THE WITHIN-PATIENT RELIABILITY OF A THREE-DIMENSIONAL CEPHALOMETRIC IMPLANT TECHNIQUE

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 1973

ACKNOWLEDGMENT

I wish to give credit to:

Dr. F.M. Sorenson and Dr. E.H. Hixon whose ideas founded the basis for the three-dimensional cephalometric implant technique.

Drs. M.I. Nixon, D.L. Cruikshank, C.E. Quinio, and H.S. Dennis for their prior work in the development of the method.

Additionally, I wish to thank:

Dr. D.L. Buck for his advice during the formulation and writing of this paper.

Mrs. Roberta Beckman for her assistance in the composition and typing of the text.

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INTRODUCTION

Cephalometrics means simply "measurement of the head," and since the nineteenth century, anthropologists have used the craniostat to make measurements on dried skulls. The desire to make these same determinations in the living patient stimulated the development of cephalometric radiology.

As early as 1896, Welcker suggested the use of lateral head x-rays for anthropological investigation.[1] The publications of Broadbent[2] and Hofrath in 1931,[3] provided standardization for the cephalometric technique that is currently employed essentially unchanged, in the study of facial growth and in orthodontic diagnosis and treatment evaluation.[4] This method has proven satisfactory for the orthodontic clinician in describing his patient's facial proportions and gross changes due to growth or treatment. It has also been useful in describing average facial changes in cross-sectional studies, since many of the random sources of error inherent in the system are cancelled out in the pooling of the data.

However, longitudinal studies of growth or treatment changes require greater reliability to describe incremental changes. The greater the error in relation to the change described, the less meaningful is the information. For example, if the error involved in measuring facial height from a cephalometric film is ±.5 mm. and in fact a 1 mm. increment of growth has occurred, one could conclude that either 0 or up to 2 mm. of growth had occurred, since error occurs in measuring both the initial and final film.[5] It should be noted that if measurement error in taking longitudinal data is so great that only trends of central tendency can be described, the advantage of having taken a longitudinal sample is lost.

Thus, there have been attempts to increase the reliability of the cephalometric technique by investigating the following problems:

1. Lack of sharpness of the radiographic image is related to movement of the subject or x-ray source, graininess caused by the film or intensifying screen, exposure time, secondary radiation, size of

the effective focal spot, and distances from the x-ray source to the object and to the film.

2. Enlargement of the radiographic image is due to x-radiation being released in random directions from a point source.

3. Two-dimensional representation of a three-dimensional object not only causes distortion of the image but also prevents one from relating any changes to the three-dimensions of space.

4. Accuracy of head repositioning of the growing patient is critical to most cephalometric techniques to allow superimpositioning of successive radiographs.

5. A stable reference is required for superimpositioning which will allow one to relate changes to that base.

Sorenson, Hixon and co-workers[6,7,8,9] combined the placement of implants in the jaws, as described in 1955 by Bjork,[10] with the concept of triangulation from a three-dimensional cephalometric technique, as presented by Schwarz[11] in 1943. It is hoped that this technique will provide sufficient reliability to allow assessments of spatial changes of the skull and teeth suitable for use in longitudinal studies. Although the reliability of the above technique has already been investigated in vitro by Dennis,[9] it is the purpose of this paper to establish the within-patient reliability. It is also intended to examine implant stability within the facial bones of the changing child.

REVIEW OF THE LITERATURE

The use of conventional cephalometric technique, as introduced by Broadbent,[2] has become a valuable tool in orthodontic research. However, many investigations have been limited by the inaccuracies of the method. Consequently, various authors have examined the reliability of standard cephalometric technique.

Potter and Meredith[12] found that measurement error was limited to ± 0.3 mm. and ± 0.5 mm. for bigonial and biparietal dimensions when measured from one frontal head film by two independent observers. Certainly these are relatively easy landmarks to locate.

Hixon[13] traced three lateral headfilms twice, and eight other independent investigators made one tracing per film. Ranges of disagreement were produced between measurements from a Downs[14] analysis. The ten determinations of mandibular plane from one film varied 14.2°, while the disagreement for facial angle on another film was only 1°.

Broadway, Healy, and Poyton[15] showed similar variation in the reliability of seven cephalometric angles. Forty lateral headfilms were traced twice by one investigator and once by another. The standard deviation of the difference between successive estimates of the same angle ranged from 1.05° (SNB) to 3.14° (I-SN) for double determinations within one tracer and 1.44° (SNB) to 5.54° (I-SN) between two independent tracers.

Bjork[16] found that the standard error ranged from 0.27 mm. to 2.84 mm. for 73 linear measurements, and from 0.26° to 2.43° for 55 angular measurements.

Hatton and Grainger[17] computed error variances involved in radiographic and tracing techniques using duplicate head films and duplicate tracings from 15 three-year-old children. They found that error variance contributed by the radiographic technique did not exceed the variance due to tracing errors whose largest component was felt to be landmark location.

Other authors[18,19,20] have also found, that of the component errors in the cephalometric method, landmark location is by far the largest source; while the measurement error and various geometric and technical radiographic errors were relatively small.

Baumrind and Frantz[21] graphically portrayed the distribution error for 16 common landmarks using their automatic coordinate-localizing procedure. They demonstrated that the distribution of variance in landmark location is not random, but dependent upon the point being located. For instance, pogonion is much more reliable in the horizontal direction (standard deviation in horizontal = .59 mm.) than the vertical (standard deviation in vertical = 1.32 mm.). Therefore, pogonion is obviously more useful in determining facial plane than, for example, mandibular plane.

Improvements in the equipment and material plus modifications in technique have improved the quality of standard cephalometric films while reducing the radiation hazards to the patient. X-ray machines capable of producing higher kilovoltage and milliamperage have allowed increased focal spot to film distance thus minimizing enlargement and penumbra. Optical blurring can be further reduced without fear of burnout by using the smaller effective focal spot provided by a rotating anode. Fogging due to secondary radiation has also been minimized by the use of higher kilovoltage, filtration of lower energy waves, and collimation. Remaining scatter from secondary radiation is further filtered by grids. Intensifying screens contribute more to graininess than high speed films,[22] yet both are necessary to reduce the radiation to the patient through decreased exposure time. A shorter exposure also minimizes blurring due to movement. Franklin[23] recommended a fixed x-ray head and cephalostat to counteract lack of sharpness due to movement. He also suggested placing the subject as close to the film as possible to reduce penumbra and enlargement. Enlargement of an object when projected as a radiographic image is described by the following relationship:[24]

$$\frac{\text{object size}}{\text{image size}} = \frac{\text{focal spot - object distance}}{\text{focal spot - film distance}}$$

It has been computed that enlargement will be six or seven percent in the midsagittal plane if the tube-to-subject distance is five feet and the patient's head is one inch from the film.[4] Projection error has been largely neutralized by using angular rather than linear measurements.[25] However, if estimates of midsagittal dimensions are required, then enlargement must be corrected. This can be accomplished by measuring the magnification of an aluminum standard calibrated millimeter scale placed in the midsagittal plane as described by Pacini[26] and Broadbent,[2] or by measuring the distances between the focal spot, object, and film and using the formula shown above. The enlargement factor can be made constant by fixing the positions of the x-ray tube, midsagittal plane, and the film. Differential enlargement of bilateral landmarks is often handled by taking the mid-point and treating the object as being in the midsagittal plane.[27]

Broadbent[2] grossly corrected for distortion due to representation of a three-dimensional object on a two-dimensional film. By studying frontal and lateral headfilms side by side on a trans-illuminated drafting table, he was able to visualize the spatial relationships of the skull parts.

Schwartz, in 1943,[11] presented a method to correct for enlargement and distortion of distances between landmarks located on frontal and lateral cephalograms. The elaborate calculations required have been computer programmed by Savara[28] who reported measurement error of ± 0.3 mm. in determining distances between metal balls (1 mm. diameter) placed on a skull. Subsequent reliability studies have shown that landmark location error in the system is five times greater than that due to measurement error.[19,20] Dahan[29] added the norma basalis view in addition to norma frontalis and lateralis to eliminate magnification and distortion, and to relate the landmarks to the horizontal, sagittal, and frontal planes of the skull.

