A THREE-DIMENSIONAL CEPHALOMETRIC STUDY
OF A MODEL SYSTEM OF TOOTH MOVEMENT

by

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This paper submitted in partial fulfillment of the requirements for a Certificate in Orthodontics, University of Oregon Dental School

June 1974

ACKNOWLEDGMENTS

I wish to thank Dr. Douglas L. Buck for his suggestions, help and guidance throughout the course of this project.

Many thanks are due Ms. Roberta Beckman for her typing of this manuscript, and Ms. D'Lorah Moretz for her help in radiological procedures associated with this project.

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INTRODUCTION

Cephalometrics have been extensively used in the field of orthodontics since the introduction of the technique by Broadbent and Hoffrath in 1931. Many studies have been done to improve the technic and its application to clinical and research dentistry.

In longitudinal study of growing individuals, it is difficult to find stable, anatomical reference points to be able to compare the sucessive films taken. The method of superimposition of the films involved many variable factors such as stability of anatomical landmarks, identical repositioning of the head, distortion of the x-rays from a three-dimensional object to a two-dimensional film, errors in landmark location, measurements, etc.

Bjork (1955) introduced the use of metallic implants in the jaws as an attempt to yield stable reference points.

Schwartz (1943), Savara (1965), and Dahan (1968) developed a three-dimensional cephalometric technic on two films which improved the error from distortion of a three-dimensional object to a two-dimensional film. The disadvantage was that there might be some patient movement between the two exposures.

Sorenson and Hixon improved the three-dimensional cephalometric technic by using two x-ray machines simultaneously on one film. The validity and reliability of this technic was investigated by Nixon and Cruikshank in 1970. In 1972, Quinio re-investigated by using an implant phantom and by handling the data by computer. The feasibility of the method lies in the fact that it was inexpensive to initiate with commonly available equipment. The validity was improved in that there is no need for identical repositioning of the head during successive exposures. The reliability was studied by Dennis in 1972, and found to be an improvement over existing technics. Hodge (1973) investigated the reliability within-patient and the stability of the implants and found that the method compared favorably with the values established in vitro by Dennis in 1972.

The purpose of this study is to verify the reliability, validity, and feasibility of the three-dimensional cephalometric technic in an in vitro tooth movement study. The results should facilitate improved experimental designs in human applications.

REVIEW OF THE LITERATURE

Prior to the time of x-rays of the skull, craniofacial measurements on live individuals were possible only by direct measurement through skin and soft tissues. This crude approximation of the skull was of little treatment value to the clinician. An improved approach of radiographic recording was made possible utilizing the application of cephalometric methods used in an anthropometric technic to orthodontic practices by Broadbent in 1931.[1] This valuable method has become a very useful clinical and research tool in orthodontics.

Potter and Meredith[2] compared the reliability of various direct and radiographic skull measurements. They found that these methodologies were equally reliable for biparietal measurements, but there was an improved reliability for radiographic measurements of bigonial distances. Radiographic measurement has an advantage over direct measurement in that it makes possible the measurement of intracranial bony landmarks which cannot be possible with the direct method.

Since cephalometric radiography has become a necessary tool in orthodontics, the technic has been improved and developed in various ways. Limitations and errors of the method have been investigated.

There are many factors which contribute to the inaccuracy of cephalometric radiography. Thurow[3] evaluated some of the basic problems which affect the accuracy of the cephalographs such as blurring, enlargement, and distortion. Blurring can be minimized through the control of motions of the subject or x-ray machine by using a high kilovoltage power supply and the highest possible milliamperage. Optical blurring can be reduced by using the smallest possible focal spot, the shortest possible subject-to-film distance, and the longest possible focal spot-to-film distance. The accuracy of measurements will improve to about 0.5 mm. by reducing blurring factors. Enlargement is about 5% to 8% for sagittal landmarks at a film target distance of 60 inches and affects only linear measurements, not angular measurements. Corrections of enlargement can be accomplished by using scales projected on the film as described by Broadbent[1] or by using the ratio:

$$\frac{\text{Target-subject distance}}{\text{Target-film distance}} = \frac{\text{subject size}}{\text{image size}}$$

Distortion results from differences in the amount of enlargement of anatomical structures not lying in the same plane parallel to the film. This can be compensated for by using the midpoint between right and left images.

Franklin[4] also pointed out that the focal film distance should be at least 60 inches, and suggested the use of a powerful x-ray machine. Horowitz and Hixon[5] stated that enlargement in the midsagittal plane can be reduced to 6-7% by placing the subject five feet from the target and one inch from the film.

Measurement accuracy is also affected by errors in measurement, errors in landmark identification, errors in tracing, and variation among tracers and measurers. Hixon[6] reported that two persons will seldom duplicate each other exactly in tracing or measuring. He tested the reliability of certain cephalographic measurements of three head films by using Downs analysis.[7] Each film was traced and measured 10 separate times by eight individuals. The results showed wide ranges of disagreement, i.e., facial angle ranged from 1^{o} to 6.5^{o}. This showed that even the same landmarks are not located with equal reliability in all patients.

Hatton and Grainger[8] found that error variance of the radiographic technic was smaller than variance of the tracing technic, but the greatest source of variation was due to a real difference between individuals. Broadway, Healy, and Poyton[9] found that the standard deviation, of the differences between successive measurements of the same angles, was higher for different tracers (1.44^{o}- 5.54^{o}) than for the same tracer (1.05^{o}- 3.14^{o}).

Measurement errors are of great concern among many investigators. Björk[10] determined the errors of linear and angular measurements of 24 different points, 31 different planes, and 55 angles. He found the errors ranged from 0.26 to 2.43 degrees for angular measurements, and from 0.27 to 2.84 mm. for linear measurements. Baumrind and Frantz[11] estimated errors of linear and angular measurements from 16 common landmarks of 23 standard cephalographs. They found that the magnitude of errors varied widely among the measurements depending on the different locations of the points, and all points were not equal in reliability. Angular measurements tended to be more variable than linear measurements. It was pointed out by Björk and Solow[12] that when the landmark is re-used for measurements, its error is contributed to the values for both measurements.

Cephalometrics used in a longitudinal study involve some important factors other than the accuracy of measurements such as reproducibility of the head position and the method of superimposition of successive cephalographs. Even though the measurement errors are small compared to other errors, and much smaller than differences between individuals,[6] these measurement errors should be considered as problems contributing to the reliability in longitudinal research, in which the small increment changes due to growth or orthodontic treatment are very important.[13] Superimposition also becomes an important problem. It is partly complicated by the continuing growth of the anatomical landmarks, which make it difficult to have stable reference points. There are various methods used for superimposition. Most of them generally accept the use of reference points or lines in the cranial base. One of the most common lines of reference is Frankfort plane (Porion-orbitale). Koski[14] found that this plane is unreliable because its systemic error of measurement exceeds the acceptable limit. Superimposition of mandible or maxilla was used to determine intramandibular or intramaxillary changes.[15] But this is not accurate because both maxilla and mandible are changing during growth through the process of apposition and resorption.[16] Broadbent[17] employed the method of superimposition of tracings from successive films by using a registration point (the point midway on the perpendicular from the Bolton-nasion plane to Sella turcica). He found that the Bolton-nasion plane and its registration point in the sphenoidal area is the most fixed point in the head or face. The nasion-sella line of superimposition was first used by Brodie.[18] This line seemed to be the most favorable line of orientation and was found to have satisfactory results, even though he realized that there are no reliable areas or points from which conclusion can be drawn in relation to the changes of other parts. He stressed that superimposing of various points is only valid assuming that they are stable, and one can state only that changes occurring in one part are in a manner related to the other parts. Björk,[19] in his study of cranial base development, considered N-S line as remaining relatively constant between the ages of 12 to 20 years. Bergersen[20] compared several methods of superimposition and found that neither sella or nasion were stable. He also found that in S-N and the common registration methods of orientation, the direction of movement of all facial landmarks were more inferior to the direction presented in the intersection method (the method that oriented on the nasion and anterior nasal spine on a straight line while centering all calvarial outlines concentrically). Scott[21] also found the change in position of nasion during growth. Ford[22] stated that the satisfactory results obtained when using N-S line for superimposition were due to the fact that during growth both N and S move superiory at the same amount relative to the face and cribriform plate. Even though there are slight growth changes taking place, Steuer[23] found that it is acceptable to use cranial surface of sphenoid bone for superimposition. In a longitudinal study with cephalometric x-rays, the methods of superimposition and reproducibility of the head position are very important to assure validity of the study. It is generally accepted that the problem of cephalograph superimposition is partly complicated by the continuing growth of the anatomical landmarks. Therefore, it is impossible to have stable fixed anatomical reference points. Björk[24] has solved this problem by placing metallic implants in the maxilla and mandible to serve as reference points. The stability of these implants was of great concern. There are many factors involving implant stability, such as the technic of placing the implants into the bones in the most favorable position, which should not be in the eruption path of the teeth or in the resorptive area of the bone. Morris[25] studied tissue reaction to implants histologically which showed macrophage and osteoblastic activity, degradation of adjacent cells, and the formation of a collagenous capsule around the vitalum implants.

