materials. 5th edition. St.Louis: CV Mosby Co, 1975:210

Craig RG, Powers JM. Restorative Dental Materials. 11th edition. St.Louis: CV Mosby Co, 2001: 99-100 & 330-389.

Cullen DR, Sandrik JL. Tensile strength of elastomeric impression materials, adhesive and cohesive bonding. J Prosthet Dent 1989; 62:142-145.

de Araujo PA, Jorgensen KD. Effect of material bulk and undercuts on the accuracy of impression materials. J Prosthet Dent 1985; 54: 791-794.

de Araujo PA, Jorgensen KD, de Araujo CRP. Effect of undercuts on the accuracy of reheated addition-reaction silicone impressions. Rev Odontol Univ Sao Paulo 1990; 4: 212-215.

Dixon DL, Breeding LC, Bosser MJ, Nafso AJ. The effect of custom tray material type and surface treatment on the tensile bond strength of an impression material/adhesive system. Int J Prosthodont 1993; 6: 303-306.

- Eames WB, Sieweke JC, Wallace SW, Rogers LB. Elastomeric impression materials: effect of bulk on accuracy. *J Prosthet Dent* 1979; 41: 304-307.
- Eames WB, Wallace SW, Suway NB, Rogers LB. Accuracy and dimensional stability of elastomeric impression materials. *J Prosthet Dent* 1979; 42:159-162.
- Elliot FC. A method that simplifies the design of partial dentures. *J Am Dent Assoc* 1940; 27:1263-1268
- Farah JW, Powers JM. Impression Materials for Fixed Prosthodontics. *The Dent Adv* 1997; 14:2-6.
- Ferguson FS, Macko DJ, Sonnenberg EM, Shakun ML. The use of regression constants in estimating tooth size in a Negro population. *Am J Orthod* 1978;73: 68-72.
- Fertig JW, Chilton NW, Varma AA. Studies in the design and analysis of dental experiments. 12. Comparison of two measurements of root divergence. *J Dent Res* 1970; 49: 768-771.
- Fung DT, Osborne J. The setting characteristics of two alginate impression materials in relation to temperature change. *Aust Dent J* 1972; 17: 33-36.
- Fusayama T, Nakazato M. The designs of stock trays and the retention of irreversible hydrocolloid impressions. *J Prosthet Dent* 1969; 21:136-142.
- Ghose LJ, Baghdady VS. Analysis of the Iraqi dentition: mesiodistal crown diameters of permanent teeth. *J Dent Res* 1979;58:1047-1054.
- Gold HO. Instrumentation for solving abutment parallelism problems in fixed prosthodontics. *J Prosthet Dent* 1985;53:172-179.
- Greensmith HW. Rupture of Rubber. VIII. Comparison of Tear and Tensile Rupture Measurement. *J Appl Polymer Sci* 1960; 3:183-193.
- Hansson O, Eklund J. A historical review of hydrocolloids and an investigation of the dimensional accuracy of the new alginates for crown and bridge impressions when using stock trays. *Swed Dent J* 1984; 8:81-95.
- Hansson O, Eklund J. Impressions for prosthodontic restorations reproducing narrow spaces and severe undercuts. *Acta Odontol Scand* 1988; 46:199-206.
- Harcourt JK. A review of modern impression materials. *Aust Dent J* 1978; 23:178-186.
- Hedegard B, Hedegard E, Harcourt JK. Retention of alginate impression material using a polyester fibre-mat textile. *Dent Mater* 1985; 1: 195-196.
- Heisler WH, Tjan AH. Accuracy and bond strength of reversible with irreversible hydrocolloid impression systems: a comparative study. *J Prosthet Dent* 1992; 68:578-584.