Early cephalometric investigators realized that the analysis of serial radiographs required an area of reference to superimpose successive tracings to assess changes due to growth or treatment. Although the Frankfort horizontal plane, as recognized at the Anthropological Congress in 1882,[30] has been retained in some cephalometric analyses, its poor reproducibility on the lateral head film has prompted a search for an alternate reference.

Broadbent[31] proposed the use of the "registration point" on the basis of the relative stability of the cranial base, while Brodie[32] used the still popular sella-nasion plane, with registration on sella. Since these works, numerous authors have devised countless methods for basicranial reference.

Although the relative stability of the cranial base is generally accepted, Bjork,[33] Ford,[34] Baume,[35] Bergerson,[36] and Steuer[37] all have noted that there are changes in nasion and the pituitary fossa that occur during growth.

Conventional methods for superimposing the maxilla and mandible have also been described.[38] But growth of separate bones involves periosteal apposition and resorption and so superimpositioning on the basis of external bony contours is inadequate according to Bjork.[10]

It is obvious that any apparent movement of a structure determined on the basis of superimpositioning will be distorted by growth or even treatment changes in the base of reference. Furthermore, any change in head repositioning will also affect the system. Stackler[39] showed that a five degree head rotation resulted in an apparent landmark change ranging from 0-4.5 mm. depending on the position of the landmark and the direction of movement. Steiner[40] demonstrated substantial movement of porion between two films even when the patient was left in the head holder.

Kaaber[41] was able to accurately reposition the heads of partially edentulous patients using an Evald cephalostat with strengthened vertical arms, adjustable stabilized chin, nose and neck rests, custom ear plugs, and an individualized maxillary acrylic base plate which held the lower jaw in centric relation and a reproducible vertical dimension. Although the standard error of the method ranged from .103 mm. to .241 mm., it should be noted that Kaaber made his duplicate exposures within two weeks on non-growing subjects.

The problem of superimpositioning was thought to be overcome by Bjork's[10] use of metallic implants which provided an easily located base of reference. This system allowed him to record growth increments within the limits of ± 0.5 mm.[42] Bjork noticed, however, that the implants occasionally altered their positions in the jaws. This was felt to be due to:

1. Placement of the implant in the path of an erupting tooth.
2. Placement of the implant on a bony surface undergoing resorption.
3. Shallow placement of the implant allowing periosteal drag.
4. An electrolytic effect which stimulates fibroblastic activity.

Morris[43] studied histologically the reaction to implants of tantalum and other metals and found that, after eight weeks, evidence of tissue irritation was shown by:

1. Macrophage activity.
2. Degradation of adjacent cells.
3. Osteoblastic activity.
4. The formation of a collegenous capsule.

Accurate head repositioning is as essential to the implant technique as it is in any system of superimpositioning. Therefore, Bjork[44] used an x-ray cephalostat with a built-in image intensifier allowing television monitoring to improve accurate head repositioning before the exposure is made.

Cruikshank and Nixon[7] set up a three-dimensional technique devised by Sorenson and Hixon[6] using two x-ray machines angulated and directed at a common film. By taking simultaneous exposures of a dried skull which had three mandibular implants, they were able to calculate the distances between markers attached to the lower left molar and cuspid teeth. They found between and within film error averaged 0.5 mm.

Quinio[8] recalibrated the above system and simplified the required computations by use of a programmable desk calculator. Quinio[8] and Dennis[9] took ten exposures on a plexiglass phantom with three metallic implants and two additional markers. The phantom was placed in differing positions between films. Dennis[9] further adapted the data in a manner to utilize a fully computerized program. From the output, he was able to establish confidence limits ($\alpha = .01$) such that computed movement greater than:

± .2 mm. in the "X" axis
± .4 mm. in the "Y" axis
± .5 mm. in the "Z" axis

would represent a real change.

MATERIALS AND METHODS

In order to study implant stability and the reliability of the three-dimensional cephalometric implant method, 16 orthodontic patients from the University of Oregon Dental School Department of Orthodontics were studied utilizing the technique described by Sorenson, Hixon, and co-workers.[6,7,8,9]

The method requires two x-ray heads capable of producing simultaneous exposures on a 10 x 12 inch film (Figs. 1 and 2). The first head is positioned so that its collimated beam would pass through the patient's face and expose no more than 2/5 of the film. Although the emission released from this head radiates in all directions, Quinio[8] located the point where the central ray formed a perpendicular with the plane of the film. This central ray was set up to pass through the ear posts of the head holder and the point where it strikes the film is defined as the origin for the Cartesian system of coordinates. The central ray becomes the "Z" axis. The distance along the central ray from the focal spot of the first head to the film was found to be 1609 mm. The focal spot of the second emitter was fixed at a distance from the focal spot of the first along a horizontal line parallel to the plane of the film so that the angulation between the beams in the region of the face is roughly 30 degrees. This tube shift distance was found to be 807.52 mm. The second head is collimated so that a simultaneous duplicate image of the structures exposed by the first head can be produced on the remaining 3/5 of the film. A line parallel to the line joining the focal spots of the first and second emitters and drawn on the plane of the film through the origin of the coordinate system forms the "X" axis. The "Y" axis is constructed as a perpendicular to the "X" axis through the origin and in the plane of the film. Perpendicular .016 diameter crosswires mounted directly in front of the film cassette were placed so that their radiographic image on the film would coincide with the "X" and "Y" axes.[8]

An example of a film taken on one of the subjects can be seen in Figure 3. The duplicate radiographic images of each implant and tooth marker allow measurements to be taken directly from a film (Fig. 4). Computations from these values describe the position of each implant and marker within the Cartesian coordinate system. Three implants placed within the maxilla or mandible thus form a fixed plane from which movement of a fourth radiopaque marker can be referenced between successive films. Since head position can never be exactly reproduced to the initial film, the triangular base of reference described by the three implants in the successive film must be made to coincide as closely as possible to the initial film. The transformation is accomplished by rotations about the geometric centers of each triangle until an optimal fit is obtained. These computations have been computerized so that the only input required on the initial film is the five measurements (Fig. 4) for the three implants (A, B, C) common to one bone and the radiopaque marker (I) whose movement is to be determined.[45] These same measurements are repeated from a successive film and entered together (Fig. 5). The output (Fig. 6) describes the two planes, the closeness of their fit, and the movement of the marker (I) (Appendix A).

At least three maxillary and three mandibular metallic implants had been placed in the 16 patients well prior to their initial radiographic exposure for this study (average: four years six months range: two years ten months to seven years six months). At the time the first film was taken, the average age of these patients was 16 years nine months with a range from 14 years eight months to 19 years 11 months. Acrylic templates were formed to a maxillary and mandibular central incisor on each patient. Amalgam was condensed into a $\frac{1}{2}$ mm. diameter cavity prepared with a No. $\frac{1}{2}$ round bur in the acrylic (Fig. 7). The markers were then cemented to the teeth and an initial exposure was made with the teeth separated slightly. The patient was then removed from the head holder and then replaced for the second exposure without unusual attention to head repositioning. Since there should be no implant or marker movement between these two films, any movement reported by the program would represent the error of method. Measurement error for calculated distances between implants can also be derived so that a confidence limit can be set up and their stability can be examined.

After recementation of the markers, a third radiograph was taken on the original patients after an average interval of 94 days (range 89 to 117 days). The primary purpose of this radiograph was to check for any implant movement which might have occurred following exposure of the initial films.

FINDINGS

In order to determine the reliability of the film measurements (Fig. 4), 16 random measurements from the original sample of 1740 were duplicated after an interval of at least two weeks. Points from which measurements were made had been already pinpricked. Thus the error variance involved in location of points along the "X" and "Y" axes, and the estimation of the geometric centers of the implants and markers on the film was not expressed. The duplicate measurements were taken with a John Bull dial point calipers as were the originals. The SEMeasure $(\sqrt{\Sigma d^2/2N})$[4] was found to be ± .035 mm. (Table I).