It is very important to have a high level of reproducibility of head position in implant studies. Even when the head is mounted on the ear posts of the cephalometer, movement still occurs in varying degrees.[26] There have been various kinds of methods developed for repositioning the head accurately for reproducibility purposes. Björk[27] used a built-in 5-inch image intensifier which enables the position of the head to be monitored by television accurately. The disadvantages of this method are that it is costly and complicated. Kaaber[28] used metallic implants and oblique 45^{o} projection in his study of 15 partially edentulous individuals. The head was stabilized and repositioned by a modified Ewald cephalostat, with adjustable stabilized nose and neck rests which were engraved with millimeter scales in order to enable a reproducible position of the head. He also used individual acrylic ear plugs and bite plates as supplimentary stabilizing equipment. The error from his method ranged between 0.10 and 0.33 mm.

The abberations in cephalometric technic due to distortion (reproduction of a three-dimensional object on a two-dimensional plane) and magnification (result of central projection) have been of great concern among investigators. Broadbent[1] developed a technic using frontal and lateral cephalograms exposed by two x-ray machines. He was able to determine the craniofacial landmarks accurately. Savara[29] developed a method used by Schwartz[30] for three-dimensional correction of landmarks located on frontal and lateral cephalograms. Coordinates are corrected for magnification and distortion by transformation formular obtained from computer program. He placed 1 mm. steel balls in five locations of the mandible, and found the fifference between actual and calculated distances ranged from -0.01 to +0.03 cm. The analysis of the errors in three-dimensional cephalometric measurements in maxilla[31] and mandible[32] showed various sources of errors. The most remarkable is the landmark location error which is about five times greater than the measurement error. Instead of using two films (frontal and lateral), Dahan[33] developed a technic using three roentgenograms taken perpendicular to each other (Norma frontalis, Norma lateralis, Norma basalis). He was able to locate landmarks accurately without distortion and magnification.

Baumrind and Frantz[34] also found that the great source of errors came from landmark identification, and the magnitude of errors varied greatly from landmark to landmark.

Sorenson and Hixon[35] introduced a new three-dimensional cephalometric technic using one lateral head film exposed by two x-ray machines angulated at 30°. This technic was investigated by Cruikshank and Nixon.[36] They placed three mandibular implants in a dry skull and calculated the distances of the markers placed between mandibular molar and cuspid teeth. The average error was 0.5 mm. between and within films. The method was re-investigated and improved by Quinio.[37] He used a plastic implant phantom with three fixed implants (A,B,C) forming a triangle which had one marker inside and another marker outside. Ten films were taken with different model positions, and taken twice at the same position. A programmable electronic desk calculator was used to calculate distances between implants. He found:

	BC (mm.)	BA (mm.)	AC (mm.)
Average calculated distance	51.272	49.651	42.177
Standard deviation	.278	.265	.08
True distance	51.5	49.75	42.3

He also found that the difference between the actual and the calculated marker movement was 0.38 mm. Dennis[38] continued the study using a computerized program for calculation. He found that at the 0.01 level of confidence the changes in landmark position between subsequent films which are greater than:

$\pm$ .2 mm. in the x axis
$\pm$ .4 mm. in the y axis
$\pm$ .5 mm. in the z axis

would represent a real change. Hodge[39] investigated the within-patient reliability of this method and examined the stability of the implants in facial bones. Acrylic templates with amalgam markers were formed to the maxillary and mandibular central incisor on each patient who had at least three maxillary and three mandibular metallic implants placed prior to this study. The results calculated for the standard error of the method were:

$\pm$ 0.255 mm. for maxilla
$\pm$ 0.222 mm. for mandible

Fiducial limits derived from these values were 0.78 mm. for the maxilla and 0.67 mm. for the mandible at 0.01 confidence level. Any movement which exceeds these limits would represent a real change. The standard errors of the estimate of linear distances between implants A, B, and C were:

	AB	BC	AC
Maxilla	0.137	0.066	0.146
Mandible	0.164	0.113	0.201

Standard error of the measure was ± 0.035 mm.

MATERIALS AND METHODS

A model system of tooth movement was set up on a dried human skull (Fig. 1). In the maxilla, three implants were placed (Fig. 2): 1) at the right side of the median suture inferior to the anterior nasal spine, about the level of root apex of the right maxillary central incisor, 2) superior to the disto-buccal root of the right maxillary first molar, and 3) superior and mesial to the mesio-lingual root of the right maxillary first molar.

In the mandible, three implants were placed (Fig. 3): 1) at the symphysis on the labial surface between the apices of the mandibular central incisors, 2) on the buccal surface inferior to the apex of the mesio-buccal root of the right mandibular first molar about the level of the mandibular foramen, and 3) inferior to the mesio-buccal root of the right mandibular second molar, inferior to the second implant.

These implants were placed with a special instrument (Fig. 4) (Björk[24,27]). The implants were hard tantalum pins with a diameter of 0.37 mm. and a length of 1.2 mm. (Björk[47]).

Bands with siamese brackets were put on the maxillary and mandibular right first molars, second premolars, and canines. The right first premolars were removed to make spaces for moving canines distally which imitated the real situation of closing the extraction spaces in orthodontic treatment. Sectional edgewise wires (.019 x .025) were placed in the brackets and fixed with cold-cure acrylic on the second premolars and molars. The canines were tied with ligature wire and ĀlastiKs. Canine bands were marked by placement of silver solder with a diameter of about 0.7 mm. at the disto-buccal near gingival edges (Fig. 5).

The first x-ray machine was set up so that the central ray was perpendicular to the film and exposed only 2/5 of the 10 x 12-inch film. The second machine was set so that the beams between the two machines were about 30 degrees apart. The focal spot to the film distance was 1609 mm. for the first x-ray machine, and the distance between the two x-ray machines which were parallel to the film was 807.52 mm. (Fig. 6). The origin of the Cartesian coordinate system was formed by the point where the central ray of the first emitter, which was set up to pass through the ear posts, struck the film. This central ray formed the "Z" axis. The "X" axis was formed by the line drawn on the film through the origin of the coordinate, parallel to the line joining the two focal spots of the x-ray machines. The line on the film, which is perpendicular to the "X" axis from the point of origin, formed the "Y" axis. The images of "X" and "Y" axes on the films were constructed by .016 round wire mounted perpendicular to each other in front of the cassette holder.

The skull was placed in the cephalometric head holder with fitted acrylic ear plugs. The first x-ray machine was set up at 100 kv., 5 Ma., and 1/30 sec. The second machine was set up at 100 kv., 42 Ma., and 3/20 sec. These two x-ray machines exposed the film simultaneously. Eight exposures were made when the maxillary and mandibular canines were initially at the starting positions and moving distally toward the extraction spaces one mm. as measured by a boley gauge for each exposure. Three sets of films were exposed: First set: eight exposures were taken for eight positions of canine movement (twice at the same position) with four different cassettes. Second set: eight exposures were taken for eight positions of canine movement (one for each position) with three different cassettes which excluded one cassette that was tested and found to be different from the other three cassettes. Third set: eight exposures for each position of canine movements were taken with one same cassette only.