- Henderson D, McGivney GP, Castleberry DJ. McCracken's Removable Partial Prosthodontics. 7th ed. St Louis: CV Mosby Co, 1985:180-185.
- Herfort TW, Gerberich WW, Macosko CW, Goodkind RJ. Tear strength of elastomeric impression materials. J Prosthet Dent 1978; 39: 59-62.
- Hisamitsu H, Iwaku M, Fusayama T. Measurements of cervical undercuts of human tooth crowns. J Dent Res 1978; 57: 484-494.
- Hochman N, Yaniv O. Comparative clinical evaluation of removable partial dentures made from impressions with different materials. Compend Contin Educ Dent 1998; 19: 200-202, 204-206.
- Hondrum SO. Tear and energy properties of three impression materials. Int J Prosthodont 1994; 7: 517-521.
- Hummert TW, Kaiser DA. Blockout technique for impressions of teeth with increased open gingival embrasures. J Prosthet Dent 1999; 82: 100-102.
- Idris B, Houston F, Claffey N. Comparison of the dimensional accuracy of one- and two-step techniques with the use of putty/wash addition silicone impression materials. J Prosthet Dent 1995; 74: 535-541.
- Johnson GH, Craig RG. Accuracy of four types of rubber impression materials compared with time of pour and a repeat pour of models. J Prosthet Dent 1985; 53: 484-490.
- Johnson GH, Craig R.G. Accuracy and bond strength of combination agar/alginate hydrocolloid impression materials. J Prosthet Dent 1986; 55:1-6.
- Keck SC, Douglas WH. Tear strength of non-aqueous impression materials. J Dent Res 1984; 63:155-157.
- Khaknagar B, Ettinger RL. Removal time: a factor in the accuracy of irreversible hydrocolloid impressions. J Oral Rehabil 1977; 4: 369-376.
- Kimura H, Sohmura T, Watanabe T. Three-dimensional shape measurement of teeth. (6) Measurement of tooth model by tilting method by means of the double sensor laser displacement meter, and the simulation of occlusion. Shika Zairyo Kikai 1990; 9: 679-686.
- Kimura H, Sohmura T, Watanabe T. Three dimensional shape measurement of teeth. (3) The measurement by the newly developed laser displacement meter with double sensors. J Osaka Univ Dent Sch 1990; 30: 31-37.
- Klooster J, Logan GI, Tjan AH. Effects of strain rate on the behaviour of elastomeric impression. J Prosthet Dent 1991; 66: 292-298.
- Lechner SK. Survey lines revisited: finding nonundercut surfaces for retainers that approach from the occlusal surface. J Prosthet Dent 1996; 76: 437-444.

- Leles CR, Compagnoni MA. A simple method to detect undercuts during tooth preparation for fixed prosthodontics. *J Prosthet Dent* 2001; 85: 521-522.
- Lepe X, Sandrik JL, Land MF. Bond strength and accuracy of combined reversible-irreversible hydrocolloid impression systems. *J Prosthet Dent* 1992; 67:621-627.
- Leung KCM, Chow TW, Woo CW, Clark RKF. Tensile, shear and cleavage bond strengths of alginate adhesive. *J Dent* 1998; 26: 617-622.
- Luk KC, Chen PS. A new device for blockout procedures in rotational path removable partial dentures. *J Prosthet Dent* 1993; 69: 491-494.
- Macko DJ, Ferguson FS, Sonnenberg EM. Mesiodistal crown dimensions of permanent teeth of black Americans. *ASDC J Dent Child* 1979; 46: 314-318.
- MacPherson GW, Craig RG, Peyton FA. Mechanical properties of hydrocolloid and rubber impression materials. *J Dent Res* 1967; 46: 714-721.
- Martensson B, Ryden H. The holodent system, a new technique for measurement and storage of dental casts. *Am J Orthod Dentofacial Orthop* 1992;102: 113-119.
- McGivney G, Carr AB. McCracken's Removable Partial Denture. 10th edition. St. Louis: CV Mosby Co, 2000:197-221.
- MicroScribe-3D, Desktop Digitizing Systems (Product brochure). Immersion Corporation, 801 Fox Lane, San Jose, CA 95131, USA.
Website: www.immersion.com
- Mornstad H, Staaf V, Welanders U. Age estimation with the aid of tooth development: a new method based on objective measurements. *Scand J Dent Res* 1994; 102: 137-143.
- Moseley JP, Dixon DL, Breeding LC. Custom impression trays. Part III: A stress distribution model. *J Prosthet Dent* 1994; 71: 532-538.
- Murakami H, Takehana S, Abe T, Yamamoto Y, Takenaka M. Correlation between the degree of deformation of the stone die and the amount of the master die undercut. Part 1. Single tooth die. *Aichi-Gakuin Dent Sci* 1989; 2:57-65.
- Nishi Y, Tsuru K, Kishita C, Hamano T, Kawahata N, Nagaoka E. Impression pressures against teeth in a partially edentulous model with a mobile tooth: influence of impression tray design. *J Oral Rehabil* 2000; 27: 380-386.
- Nissan J, Laufer B-Z, Brosh T, Assif D. Accuracy of three polyvinyl siloxane putty-wash impression techniques. *J Prosthet Dent* 2000; 83:161-165.
- O'Brien WJ. Dental materials and their selection. 3rd edition. Quintessence Publishing Co, Inc, 2002:90-112.
- Ortensi L, Strocchi ML. Modified custom tray. *J Prosthet Dent* 2000; 84: 237-240.