The standard error of the estimate of computed linear distances between the maxillary and mandibular implants A, B, and C was calculated from the two films taken on the same day (Table II). Fiducial limits ($\alpha = .01$) were then established for differences between the first and second computed estimates for each of the distances. In the cases where the difference exceeded this confidence limit, one could suspect implant movement.

The results of a test for implant stability between two films taken approximately three months apart is presented in Table III. Three patients showed differences in distances between implants which exceeded the established fiducial limits. The confidence limit was broken twice in the maxilla (N=13) and three times in the mandible (N=15).

Movement expressed between the two films taken on the same day represented the error of the system. From these values the standard error of the method (Table IV) was calculated for the maxilla (±.255 mm.) and mandible (±.222 mm.). The error in each of the coordinate components was also computed. From fiducial limits derived from the above standard errors, it can be said that any movement which exceeds .78 mm. in the maxilla and .67 mm. in the mandible represents a real change at the α =.01 confidence level.

DISCUSSION

Limitations of the three-dimensional cephalometric implant technique include:

1) Any structure to be examined for movement must be marked with a radiopaque material.

2) Radiopaque objects such as metallic dental restorations may obscure the images of the implants or markers.

3) Implant stability during the interval described is essential to this or any other system utilizing metallic implants as a reference base.

From the paired initial films, fiducial limits (at the $\alpha = .01$ level) were derived from the standard error of the estimate of distances between the base implants. This provided checks for either excessive error in the film measurements or implant movement which might have occurred during the time interval between film exposures.

Measurement error as a source can be tested by duplicating the film measurements. Any difference greater than the fiducial limit ($\alpha = .01$) of ± .10 mm. (Table I) should be considered excessive.

Once measurement error is eliminated as an error source, then implant movement is implicated. Instability of the metallic implants was suspected in three patients after a three-month interval (Table III).

It should be noted that implant instability might be obscured if any or all of the implants moved in such a way that the distances between each did not change between the initial and subsequent film exposures (Fig. 8). This undetected implant movement would not affect the goodness of fit of the reference bases, but would induce error into the calculated movement of the marker. It has been suggested that the use of four implants as the reference base would eliminate undetected implant movement.[9] While it would reduce the probability, it would still be possible for movement to occur without a change in distance between each implant. Therefore, great care should be taken in the placement of the implants.

It is recognized that a three-month interval is insufficient to adequately examine implant stability; therefore, in future studies, successive films could be taken at an interval of one year or more to re-examine this question. Also, since the implants had been inserted well prior to this study, short term stability has not been assessed nor is the quality of technique for implant placement known.

In order to prevent the obscuring of the implants and markers by radiopaque substances, objects such as earrings should be removed if possible prior to exposure of the film. Markers on the teeth should be placed on or above the incisal edge, and the occlusal plane should be oriented parallel to the "X" axis to avoid the superimposition of the radiographic image of the marker and dental restorations.

The advantages of the three-dimensional cephalometric implant technique are: (1) Marker movement can be related to a stable base established by the three metallic implants placed in the maxilla or mandible. (2) This movement can be described in three dimensions. (3) Error due to repositioning the head of the changing individual is minimized.

SUMMARY AND CONCLUSION

Sixteen previously implanted orthodontic patients from the University of Oregon Dental School Department of Orthodontics were studied using the three-dimensional cephalometric implant methods originated b Sorenson, Hixon, and co-workers.[6,7,8,9] Two films were taken on one visit to establish the reliability of the method, while another film was taken three months later to test implant stability. Implant movement was suspected in three patients, two of whom showed probable movement in both the maxillary and mandibular arch.

The within-patient reliability of the three-dimensional cephalometric implant method compared favorably with the values established in vitro for the same system by Dennis.[9] At the $\alpha = .01$ level of confidence, real movement of the marker is established if values exceed:

(1) In vitro[9]

± .19 in the "X" axis
± .39 in the "Y" axis
± .44 in the "Z" axis
± .62 total

(2) Within-patient

(a) Maxilla

±.43 in the "X" axis

±.22 in the "Y" axis

±.61 in the "Z" axis

±.78 total

(b) Mandible

±.32 in the "X" axis

±.21 in the "Y" axis

±.55 in the "Z" axis

±.67 total

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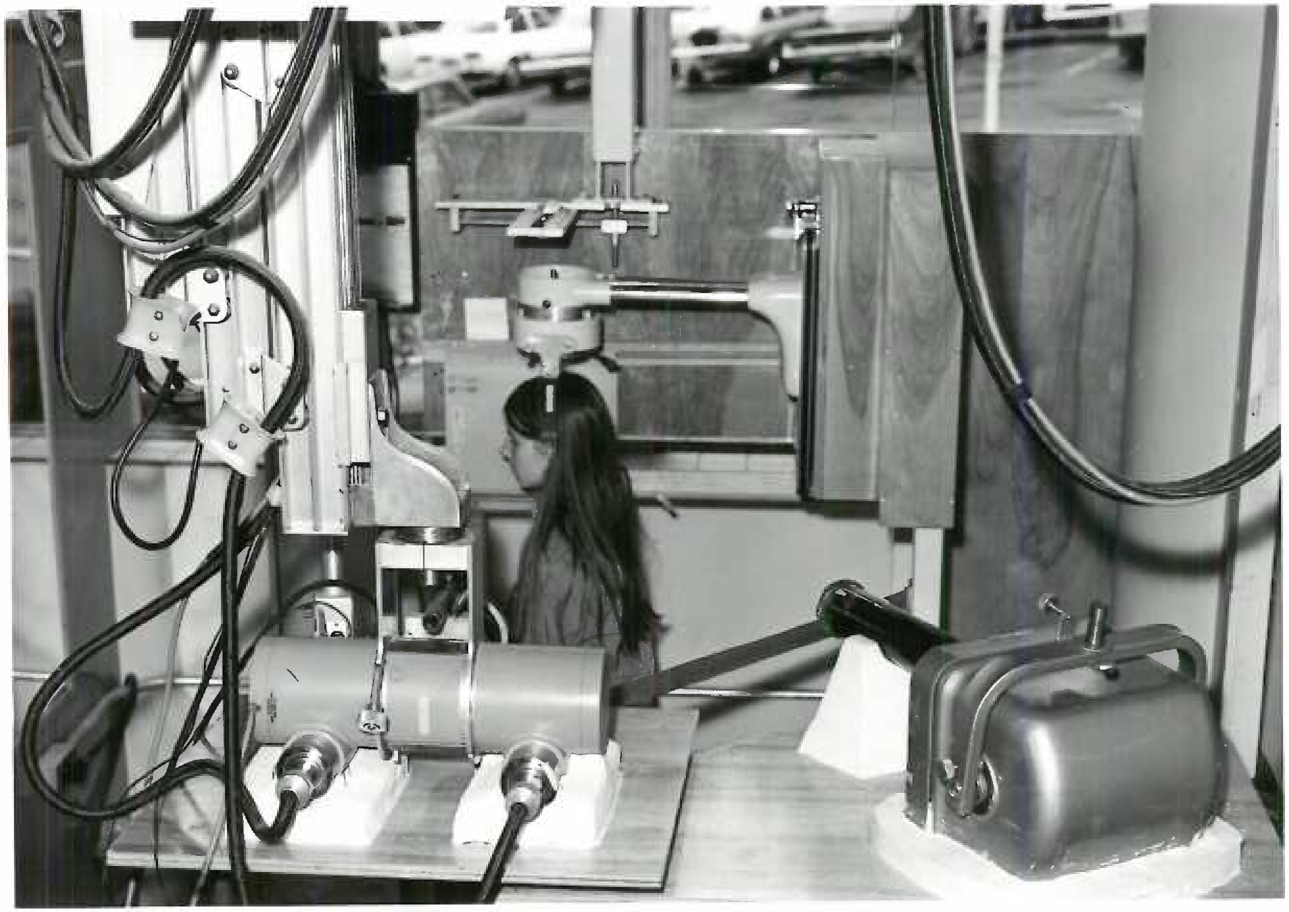