Measurements were made directly on the films with a John Bull caliper. The images of the implants and markers on the canines were pin-pricked with a sharp pointed caliper (Fig. 7). Five measurements (Fig. 8) of each implant and marker were entered as the input (Fig. 9) for the computer program.[40] Each distance was measured to the nearest 1/100 mm. The output (Fig. 10) described: 1) the position of each implant and marker within the Cartesian Coordinate System, 2) the closeness of fit of the transformation of the triangular bases formed by implants "A," "B," and "C" of successive films taken from the same individual, and 3) the movements of the markers. The transformation of the triangular base was done by rotating around the geometric centers of each triangle until an optimal fit was obtained. Calculations which served as the basis for the computer program can be found in Hodge's study.[39]

FINDINGS

Sixteen x-ray cephalograms were taken from a model system of tooth movement which was performed at the right sides of the maxilla and mandible on a dried human skull. Three implants were placed in the maxilla and in the mandible to serve as reference bases. Canines were marked by radiopaque markers and moved one millimeter toward the extraction spaces after each exposure. The reliability of this method was checked. The errors of the system presented by movements obtained from measurements of eight exposures of canine movement. Two films were taken twice at the same position without any movement (Table VI). The standard error of the movement ($\sqrt{\frac{\Sigma D^2}{2N}}$) in the maxilla was 0.353 and in the mandible was 0.321. These errors included the errors of measurements, the errors of landmark location, and other technical errors either known or unknown.

The errors of the measurement were obtained by measuring 15 distances of three films twice (with a John Bull caliper) at different times.

$$\text{SEMeasure } \left(\sqrt{\frac{\Sigma D^2}{2N}}\right) = 0.033 \text{ (Table VII)}$$

The standard error of landmark location ($\sqrt{\frac{\Sigma D^2}{2N}}$) was found to be 0.298 (Table VIII). This error also included measurement error; therefore, the actual landmark location error should have been 0.265 (0.298 - 0.033 [SEMeasure]) which is approximately eight times the SEMeasure. These landmark location errors came from measurements of three films and their duplicates, which were pin-pricked with a sharp pointed caliper independently.

The standard error of the estimate of computed linear distances between implants (ΔAB, ΔBC, ΔAC) obtained from the films taken twice at the same position with different cassettes (Table I) were higher than those obtained from the films taken at each position with the same cassette and fixed implants (Table III). Therefore, confidence limits were set up from Table III which should be more reliable with fixed implants, and one same cassette used for every exposure. Any time the differences of the distance AB, BC, and AC exceeded these limits, implant movements should be suspected. Data obtained from films taken with different cassettes for each position of cuspid movement (Table II) showed that all differences of distances AB in the maxilla, except one, exceeded the confidence limit of Hodge's study (.41).[39] In this case, implant movements were suspected. When applied confidence limits obtained from Table III to Table II in the maxilla, a large proportion of data exceeded these limits.

Calculated movements of the canines in the maxilla and mandible were obtained from films taken with different cassettes (Table IV, Graph 2). Improved results were obtained when the films were taken with the same cassette (Table V, Graph 1).

Films taken with different cassettes showed: Standard error of the movement, $\sqrt{\frac{\Sigma D^2}{2N}}$ = 0.268 for the maxilla = 0.320 for the mandible. A correlation coefficient was computed between calculated and real movement and resulted in 0.992 for the maxilla = 0.994 for the mandible.

Films taken with the same cassettes showed: Standard error of the movement, $\sqrt{\frac{\Sigma D^2}{2N}}$ = 0.203 for the maxilla = 0.269 for the mandible. Correlation coefficient, r = 0.999 for the maxilla = 0.999 for the mandible.

DISCUSSION

The reliability of the cephalometric radiography in longitudinal research has been improved by the use of metallic implants as reference points instead of anatomical landmarks. The application of three-dimensional cephalometric technics has minimized the problem of magnification and distortion. The errors due to head repositioning were also minimized by the use of several methods.

The method used in this study has some advantages in that: 1) it is an uncomplicated set up and easy to operate, 2) the magnification and distortion of the images are minimized by three-dimensional projections obtained from two x-ray machines exposed on one film, and 3) the errors due to variation in head positioning are minimized by the transformation of the triangular bases which are formed by the metallic implants.

The errors of the method were investigated. Measurements obtained from the first set of films, taken twice at each position with different cassettes, showed remarkable errors in measurements four and five of six films (out of 16 films) both in the maxilla and the mandible (Tables IX, X). These errors were investigated by exposure of four films at the same skull position, with the four different cassettes used in the study. The same type of errors of measurements four and five were found in one cassette. This cassette was excluded from the study. A new set of films was taken with the three remaining cassettes to replace the ones with substantial errors. Data obtained from the replaced films showed remarkable minimizing of the errors (Table XI):

Measurement 4, standard error $\sqrt{\frac{\Sigma D^2}{2N}}$

in the maxilla reduced from 0.6943 to 0.1471
in the mandible reduced from 0.7041 to 0.1709

Measurement 5, standard error $\sqrt{\frac{\Sigma D^2}{2N}}$

in the maxilla reduced from 0.6689 to 0.1752
in the mandible reduced from 0.6758 to 0.1329

All measurements obtained from 16 films (eight positions exposed twice), after excluding the error cassette, were entered together for the computer program. The output described the error of the method (Table VI).

The second set of data from the output, which was derived from entering five measurements of each position of canine movement together with measurements of the starting position, described the canine movement in relation to the stable reference triangular base formed by the implants (Table IV, Graph 2). The standard error of the estimate of linear distances between implants A, B, and C from this set of data (Table II), when compared to Hodge's study,[39] found that in the maxilla, distance AB of every film except one exceeded his fiducial limit (0.41). The possible source of errors was either the implant movements or the variation between the different cassettes used. Since implant movement was impossible in a dried skull, the cassettes were strongly implicated.

The third set of the canine movement exposures was performed to minimize the errors found in the second set of data. Before the exposures, all implants in the maxilla and mandible were glued to the bone to obtain the stable fixed positions. Eight positions of the canine movements were exposed with one same cassette only. The output of data showed remarkable reducing of the differences of distances AB, BC, and AC in the maxilla (Table III). Comparing standard error of linear measurements of the second set of data to the third set showed:

$\sqrt{\frac{\Sigma D^2}{2N}}$ for ΔAB reduced from 0.530 to 0.049

$\sqrt{\frac{\Sigma D^2}{2N}}$ for ΔBC reduced from 0.139 to 0.029

$\sqrt{\frac{\Sigma D^2}{2N}}$ for ΔAC reduced from 0.137 to 0.043

The calculated movements of the canines were also improved (Table V, Graph 1) when compared to the second set of data: $\sqrt{\frac{\Sigma D^2}{2N}}$ standard error of the movement in the maxilla reduced from 0.268 to 0.203 and in the mandible reduced from 0.320 to 0.269.

The improvement could have come from the stable positions of the implants and also from the minimized variation of the cassettes.

SUMMARY

A model system study of tooth movement, by using the three-dimensional cephalometric and implant technics, was performed on a dried human skull. The reliability of the method was investigated. The basic errors such as the errors of measurements and landmark locations were presented. Another source of error which we were unaware of is the cassette-variation error, which was found to be remarkable in this study.

The calculated tooth movement was found to be correlated highly with the real tooth movement (0.999). The improvement of the results in the maxilla were found when using a single cassette for every exposure, compared to the results obtained from using different cassettes.

This improvement did not apply for the data obtained from the mandible which needs to be further investigated. It would be worthwhile to continue this study in human beings to investigate and improve the reliability and validity of the technic, which might be valuable for the longitudinal study of growth and orthodontic treatment changes.