- Otto T, De Nisco S. Computer-aided direct ceramic restorations: a 10-year prospective clinical study of Cerec CAD/CAM inlays and onlays. *Int J Prosthodont* 2002;15: 122-128.
- Ozaki T, Satake T, Kanazawa E. Morphological significance of root length variability in comparison with other crown dimensions. I. Basic statistics and sex difference. *J Nihon Univ Sch Dent* 1987; 29: 233-240.
- Payne JA, Pereira BP. Bond strength of two nonaqueous elastomeric impression materials bonded to two thermoplastic resin tray materials. *J Prosthet Dent* 1995; 74: 563-568.
- Peters MC, Tieleman A. Accuracy and dimensional stability of a combined hydrocolloid impression system. *J Prosthet Dent* 1992; 67: 873-878.
- Peutzfeldt A, Asmussen E. Accuracy of alginate and elastomeric impression materials. *Scand J Dent Res* 1989; 97: 375-379.
- Procera AllCeram-Strong and Beautiful. Clinical Manual. Nobel Biocare 2002.
- Ragain JC, Grosko ML, Raj M, Ryan TN, Johnston WM. Detail reproduction, contact angles, and die hardness of elastomeric impression and gypsum die material combinations. *Int J Prosthodont* 2000; 13: 214-220.
- Ragnarson N, Astrand P. The ability of rubber impression materials in reproducing undercuts. A laboratory technical investigation on silicone and thiokol materials. *Sven Tandlak Tidskr* 1965; 58:403-418
- Reeves GW. One-step impression technique for patients with severe undercuts. *Compendium* 1992; 13: 532-533.
- Revised American Dental Association Specification no.19 for Non-aqueous, Elastomeric Dental Impression Materials. *J Am Dent Assoc* 1977; 94:733-741.
- Rivlin RS, Thomas AG. Rupture of Rubber. I. Characteristic energy for tearing. *J Polymer Sci* 1953; 10:291-318.
- Roach FE. Principles and essentials of bar clasp partial dentures. *J Am Dent Assoc* 1930; 17: 124-138.
- Rosenstiel E. Inlay and crown preparations with undercuts. *Brit Dent J* 1968;125: 344-346.
- Rosenstiel S, Fujimoto J, Land M. Contemporary Fixed Prosthodontics. 2nd edition. St.Louis: CV Mosby Co ,1995: 311-314.
- Salem NS, Combe EC, Watts DC. Mechanical properties of elastomeric impression materials. *J Oral Rehabil* 1988; 15: 125-132.

- Samman JM, Fletcher A. A study of impression tray adhesives. *Quintessence Int* 1985; 16: 305-309.
- Sandrik JL, Vacco JL. Tensile and bond strength of putty-wash elastomeric impression materials. *J Prosthet Dent* 1983; 50: 358-361.
- Sato Y, Sato M. Use of a silicone disclosing material in patients with embrasure undercuts. *J Prosthet Dent* 2001; 86:135-136.
- Saunders WP, Sharkey SW, Smith GMcR, Taylor WG. Effect of impression tray design upon the accuracy of stone casts produced from a single-phase medium-bodied polyvinyl siloxane impression material. *J Dent* 1992 ; 20:189-192.
- Savara BS, Sanin C. A new data acquisition method for measuring dentitions and tests for accuracy. *Am J Phys Anthropol* 1969; 30: 315-318.
- Sawyer HF, Sandrik JL, Neiman R. Accuracy of casts produced from alginate and hydrocolloid impression materials. *J Am Dent Assoc* 1976; 93: 806-808.
- Sneed WD, Miller R, Olson J. Tear strength of ten elastomeric impression materials. *J Prosthet Dent* 1983; 49: 511-513
- Sotiriou M, Hobkirk JA. An in vivo investigation of seating and removal forces associated with recording impressions in dentate patients. *J Prosthet Dent* 1995; 74: 455-462.
- Stern WJ. Guiding planes in clasp reciprocation and retention. *J Prosthet Dent* 1975; 34: 408-414.
- Tam LE, Brown JW. The tear resistance of various impression materials with and without modifiers. *J Prosthet Dent* 1990; 63: 282-285.
- Taverne PP, Amesz-Voorhoeve WH, Leertouwer HL. A photogrammetric method which provides geometric data in dental morphology. *Z Morphol Anthropol* 1979; 70: 163-173.
- Taylor GR, Darin SR. The tensile strength of elastomers. *J Polymer Sci* 1955; 17: 511-525.
- Taylor RL, Reese R. Removable partial denture restoration: function and aesthetics. Austenal Products Laboratory. Chicago: Howmedica Inc, 1984:9-15.
- The Australian Standards. Dental Alginate Impression Material AS 1282-1972
The Standards Association of Australia Standards House, 80 Arthur street, North Sydney, NSW, Australia. 1972:16-17
- The Australian Standards. Elastomeric Impression Materials AS 1185-1985.
The Standards Association of Australia Standards House, 80 Arthur street, North Sydney, NSW, Australia. 1985:1-16