Figure 1 X-RAY SET-UP

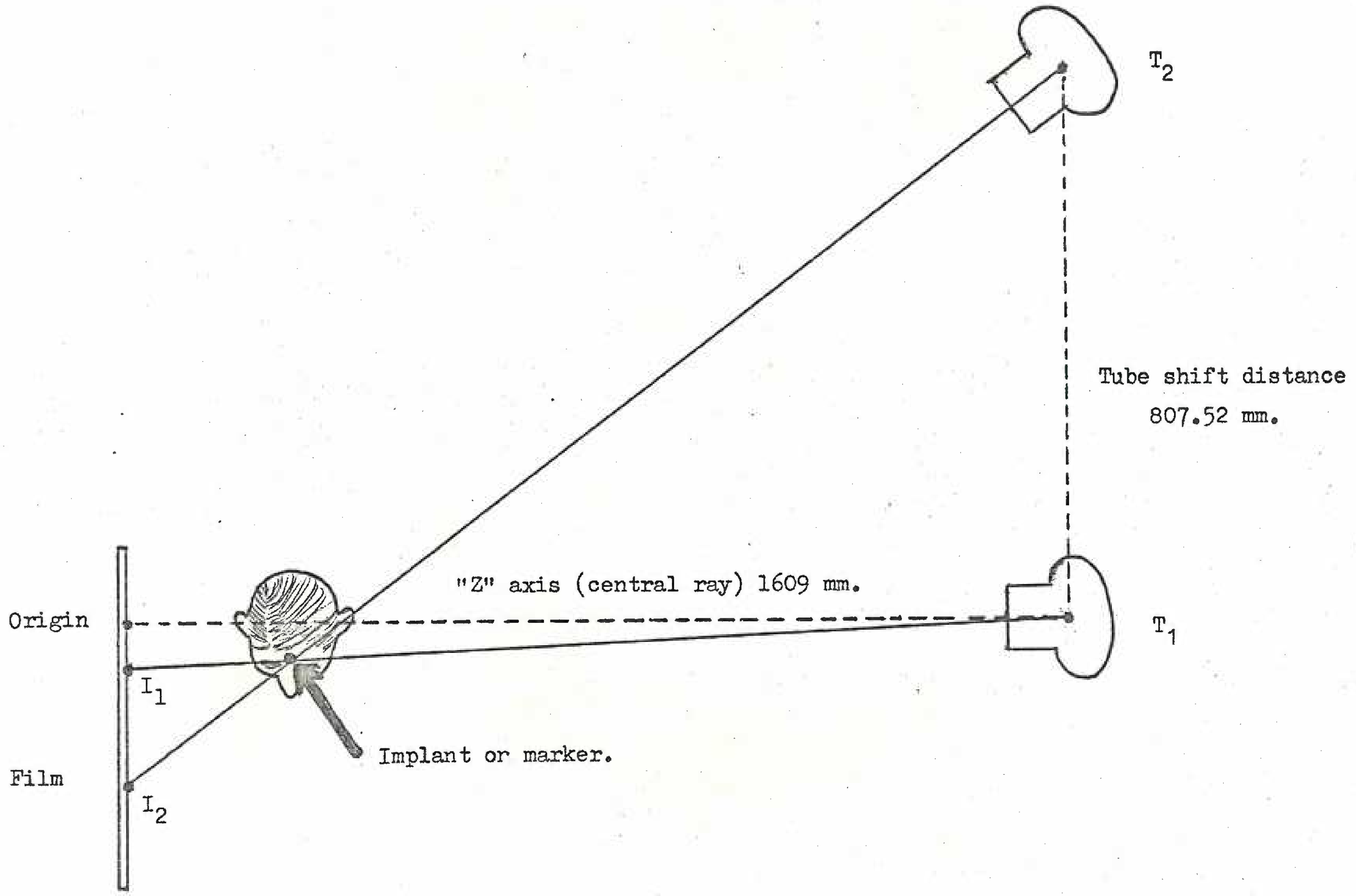


Figure 2 DIAGRAM OF SET-UP

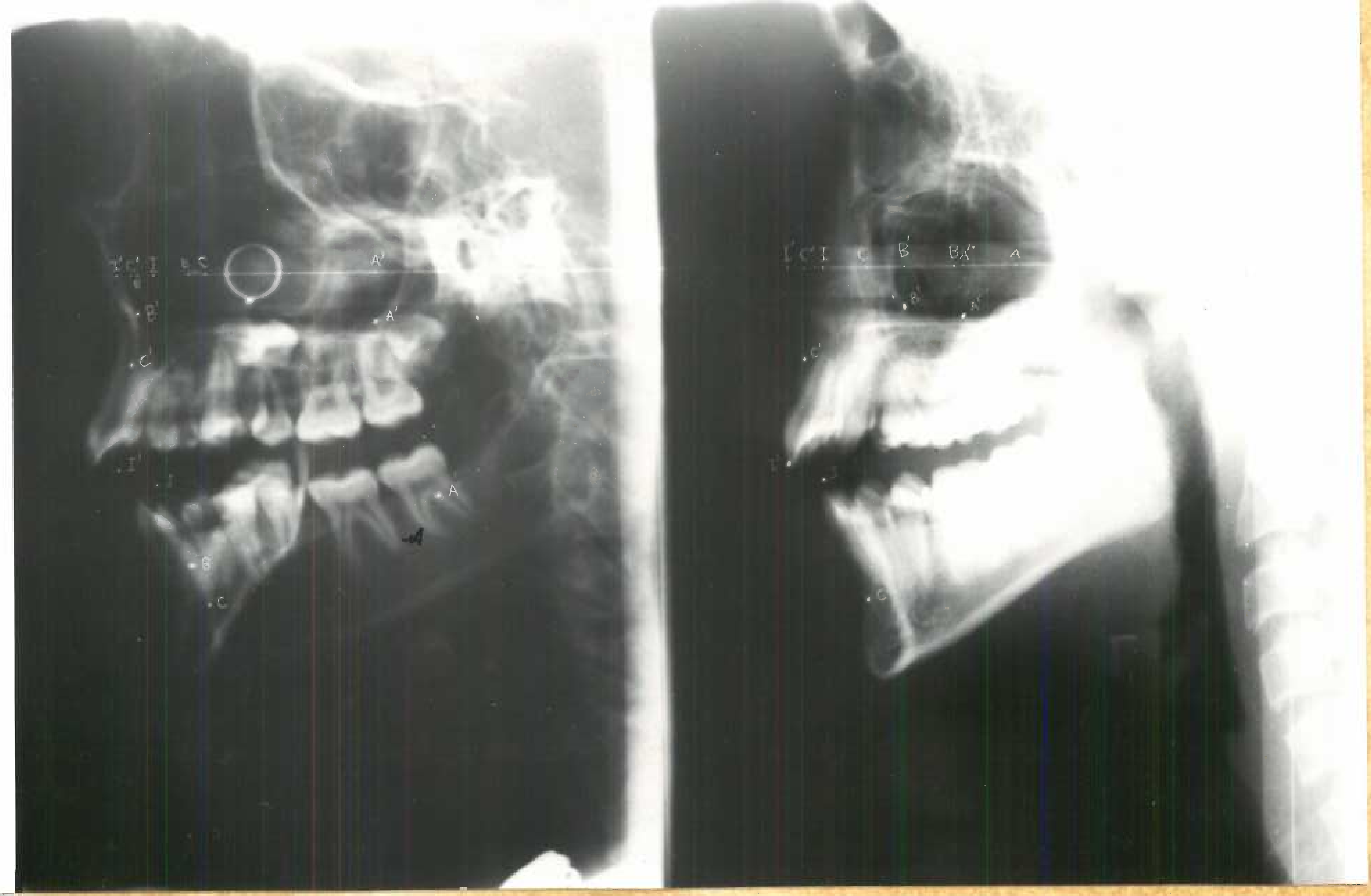


Figure 3 · RADIOGRAPH TAKEN BY 3-D TECHNIQUE

Image on left exposed by the angulated head. Image on right exposed by the head normal to the film.