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Fig. 1 The x-ray set up

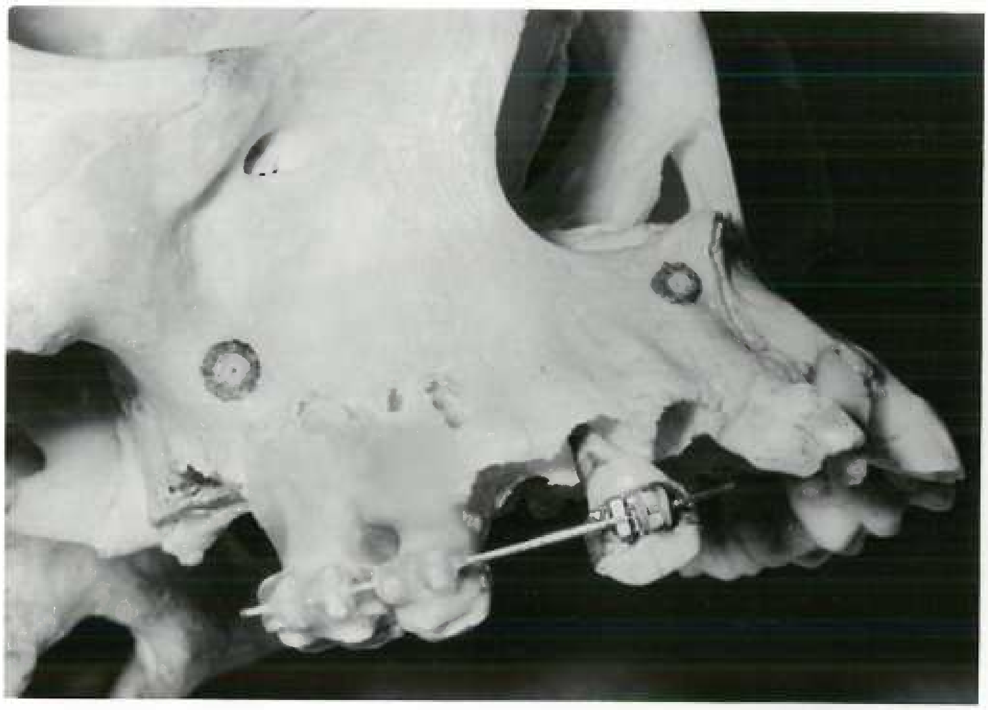


Fig. 2 a. The maxillary implants (lateral view)

Fig. 2 b. Maxillary implants (palatal view)

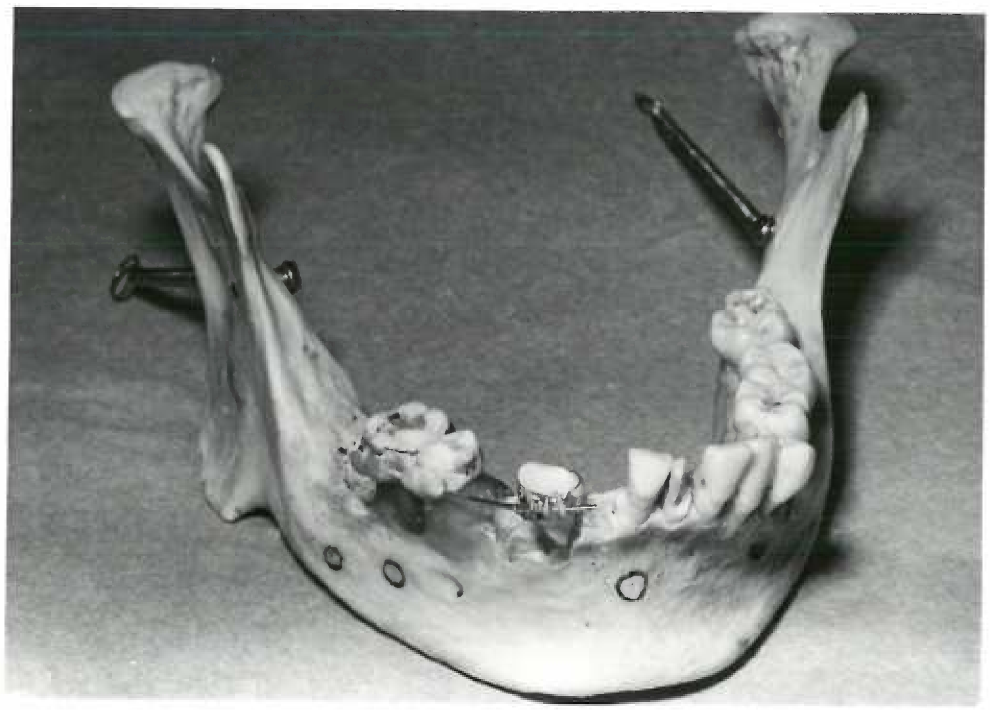


Fig. 3 The mandibular implants

Fig. 4 Björk instrument for the placement of tantalum implants

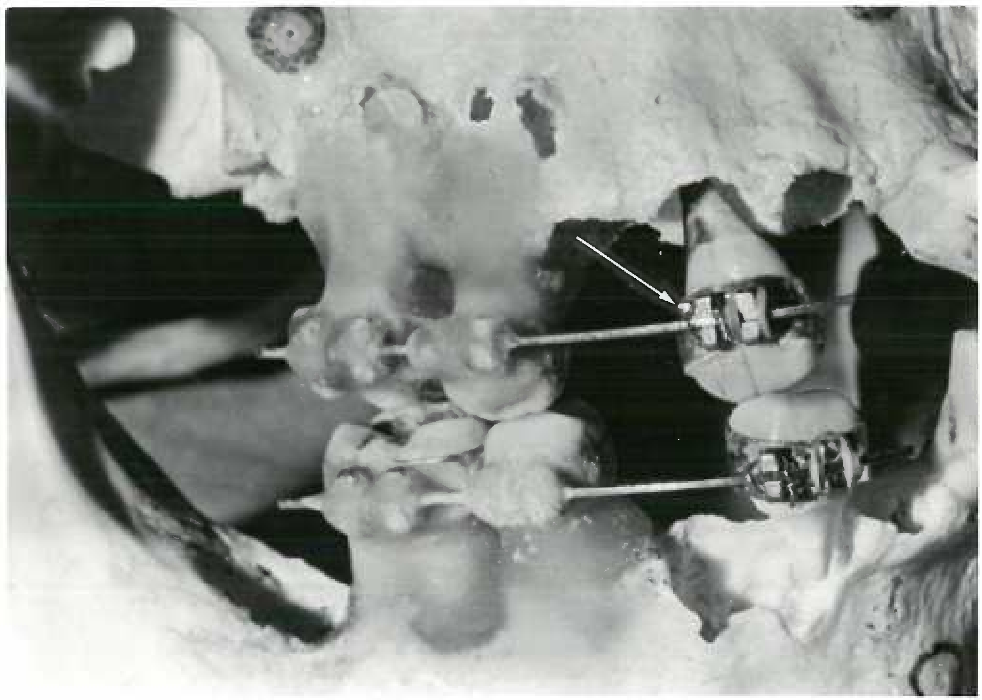


Fig. 5 The radiopaque marker on the canine band (at the arrow point)