- The American Standards For Testings and Materials (ASTM). Standard Test Method for Initial Tear Resistance of Plastic Film and Sheeting. D 1004-93:240-42
- The American Standards For Testings and Materials. Standard Test Method for Initial Tear Resistance of Plastic Film and Sheeting. D 1004-94a: 1-4
- The American Standards For Testings and Materials. Standard Test Method for Vulcanized Rubber and Thermoplastic Elastomers-Tension. D 412-98a: 43-55
- The American Standards For Testings and Materials (ASTM). Standard Test Method for Tear Strength of Conventional Vulcanized Rubber and Thermoplastic Elastomers. D 624-00:1-9
- The American Standards For Testings and Materials. Standard Test Method for Tensile Properties of Thin Plastic Sheeting. D 882-01:162-170
- The American National Standard. Specification No.18, Alginate Impression Materials.American Dental Association, Council on Scientific Affairs 2001:1-20
- Thomas AG. Rupture of Rubber. VI. Further experiments on the tear criterion. J Appl Polymer Sci 1960; 3; 8:168-174.
- Tjan AH, Heisler WH. Dimensional accuracy and bond strength of addition silicones. Am J Dent 1992; 5: 223-5.
- Van der Linden FPGM, Boersma H, Zelders T, Peters KA, Raaben JH. Three-dimensional analysis of dental casts by means of the optocom. J Dent Res 1972; 51:1100.
- Vrijhoef MM, Battistuzzi PG. Tear energy of impression materials. J Dent 1986;14:175-177.
- Vrijhoef MMA, Lourens FL, Leydekkersgovers GFM. A modified technique to determine the tear energy of impression materials. J Oral Rehabil 1986;13:325-328.
- Wada K. Studies on dimensional accuracy of working casts made by various impression techniques-influence of undercuts on dimensional accuracy. Kokubyo Gakkai Zasshi, 1992; 59: 518-540.
- Wang RR, Nguyen T, Boyle AM. The effect of tray material and surface condition on the shear bond strength of impression materials. J Prosthet Dent 1995 ; 74:449-454.
- Wassell RW, Abuasi HA. Laboratory assessment of impression accuracy by clinical simulation. J Dent 1992; 20: 108-114.
- Webber RL, Ryge G. The determination of tear energy of extensible materials of dental interest. J Biomed Mater. Res.1968; 2:281-296.
- Wilson HJ, Smith DC. The bonding of alginate impression materials to impression trays. Br Dent J 1963; 114:291-294

Wood BA. Tooth size and shape and their relevance to studies of hominid evolution. *Philos Trans R Soc Lond B Biol Sci* 1981; 292: 65-76.

Yardeni J. Highlights of functional dental morphology: a brief survey. *Dent Dig* 1969;75: 410-414.

Zarb GA, Bergman B, Clayton JA, Mackay HF. *Prosthodontic treatment for partially edentulous patients*. St.Louis: CV Mosby Co, 1978: 463-476.

Zoeller GN, Tischler PH. Technique to improve surveying in confined areas. *J Prosthet Dent* 1995;73: 223-224.