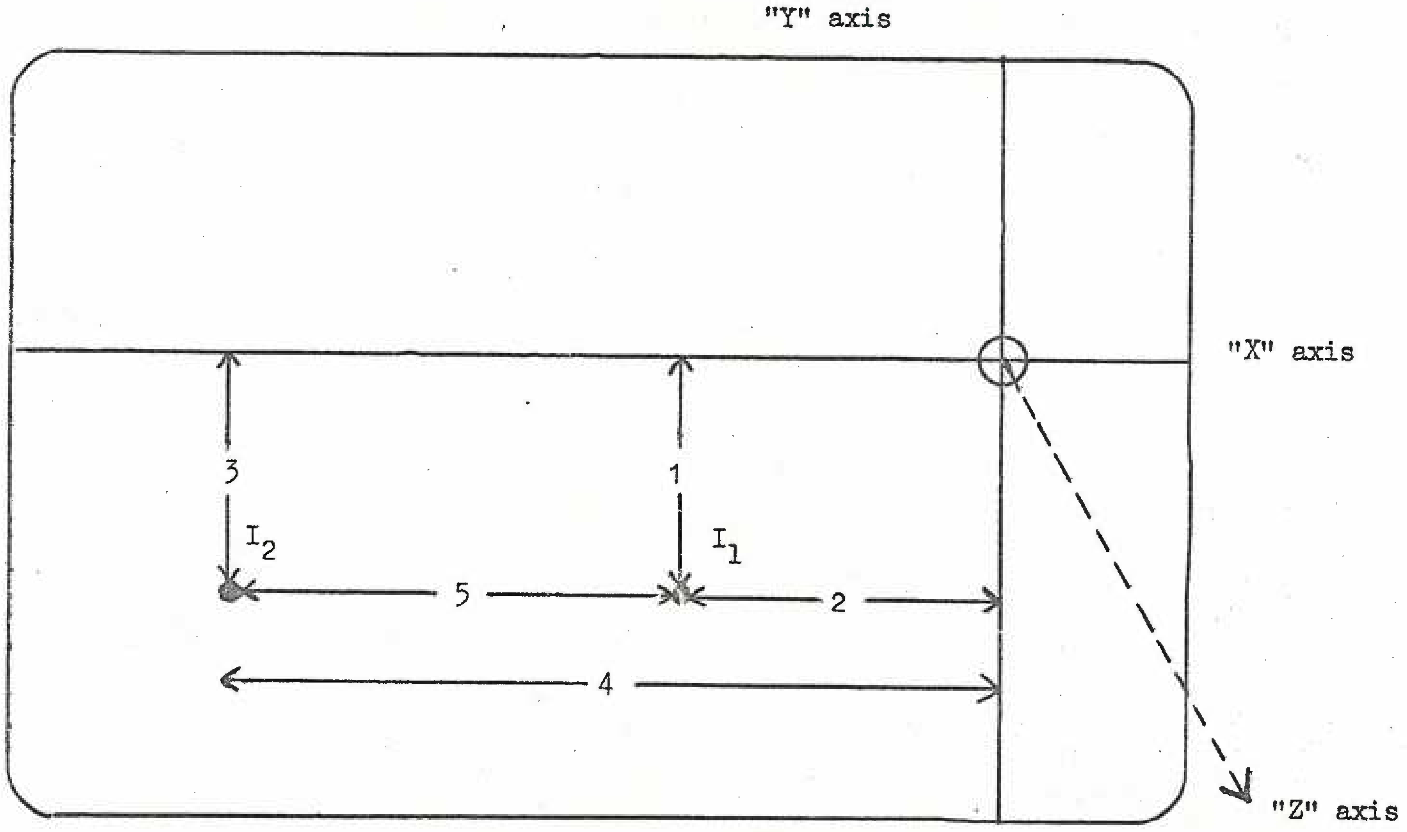
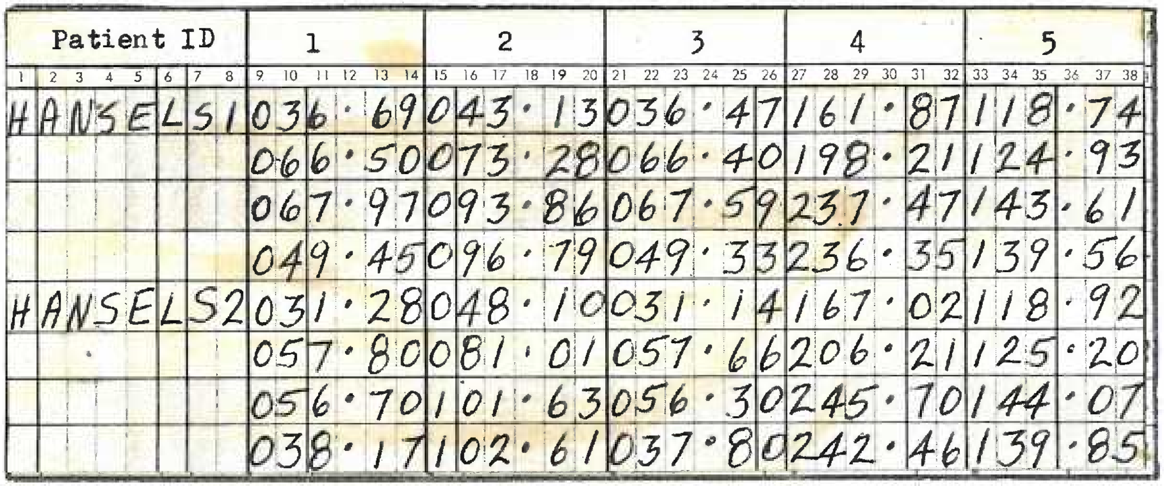


Figure 4 MEASUREMENTS TAKEN FROM THE DUAL IMAGES OF EACH IMPLANT (A, B, or C) AND MARKER (I). MEASUREMENTS ARE DESIGNATED VARIABLES I-5.



Patient ID	1	2	3	4	5	
1 2 3 4 5 6 7 8	9 10 11 12 13 14	15 16 17 18 19 20	21 22 23 24 25 26	27 28 29 30 31 32	33 34 35 36 37 38	
HANSELS1	036.69	043.13	036.47	161.87	118.74	A 1st measurement
	066.50	073.28	066.40	198.21	124.93	B
	067.97	093.86	067.59	237.47	143.61	C
	049.45	096.79	049.33	236.35	139.56	I
HANSELS2	031.28	048.10	031.14	167.02	118.92	A' 2nd measurement
	057.80	081.01	057.66	206.21	125.20	B'
	056.70	101.63	056.30	245.70	144.07	C'
	038.17	102.61	037.80	242.46	139.85	D'

Figure 5

INPUT SHEET

```
                         3 D .   D O U B L E   F I L M   C E P H A L A M E T R I C S

                                         U N C O R R E C T E D

FIRST MEASUREMENT     HANSELS    1                       SECOND MEASUREMENT     HANSELS    2

CORD           A          B          C          I          A          B          C          I

X         37.600     63.460     79.690     82.530     41.930     70.140     86.240     87.460

Y         31.890     57.550     57.550     42.110     27.200     49.980     47.950     32.380

Z        206.260    215.580    242.950    237.100    206.530    215.980    243.610    237.520

                                          C O R R E C T E D

CORD           A          B          C          I          A          B          C          I

X         37.600     63.460     79.690     82.530     37.659     63.403     79.637     82.485

Y         31.890     57.550     57.550     42.110     31.935     57.578     57.477     42.056

Z        206.260    215.580    242.950    237.100    206.300    215.447    243.043    237.096

ERROR IN A =     0.084

ERROR IN B =     0.147                   FIRST MEASUREMENT            SECOND MEASUREMENT

ERROR IN C =     0.119                   DIST AB =  37.604            DIST AB =  37.470

RMS ERROR  =     0.120                   DIST BC =  31.820            DIST BC =  32.043

MOVMENT    =     0.070                   DIST AC =  61.450            DIST AC =  61.391

DELTA X    =    -0.045

DELTA Y    =    -0.054

DELTA Z    =    -0.004
```

Figure 6   OUTPUT

Figure 7 MARKERS

All implants move in the same direction an equal distance.