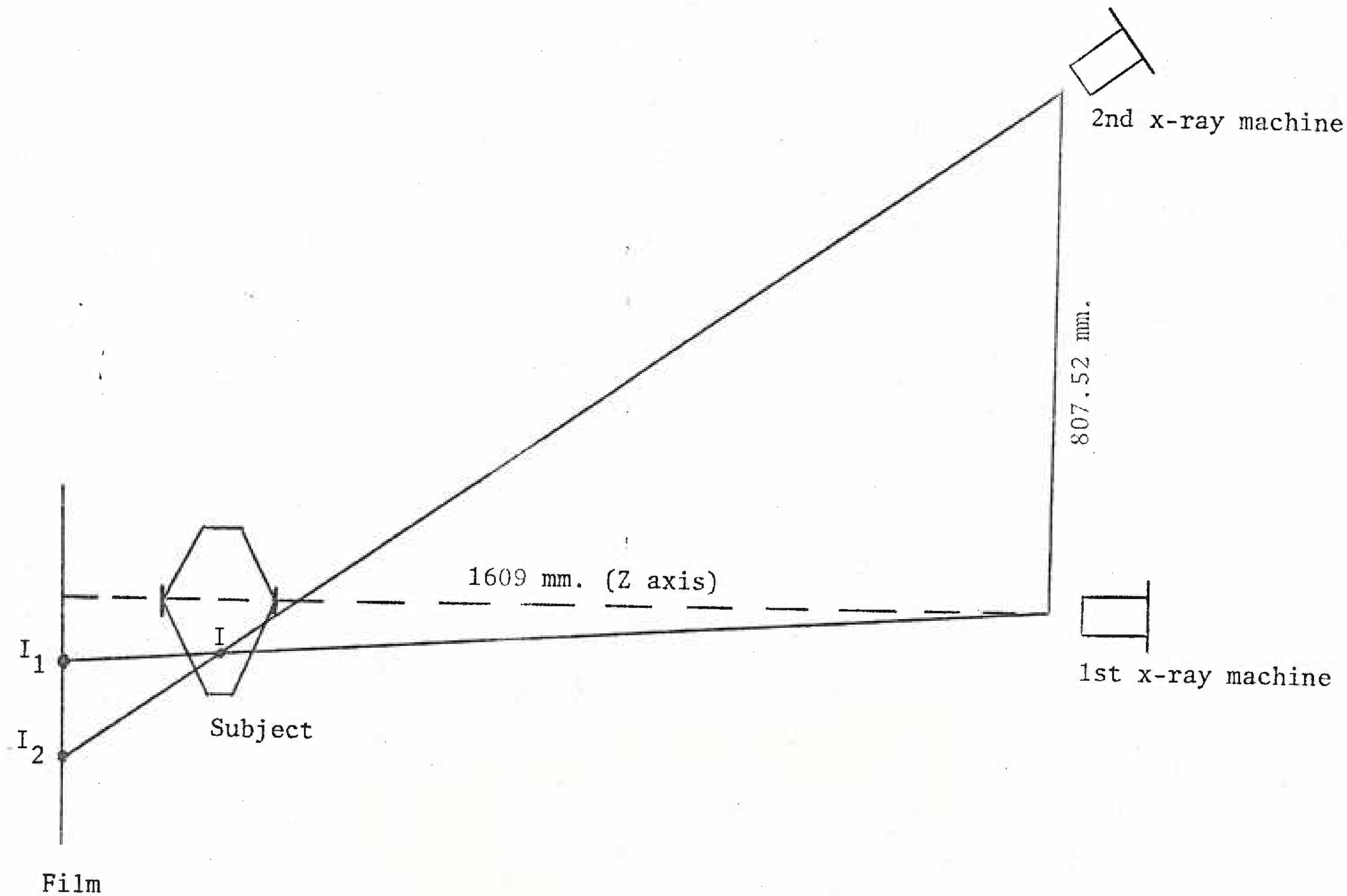


Fig. 6 Diagram of the three-dimensional cephalometric technic set up.