Implant "B" rotates around the axis connecting "A" and "C". "r" is the radius of the arc.

Figure 8

TWO EXAMPLES OF POSSIBLE UNDETECTABLE IMPLANT MOVEMENT

Table I

WITHIN FILM RELIABILITY

#	Random Measure	Original	Duplicate	Difference (Orig.-Dup.)
1	0654	223.64	223.69	-.05
2	0175	140.60	140.54	.06
3	0756	051.10	051.19	-.09
4	1708	067.49	067.45	.04
5	0259	249.69	249.78	-.09
6	0372	102.81	102.87	-.06
7	0975	139.29	139.34	-.05
8	0641	045.68	045.67	.01
9	1298	042.69	042.74	-.05
10	1286	018.20	018.19	.01
11	0708	016.40	016.40	.00
12	0247	083.88	083.88	.00
13	1367	075.60	075.61	-.01
14	1433	071.74	071.79	-.05
15	0531	056.91	056.85	.06
16	0728	066.45	066.47	-.02

$N = 16$

$\Sigma d = -.29$

$\Sigma d^2 = .0393$

$\Sigma d^2/2N = .001$

$\sqrt{\Sigma d^2/2N} = .035$

SEmeasure = .035

Fiducial limit = .10 mm.

($\alpha = .01$)

how [illegible]

Table II

STANDARD ERROR OF THE ESTIMATE OF LINEAR DISTANCES BETWEEN IMPLANTS A, B, AND C

(△ = 1st measurement - 2nd measurement)

	MAXILLA			MANDIBLE		
$\bar{X}$:	.148	.084	.155	.161	.136	.205
	△AB	△BC	△AC	△AB	△BC	△AC
K.H.	.051	.044	.103	.070	-.105	-.185
T.H.	-.291	-.098	-.468	-.110	-.380	-.556
S.L.	.210	.146	.337	.027	.036	.029
D.O.	.219	.030	.241	.054	-.044	.092
T.W.	.024	.115	.072	.676	.230	.762
P.F.	.482	.129	.003	.343	.074	.121
K.E.	.056	-.052	.022	.170	-.142	.066
R.R.	-	-	-	0	-.036	-.095
R.D.	-.151	-.110	-.284	.008	-.028	.023
L.P.	.020	-.101	-.214	-.019	-.093	-.102
P.L.	-	-	-	-	-	-
S.R.	-.073	-.141	-.179	-.008	-.128	-.067
B.T.	.242	-.073	.141	.397	.040	.275
P.N.	.082	-.066	.009	-.028	.171	.009
B.G.	.093	.006	.099	.161	.148	.380
D.D.	.079	-.073	.011	-.050	.256	.114
$\sqrt{\Sigma d^2/2N}$	.137	.066	.146	.164	.113	.201
Fiducial Limit	.41	.20	.44	.49	.34	.60

$\alpha = .01$

Table III

TEST FOR IMPLANT STABILITY

(Circled values exceed fuducial limit at $\alpha = .01$)

$\bar{X}$	MAXILLA			MANDIBLE		
	.135	.099	.167	.181	.174	.171
	△ AB	△BC	△AC	△ AB	△BC	△AC
K.H.	-.022	.061	.072	.134	-.223	.059
T.H.	-.243	.122	-.185	.467	◯ -.365	.174
S.L.	-.093	.045	0	.451	-.060	.141
D.O.	-	-	-	-	-	-
T.W.	-.223	.174	-.052	-.185	.296	.238
P.F.	◯ .462	.025	.343	-.060	-.224	.247
K.E.	-.055	-.174	-.232	.050	-.083	-.024
R.R.	-	-	-	.110	.009	.138
R.D.	-.258	-.046	-.194	-.100	-.132	-.169
L.P.	-.038	-.043	-.145	.088	-.218	-.171
P.L.	-	-	-	-.005	.111	.134
S.R.	.062	-.102	-.104	.035	-.027	-.098
B.T.	.085	◯ -.364	.346	◯ .619	◯ -.482	.419
P.N.	-.113	-.096	-.267	.019	.074	.059
B.G.	-.047	.007	-.040	.382	.093	.427
D.D.	.060	.035	.104	-.010	.221	.077
Fiducial Limit	.41	.20	.44	.49	.34	.60

$\alpha = .01$

Table IV

STANDARD ERROR OF THE METHOD

	ERROR MAXILLA				ERROR MANDIBLE			
	Total	$\triangle X$	$\triangle Y$	$\triangle Z$	Total	$\triangle X$	$\triangle Y$	$\triangle Z$
K.H.	.517	-.305	.098	.405	.092	.004	.015	.091
T.H.	.116	.031	-.022	.110	.428	-.101	.081	.408
S.L.	.331	.228	-.228	-.075	.151	-.065	-.064	-.120
D.O.	.524	-.323	.064	.408	.139	-.020	-.033	-.134
T.W.	-	-	-	-	-	-	-	-
P.F.	.184	.050	.054	.168	.134	-.110	.070	.029
K.E.	.573	-.058	.103	.561	.207	-.043	-.188	.076
R.R.	-	-	-	-	.458	.288	.109	-.339
R.D.	.160	.054	-.061	.138	.232	.121	-.009	-.198
L.P.	.477	-.333	.145	.310	.260	.135	.034	.219
P.L.	-	-	-	-	-	-	-	-
S.R.	.113	-.024	.039	.103	.256	.071	-.052	.240
B.T.	.147	.024	-.134	.055	.059	-.039	.037	.024
P.N.	.423	-.275	.021	.321	.261	.197	-.170	-.020
B.G.	.329	-.049	.045	.323	.500	-.330	-.186	-.326
D.D.	.298	-.275	.115	-.017	.604	.113	.068	-.590
$\sqrt{\Sigma d^2/2N}$	.255	.142	.073	.199	.222	.105	.070	.182
Fiducial Limit $\alpha = .05$	.56	.31	.16	.43	.48	.23	.15	.39
Fiducial Limit $\alpha = .01$	.78	.43	.22	.61	.67	.32	.21	.55

APPENDIX A

CALCULATIONS THAT SERVE AS THE BASIS FOR THE COMPUTER PROGRAM

Calculation of x, y, and z coordinate values for the marker and implants, before and after (Figure a).[7]

1. Calculate distance b:

$$\frac{b}{e} = \frac{1609 - b}{807.52}$$

$$807.52b = 1609e - be$$
$$807.52b + be = 1609e$$
$$b(807.52 + e) = 1609e$$

$$b = \frac{1609e}{807.52 + e}$$

2. Calculate angle α:

$$\tan \alpha = \frac{e}{b}$$

$$\text{angle } \alpha = \arctan \frac{e}{b}$$

3. Calculate angle θ:

$$\tan \theta = \frac{f}{1609}$$

$$\text{angle } \theta = \arctan \frac{f}{1609}$$

4. Calculate angle β:

$$\text{angle } \beta = \text{angle } \alpha - \text{angle } \theta$$

5. Calculate angle ϕ:

$$\text{angle } \phi = 90^\circ - \text{angle } \alpha$$

6. Calculate distance g:

$$\sin \phi = \frac{g}{d}$$

$$g = d \sin \phi$$

7. Calculate distance h:

$$\sin \beta = \frac{g}{h}$$

$$h = \frac{g}{\sin \beta}$$

8. Calculate distance c:

$$\sin \theta = \frac{c}{h}$$

$$c = h \sin \theta$$

9. Calculate z coordinate:

$$\cos \theta = \frac{z}{h}$$

$$z = h \cos \theta$$

10. Calculate x coordinate:

$$x = f - c$$

11. Calculate y coordinate (Figure b):

$$\frac{1609 - z}{x} = \frac{1609}{\text{variable 2}}$$

$$1609 - z = \frac{1609x}{\text{variable 2}}$$

$$\frac{1609 - z}{y} = \frac{1609}{\text{variable 1}}$$

$$1609 - z = \frac{1609y}{\text{variable 1}}$$

$$\therefore \frac{1609x}{\text{variable 2}} = \frac{1609y}{\text{variable 1}}$$

$$\therefore y = \frac{x(\text{variable 1})}{\text{variable 2}}$$

Coordinate transformation is accomplished by a translation followed by three rotations.