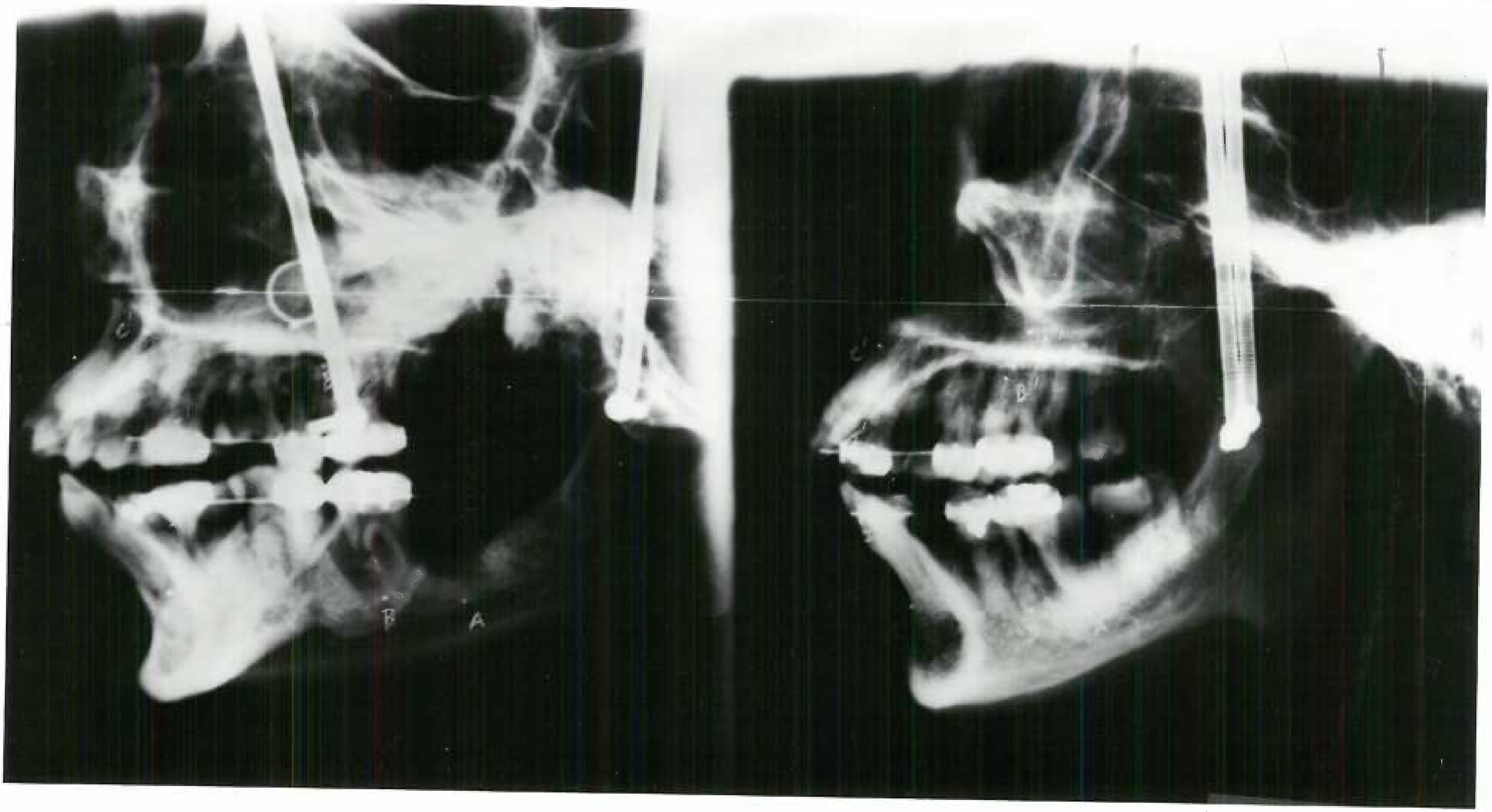


Fig. 7 Radiograph taken by the three dimensional cephalometric technic

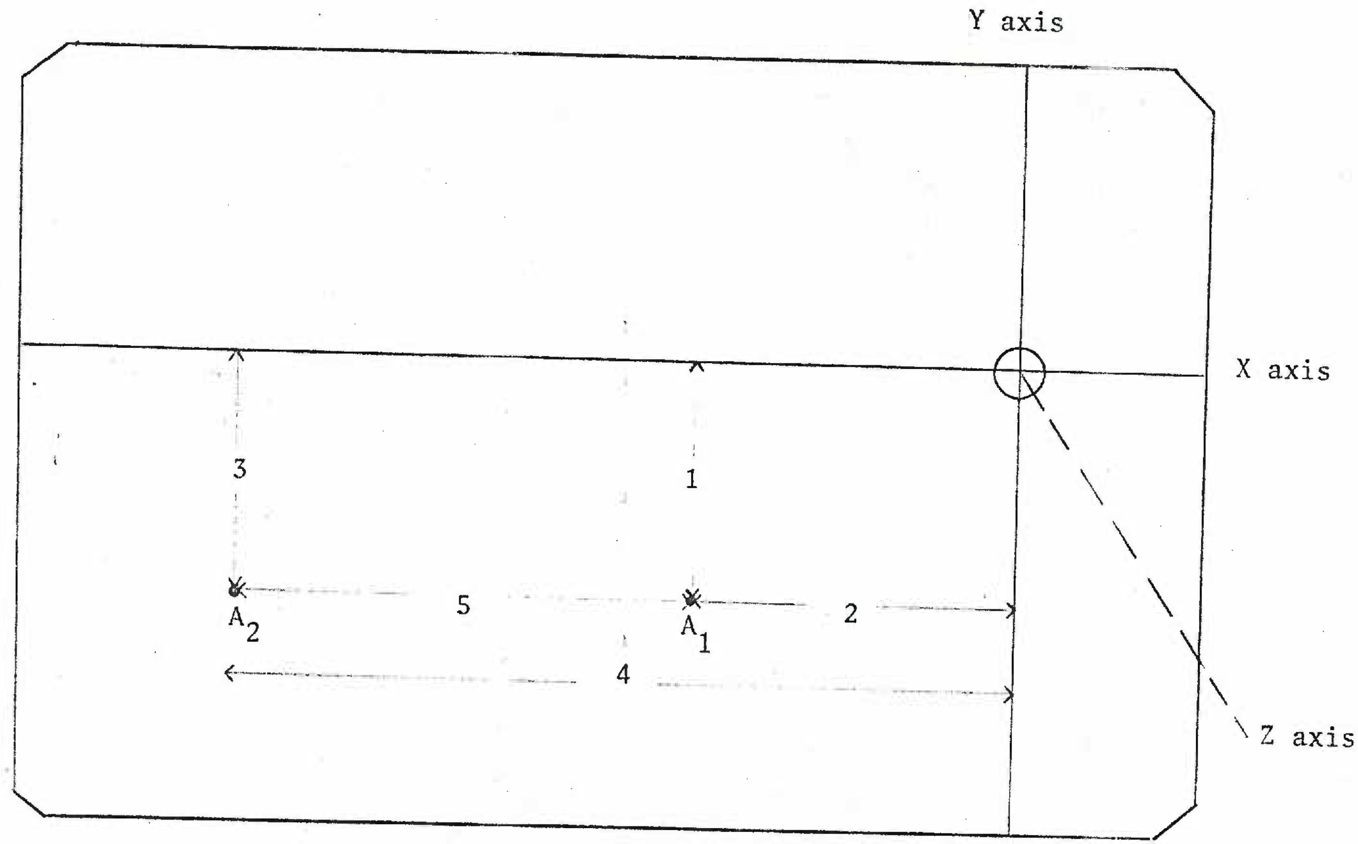


Fig. 8 Five measurements from the cephalograph of the dual images of each implant and marker.

Film number	Arch	Exposure number	1	2	3	4	5	
329	MAX	01	004.97	073.20	004.65	191.63	118.45	A
			013.41	077.50	013.11	204.29	126.70	B
			007.94	100.91	007.49	237.10	137.10	C
			026.33	101.99	026.01	227.29	125.29	I
030	MAX	01	002.98	073.50	002.71	192.03	118.58	A
			011.29	077.91	010.90	204.83	126.81	B
			005.07	101.25	004.79	237.30	136.10	C
			023.50	101.95	023.12	227.10	125.12	I

Fig. 9 Input sheet

3 D . DOUBLE FILM CEPHALAMETRICS

UNCORRECTED

FIRST MEASUREMENT	329MAXO	1			SECOND MEASUREMENT		030MAXO	1
CORD	A	B	C	I	A	B	C	I
X	63.840	66.990	86.360	88.290	64.090	67.340	86.650	88.270
Y	4.190	11.460	6.600	22.650	2.480	9.590	4.220	20.180
Z	205.820	218.200	232.050	216.110	206.030	218.360	232.090	215.860

CORRECTED

CORD	A	B	C	I	A	B	C	I
X	63.840	66.990	86.360	88.290	63.888	66.963	86.339	87.686
Y	4.190	11.460	6.600	22.650	4.208	11.466	6.575	22.452
Z	205.820	218.200	232.050	216.110	205.892	218.181	231.997	215.660

ERROR IN A	=	0.089
ERROR IN B	=	0.034
ERROR IN C	=	0.062
RMS ERROR	=	0.065
MOVEMENT	=	0.779
DELTA X	=	-0.604
DELTA Y	=	-0.198
DELTA Z	=	-0.450

FIRST MEASUREMENT

DIST AB = 14.698
DIST BC = 24.303
DIST AC = 34.655

SECOND MEASUREMENT

DIST AB = 14.599
DIST BC = 24.295
DIST AC = 34.512

Fig. 10 Output sheet

TABLE I. STANDARD ERROR OF THE ESTIMATE OF LINEAR DISTANCES BETWEEN IMPLANTS A, B, AND C (1st Set)

(Δ = Difference between original and successive films)

	MAXILLA			MANDIBLE		
No.	ΔAB	ΔBC	ΔAC	ΔAB	ΔBC	ΔAC
029	-0.353	-0.171	-0.054	-0.084	0.111	0.028
030	-0.130	-0.050	-0.169	0.011	-0.012	-0.001
031	-0.027	0.183	0.183	0.105	-0.030	0.151
032	-0.429	0.043	-0.468	-0.195	-0.118	-0.293
033	-0.173	0.169	0.023	0.113	0.030	0.079
034	-0.919	0.520	-0.103	-0.183	0.304	0.080
035	0.039	-0.005	0.027	-0.114	-0.040	-0.156
036	0.259	0.017	0.285	-0.052	0.431	0.354
Standard Error $\sqrt{\frac{\Sigma D^2}{2N}}$ =	0.2816	0.1513	0.1514	0.0859	0.1387	0.1310

TABLE II. STANDARD ERROR OF THE ESTIMATE OF LINEAR DISTANCES BETWEEN IMPLANTS A, B, AND C (2nd Set)

(Δ = difference between original and successive films)

	MAXILLA			MANDIBLE		
No.	ΔAB	ΔBC	ΔAC	ΔAB	ΔBC	ΔAC
030	-0.744	0.126	-0.088	0.037	-0.005	0.097
031	-0.796	0.008	-0.145	-0.042	0.045	-0.025
032	-0.619	-0.055	-0.092	0.065	0.169	0.214
033	-0.781	-0.044	-0.288	-0.097	0.009	-0.069
034	-0.341	-0.465	-0.235	0.173	-0.015	0.188
035	-0.913	0.156	-0.120	0.059	0.190	0.250
036	-0.897	0.095	-0.270	-0.027	-0.141	-0.175
$\sqrt{\frac{\Sigma D^2}{2N}}$ =	0.5301	0.1389	0.1369	0.0603	0.0787	0.1162
Confidence limit from data of Hodge						
α .01	.41	.20	.44	.49	.34	.60

TABLE III. STANDARD ERROR OF THE ESTIMATE OF LINEAR DISTANCES BETWEEN IMPLANTS A, B. AND C (3rd Set)

(Δ = Difference between original and successive films)

	MAXILLA			MANDIBLE		
No.	ΔAB	ΔBC	ΔAC	ΔAB	ΔBC	ΔAC
330	0.099	0.008	0.143	0.050	0.160	0.088
331	0.042	0.060	0.032	0.099	0.140	0.185
332	0.053	0.005	0.002	0.074	0.458	0.274
333	0.039	0.018	0.016	0.074	0.336	0.216
334	0.080	0.069	0.054	0.060	0.355	0.260
335	0.070	0.034	0.036	0.245	0.106	0.344
336	0.081	0.043	0.021	0.168	0.246	0.010
Standard Error $\sqrt{\frac{\Sigma D^2}{2N}}$ =	0.0491	0.0290	0.0434	0.0906	0.2010	0.1580
Confidence Limit						
α .01	0.1974	0.1168	0.1732	0.3667	0.8100	0.6367
α .05	0.1259	0.0745	0.2866	0.2328	0.5165	0.4060

TABLE IV. CANINE MOVEMENT RELIABILITY (2nd Set)

	MAXILLA			MANDIBLE		
No.	Calculated Movement (mm.)	Real Movement (mm.)	Difference (mm.)	Calculated Movement (mm.)	Real Movement (mm.)	Difference (mm.)
030	0.893	1	0.107	0.994	1	0.006
031	1.621	2	0.379	2.212	2	-0.212
032	2.678	3	0.322	2.672	3	0.328
033	3.759	4	0.241	3.533	4	0.467
034	5.236	5	-0.236	4.814	5	0.186
035	5.470	6	0.530	5.197	6	0.803
036	6.408	7	0.592	6.378	7	0.622

Maxilla: Standard error of the canine movement, $\sqrt{\frac{\sum D^2}{2N}}$ = 0.2677

Correlation coefficient between calculated and real movement, r = 0.9919

Mandible: Standard error of the canine movement, $\sqrt{\frac{\sum D^2}{2N}}$ = 0.3203

Correlation coefficient between calculated and real movement, r = 0.9941

TABLE V. CANINE MOVEMENT RELIABILITY (3rd Set)

	MAXILLA			MANDIBLE		
No.	Calculated Movement (mm.)	Real Movement (mm.)	Difference (mm.)	Calculated Movement (mm.)	Real Movement (mm.)	Difference (mm.)
330	0.779	1	0.221	1.024	1	-0.024
331	2.011	2	-0.011	1.865	2	0.135
332	2.783	3	-0.217	2.591	3	0.409
333	3.705	4	0.295	3.673	4	0.327
334	4.651	5	0.349	4.564	5	0.436
335	5.562	6	0.438	5.572	6	0.428
336	6.719	7	0.281	6.414	7	0.586