12. Compute the x, y, and z coordinate values for the geometric centers (G and G') of the triangles ABC and A'B'C':

$$G_x = \frac{A_x + B_x + C_x}{3},\ \text{repeat for y and z.}$$

$$G'_x = \frac{A'_x + B'_x + C'_x}{3},\ \text{repeat for y and z.}$$

13. Translation of the origin of the coordinate system to G and G', and computation of new coordinate values for A,B,C,I and A',B',C',I':

$$\underline{A}_x = A_x - G_x,\ \text{repeat for y and z. Repeat for B,C,I.}$$

$$\underline{A}'_x = A'_x - G'_x,\ \text{repeat for y and z. Repeat for B',C',I'.}$$

14. Rotation about the "Z" axis (Figure c):

$$\begin{pmatrix} \underline{\underline{A}}'_x \\ \underline{\underline{A}}'_y \\ \underline{\underline{A}}'_z \end{pmatrix} = \begin{pmatrix} \dfrac{\underline{A}'_x}{\sqrt{\underline{A}'^2_x + \underline{A}'^2_y}} & \dfrac{+\ominus\,\underline{A}'_y}{\sqrt{\ }} & 0 \\ \dfrac{\oplus -\underline{A}'_y}{\sqrt{\ }} & \dfrac{\underline{A}'_x}{\sqrt{\ }} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \underline{A}'_x \\ \underline{A}'_y \\ \underline{A}'_z \end{pmatrix}$$

Repeat for $\underline{B}'$, $\underline{C}'$, $\underline{I}'$.

15. Rotation about the "Y" axis (Figure d):

$$\begin{pmatrix} \underline{\underline{\underline{A}}}'_x \\ \underline{\underline{\underline{A}}}'_y \\ \underline{\underline{\underline{A}}}'_z \end{pmatrix} = \begin{pmatrix} \dfrac{\sqrt{\underline{A}'^{2}_x + \underline{A}'^{2}_y}}{\sqrt{\underline{A}'^{2}_x + \underline{A}'^{2}_y + \underline{A}'^{2}_z}} & 0 & + \ominus \dfrac{\underline{A}'_z}{\sqrt{\quad}} \\ 0 & 1 & 0 \\ \oplus - \dfrac{\underline{A}'_z}{\sqrt{\quad}} & 0 & \dfrac{\sqrt{\underline{A}'^{2}_x + \underline{A}'^{2}_y}}{\sqrt{\quad}} \end{pmatrix} \begin{pmatrix} \underline{\underline{A}}'_x \\ \underline{\underline{A}}'_y \\ \underline{\underline{A}}'_z \end{pmatrix}$$

Repeat for $\underline{\underline{B}}'$, $\underline{\underline{C}}'$, $\underline{\underline{I}}'$.

16. Rotation about the "X" axis (Figure e):

$$\begin{pmatrix} \underline{\underline{\underline{A}}}'_x \\ \underline{\underline{\underline{A}}}'_y \\ \underline{\underline{\underline{A}}}'_z \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \dfrac{\underline{B}'_y}{\sqrt{\underline{B}'^{2}_y + \underline{B}'^{2}_z}} & + \ominus \dfrac{\underline{B}'_z}{\sqrt{\quad}} \\ 0 & \oplus - \dfrac{\underline{B}'_z}{\sqrt{\quad}} & \dfrac{\underline{B}'_y}{\sqrt{\quad}} \end{pmatrix} \begin{pmatrix} \underline{\underline{A}}'_x \\ \underline{\underline{A}}'_y \\ \underline{\underline{A}}'_z \end{pmatrix}$$

Repeat for $\underline{\underline{B}}'$, $\underline{\underline{C}}'$, $\underline{\underline{I}}'$.

17. Reverse rotation about the "X" axis:

    From $\underset{\equiv}{A}'_{xyz}$ solve for $\underset{\vdots}{A}'_{xyz}$ using the same matrix, but with the circled sign changes and the substitution of $\underline{B}_y$ for $\underline{B}'_y$ and $\underline{B}_z$ for $\underline{B}'_z$. Repeat for $\underset{\equiv}{B}'_{xyz}$, $\underset{\equiv}{C}'_{xyz}$, $\underset{\equiv}{I}'_{xyz}$.

18. Reverse rotation about the "Y" axis:

    From $\underset{\vdots}{A}'_{xyz}$ solve for $\underset{:}{A}'_{xyz}$ using the same matrix, but with the circled sign changes and the substitution of $\underline{A}_x$ for $\underline{A}'_x$, $\underline{A}_y$ for $\underline{A}'_y$, and $\underline{A}_z$ for $\underline{A}'_z$. Repeat for $\underset{\vdots}{B}'_{xyz}$, $\underset{\vdots}{C}'_{xyz}$, $\underset{\vdots}{I}'_{xyz}$.

19. Reverse rotation about the "Z" axis:

    From $\underset{:}{A}'_{xyz}$ solve for $\underset{\cdot}{A}'_{xyz}$ using the same matrix, but with the circled sign changes and the substitution of $\underline{A}_x$ for $\underline{A}'_x$, $\underline{A}_y$ for $\underline{A}'_y$, and $\underline{A}_z$ for $\underline{A}'_z$. Repeat for $\underset{:}{B}'_{xyz}$, $\underset{:}{C}'_{xyz}$, $\underset{:}{I}'_{xyz}$.

20. Translations of the geometric centers of triangles $\underline{ABC}$ and $\underset{\cdot}{A}'\underset{\cdot}{B}'\underset{\cdot}{C}'$ from the origin of the coordinate system to G_{xyz} and the computation of coordinate values for $\underline{A}$, $\underline{B}$, $\underline{C}$, $\underline{I}$ and $\underset{\cdot}{A}'$, $\underset{\cdot}{B}'$, $\underset{\cdot}{C}'$, $\underset{\cdot}{I}'$:

    $A_x = \underline{A}_x + G_x$, repeat for y and z. Repeat for $\underline{B}$, $\underline{C}$, $\underline{I}$.

    $\underset{*}{A}'_x = \underset{\cdot}{A}'_x + G_x$, repeat for y and z. Repeat for $\underset{\cdot}{B}'$, $\underset{\cdot}{C}'$, $\underset{\cdot}{I}'$.

    $\underset{*}{A}'_{xyz}$, $\underset{*}{B}'_{xyz}$, $\underset{*}{C}'_{xyz}$, and $\underset{*}{I}'_{xyz}$ are the corrected coordinate values for A'_{xyz}, B'_{xyz}, C'_{xyz}, and I'_{xyz}.

21. Calculations for the vector distances between A, B, C and between A', B', C':

$$\text{distance AB} = \sqrt{(A_x - B_x)^2 + (A_y - B_y)^2 + (A_z - B_z)^2}$$

Repeat for BC, AC, A'B', B'C', A'C'.