Maxilla: Standard error of the canine movement, $\sqrt{\frac{\Sigma D^2}{2N}} = 0.2028$

Correlation coefficient between calculated and real movement, r = 0.9987

Mandible: Standard error of the canine movement $\sqrt{\frac{\Sigma D^2}{2N}} = 0.2685$

Correlation coefficient between calculated and real movement, r = 0.9990

TABLE VI. RELIABILITY OF THE METHOD (1st Set)

	MAXILLA				MANDIBLE			
No.	Calculated Movement (mm.)	ΔX	ΔY	ΔZ	Calculated Movement (mm.)	ΔX	ΔY	ΔZ
029	0.381	0.483	0.593	0.442	0.341	0.073	0.084	0.022
030	0.696	0.270	0.407	0.495	0.096	0.041	0.084	0.022
031	0.335	0.092	0.207	0.246	0.837	0.541	0.431	0.471
032	0.486	0.067	0.200	0.438	0.471	0.242	0.367	0.170
033	0.407	0.177	0.167	0.327	0.296	0.172	0.197	0.137
034	0.867	0.511	0.541	0.446	0.539	0.311	0.409	0.160
035	0.177	0.049	0.129	0.111	0.261	0.130	0.214	0.075
036	0.268	0.191	0.120	0.145	0.395	0.168	0.281	0.221
$\sqrt{\frac{\Sigma D^2}{2N}}$	0.3534	0.2016	0.2438	0.2539	0.3211	0.1819	0.2113	0.1665

TABLE VII. WITHIN FILM RELIABILITY

No.	Distance Measured	First Measurement	Second Measurement	Difference
1	022 MAX-1	5.29	5.33	0.04
2	022 MAX-2	73.93	73.84	0.09
3	022 MAX-3	4.75	4.79	0.04
4	022 MAX-4	192.60	192.62	0.02
5	022 MAX-5	118.63	118.71	0.08
6	023 MAX-1	13.69	13.62	0.07
7	023 MAX-2	78.10	78.10	0.00
8	023 MAX-3	13.31	13.31	0.00
9	023 MAX-4	205.26	205.23	0.03
10	023 MAX-5	127.05	127.02	0.03
11	024 MAX-1	8.19	8.18	0.01
12	024 MAX-2	101.45	101.49	0.04
13	024 MAX-3	7.66	7.74	0.08
14	024 MAX-4	237.91	237.93	0.02
15	024 MAX-5	136.40	136.39	0.01

Standard error of the measure, $\sqrt{\frac{\Sigma D^2}{2N}} = 0.0333$

TABLE VIII. RELIABILITY OF LANDMARK LOCATION

No.	Distance Measured	Original	Duplicate	Difference
1	022 MAX-1	5.29	5.21	0.08
2	022 MAX-2	73.93	74.13	0.20
3	022 MAX-3	4.75	4.80	0.05
4	022 MAX-4	192.60	193.34	0.74
5	022 MAX-5	118.63	119.12	0.49
6	023 MAX-1	13.69	13.79	0.10
7	023 MAX-2	78.10	78.43	0.33
8	023 MAX-3	13.31	13.30	0.01
9	023 MAX-4	205.26	205.99	0.73
10	023 MAX-5	127.05	127.49	0.44
11	024 MAX-1	8.19	8.20	0.01
12	024 MAX-2	101.45	101.80	0.35
13	024 MAX-3	7.66	7.61	0.05
14	024 MAX-4	237.91	238.70	0.79
15	024 MAX-5	136.40	136.89	0.49

Landmark location error, (including measurement error) $\sqrt{\frac{\Sigma D^2}{2N}} = 0.2984$

Landmark location error, (excluding measurement error) $\sqrt{\frac{\Sigma D^2}{2N}} = 0.2984 - 0.0333 = 0.2651$

TABLE IX. STANDARD ERRORS OF CASSETTE VARIATIONS
(for maxilla)

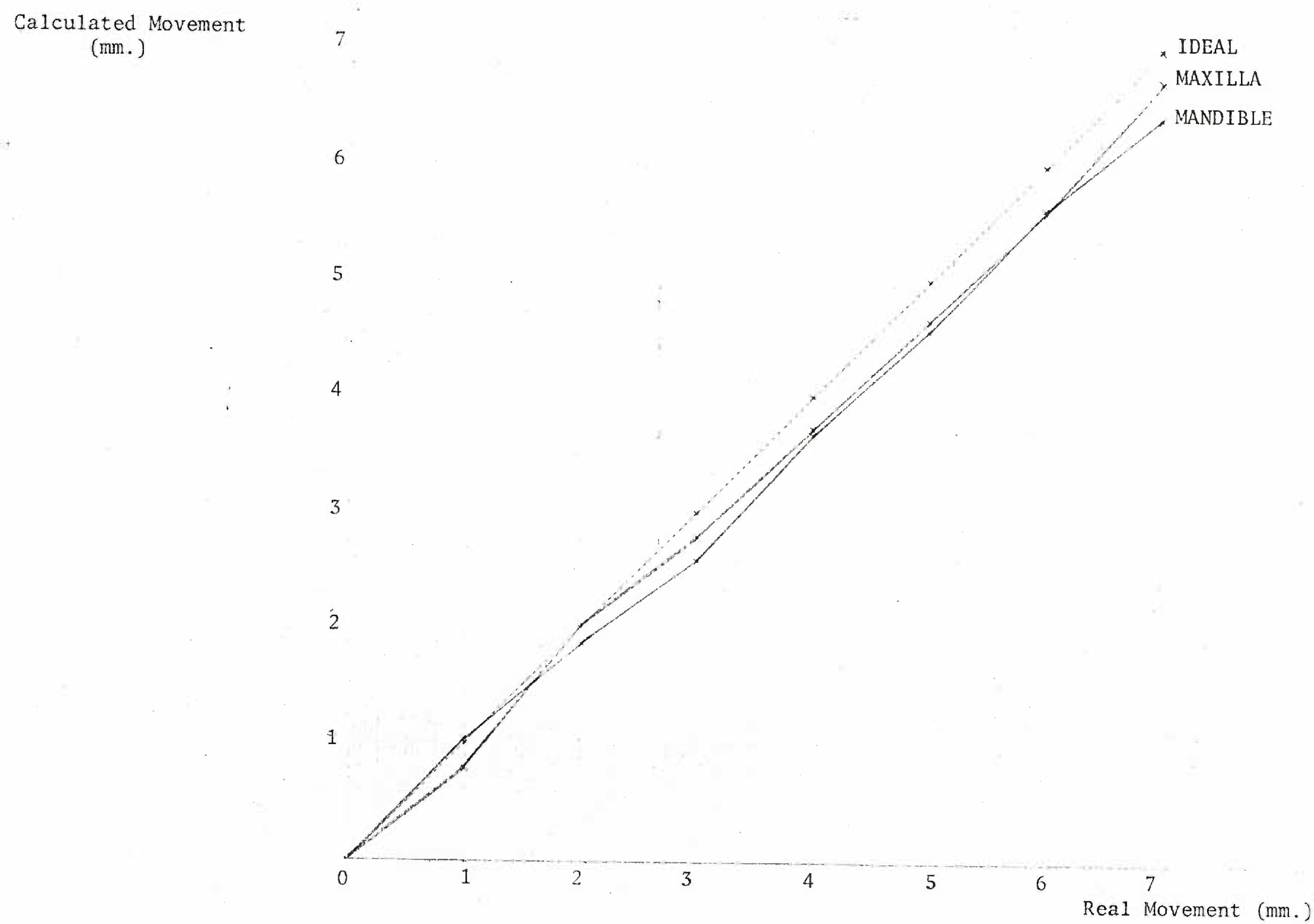
	Measurements				
Film	1	2	3	4	5
31-1	3.53	74.91	3.11	194.09	118.76
	11.86	79.21	11.39	206.59	127.28
	5.56	102.40	5.17	239.18	136.71
	24.26	102.58	23.72	227.81	125.30
31-2	3.79	74.99	3.31	194.92	120.00
	12.13	79.34	11.53	207.59	128.12
	5.87	102.51	5.22	240.02	137.59
	24.46	102.59	23.80	228.69	126.20
33-1	5.30	74.70	4.81	194.69	119.78
	13.78	78.72	13.09	206.95	127.99
	8.00	102.19	7.39	239.82	137.50
	26.59	99.82	25.70	225.32	125.28
33-2	5.32	74.80	4.87	193.67	118.78
	13.71	78.79	13.50	206.02	127.10
	7.91	102.11	7.50	238.95	136.67
	26.50	99.74	25.97	224.22	124.29
35-1	5.42	74.85	4.89	194.69	119.80
	13.91	78.78	13.33	207.13	128.12
	8.18	102.22	7.39	239.81	137.41
	26.72	97.84	26.10	222.50	124.51
35-2	5.50	74.63	4.93	193.59	118.71
	13.98	78.80	13.40	205.99	127.08
	8.28	102.11	7.60	238.79	136.72
	26.78	97.81	26.28	221.51	123.67
$\sqrt{\frac{\Sigma D^2}{2N}}$	0.1160	0.0721	0.1080	0.6943	0.6689

TABLE X. STANDARD ERRORS OF CASSETTE VARIATIONS (for mandible)

	Measurements				
Films	1	2	3	4	5
31-1	54.69 54.03 53.20 37.01	64.60 74.92 96.89 98.86	54.12 53.69 52.77 36.53	180.87 195.69 235.30 227.41	116.05 120.59 138.38 128.32
31-2	54.92 54.34 53.46 37.38	64.56 75.11 97.00 98.99	54.62 53.99 52.84 36.88	181.98 196.70 236.46 228.09	117.27 121.68 139.20 128.89
33-1	56.17 55.81 55.40 39.28	63.09 73.55 95.61 96.32	55.63 55.41 54.85 38.61	180.39 195.27 234.63 224.59	117.12 121.52 139.01 128.08
33-2	56.16 55.89 55.51 39.29	63.00 73.49 95.47 96.15	55.82 55.33 54.92 38.72	180.78 194.11 233.82 223.49	115.99 120.51 138.17 127.30
35-1	56.39 56.15 55.71 39.44	63.08 73.47 95.50 94.49	55.75 55.50 55.08 38.55	180.32 195.13 234.68 220.10	117.21 121.60 139.15 127.44
35-2	56.33 56.08 55.59 39.47	62.90 73.37 95.30 94.38	55.88 55.59 55.19 38.85	179.08 193.91 233.79 220.91	116.10 120.50 138.41 126.61
$\sqrt{\frac{\Sigma D^2}{2N}}$	0.1284	0.0960	0.1650	0.7041	0.6758

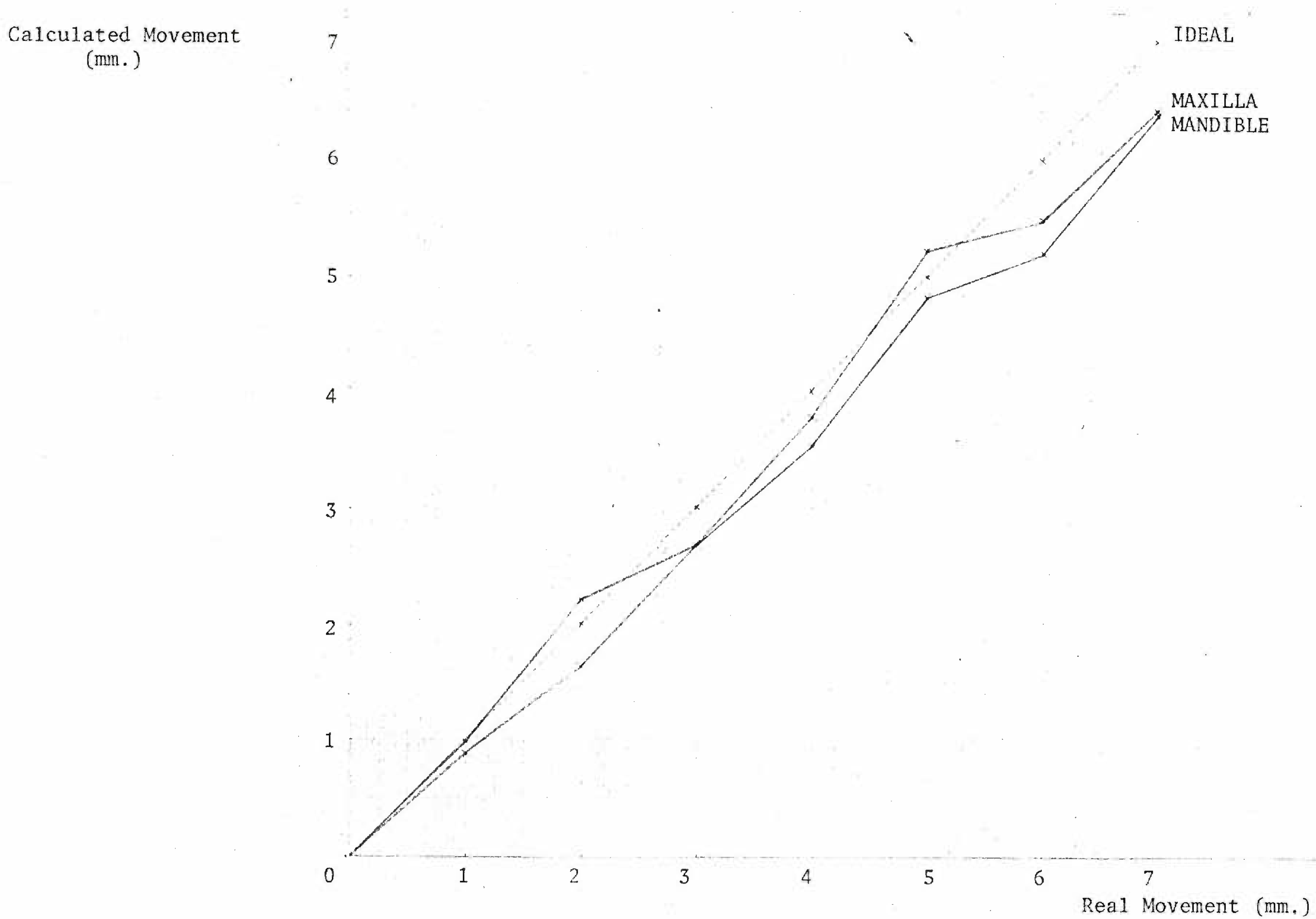
TABLE XI. IMPROVED STANDARD ERRORS OF CASSETTE VARIATIONS (excluding the error cassette)

Film	MAXILLA 4	MAXILLA 5	MANDIBLE 4	MANDIBLE 5
	MEASUREMENTS			
38-1	193.66	118.97	179.61	116.11
	206.09	127.30	194.70	120.67
	238.87	136.94	234.60	138.59
	227.08	125.50	226.58	128.46
38-2	193.59	118.83	179.70	116.23
	206.09	127.20	194.66	120.57
	238.73	136.60	234.50	138.50
	227.05	125.20	226.35	128.23
39-1	191.60	118.55	175.89	115.86
	203.91	126.79	190.92	120.25
	237.08	136.32	230.80	138.03
	221.38	123.90	220.71	126.88
39-2	191.33	118.23	175.69	115.70
	203.72	126.62	190.48	120.03
	236.70	136.10	230.50	137.80
	221.09	123.59	220.43	126.72
40-1	193.66	119.01	179.61	116.39
	206.13	127.42	194.53	120.80
	238.93	136.98	234.49	138.62
	221.91	124.10	221.58	127.00
40-2	193.40	118.81	179.62	116.20
	206.02	127.22	194.39	120.64
	238.79	136.72	234.24	138.47
	221.67	123.82	221.20	126.68
$\sqrt{\frac{\Sigma D^2}{2N}}$	0.1471	0.1752	0.1709	0.1329



GRAPH 1. CANINE MOVEMENT IN MAXILLA AND MANDIBLE

(From 3rd Set of data of films from one same cassette.)



GRAPH 2. CANINE MOVEMENT IN MAXILLA AND MANDIBLE

(From 2nd Set of data of films from different cassettes.)