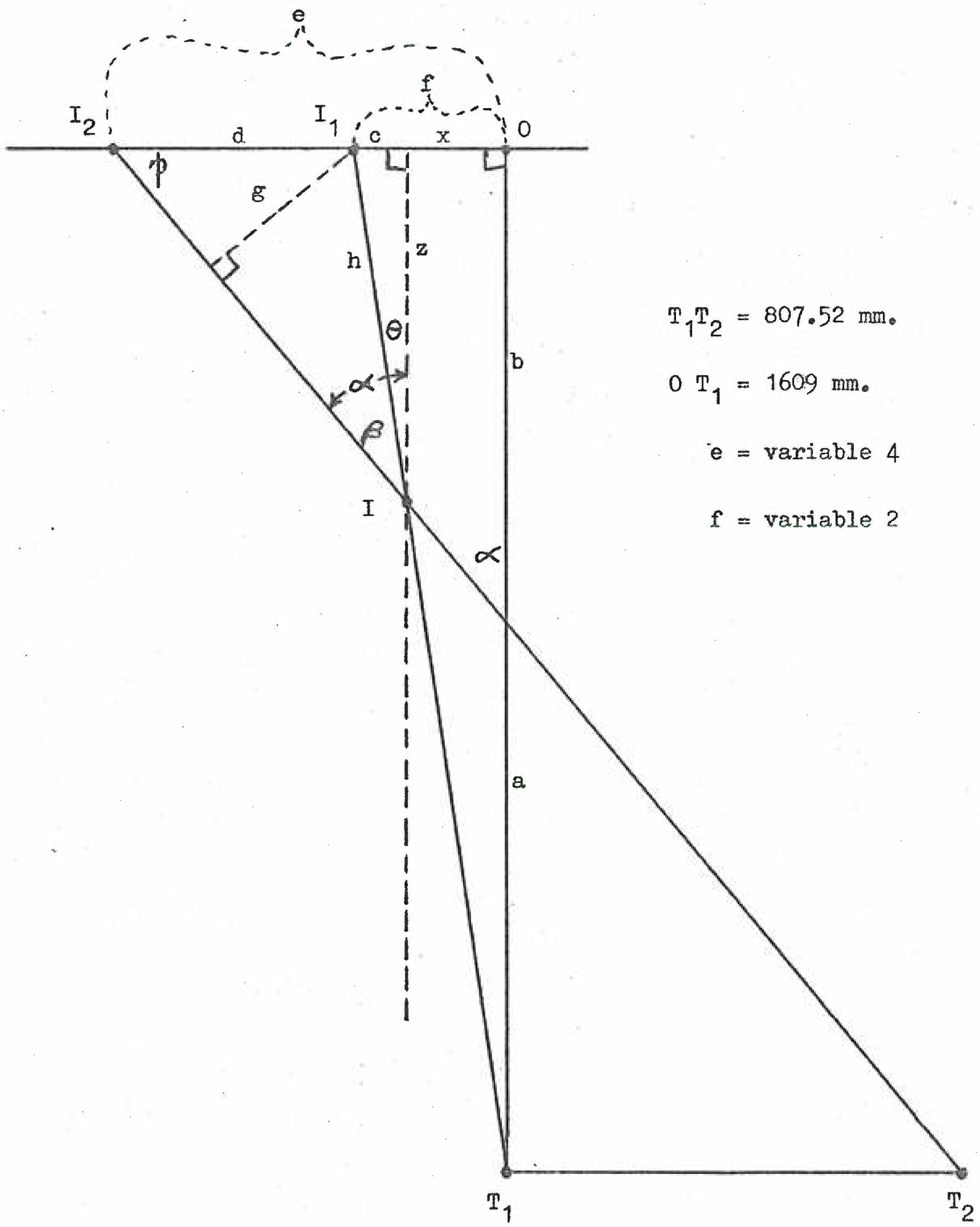
22. Calculations for the vector distances between A and $\underset{*}{A}'$, B and $\underset{*}{B}'$, C and $\underset{*}{C}'$:

$$\text{Error}_A = \sqrt{(A_x - \underset{*}{A}'_x)^2 + (A_y - \underset{*}{A}'_y)^2 + (A_z - \underset{*}{A}'_z)^2}$$

Repeat for Error_B and Error_C.

23. Calculate the root mean square for Error_A, Error_B, and Error_C:

$$\text{RMS Error} = \sqrt{(\text{Error}_A{}^2 + \text{Error}_B{}^2 + \text{Error}_C{}^2)/3}$$



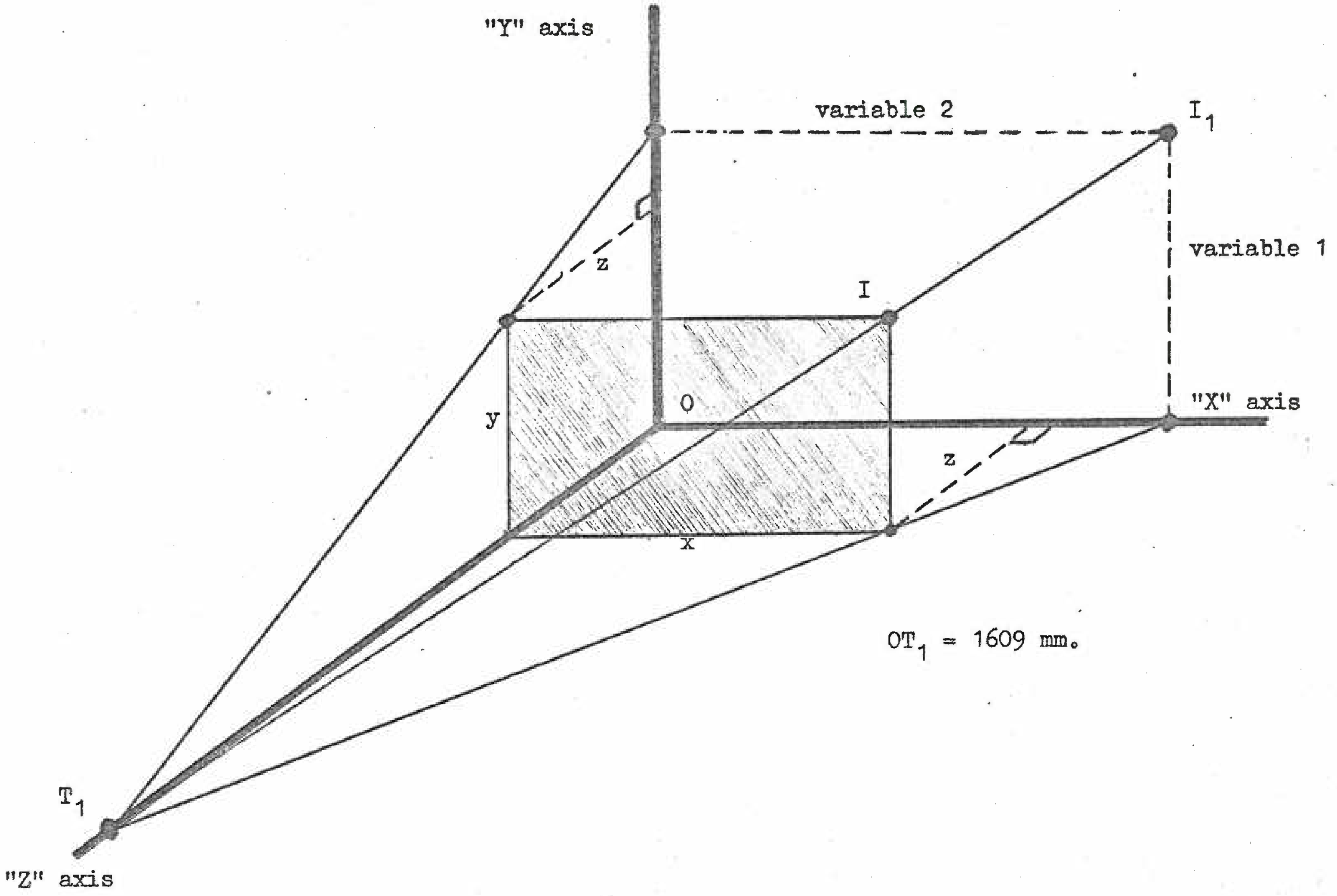
T_1T_2 = 807.52 mm.

$0\ T_1$ = 1609 mm.

e = variable 4

f = variable 2

Figure a Diagram for calculation of x and z coordinate values for an implant or marker.



$OT_1 = 1609$ mm.

Figure b Diagram for calculation of y coordinate for an implant or marker.

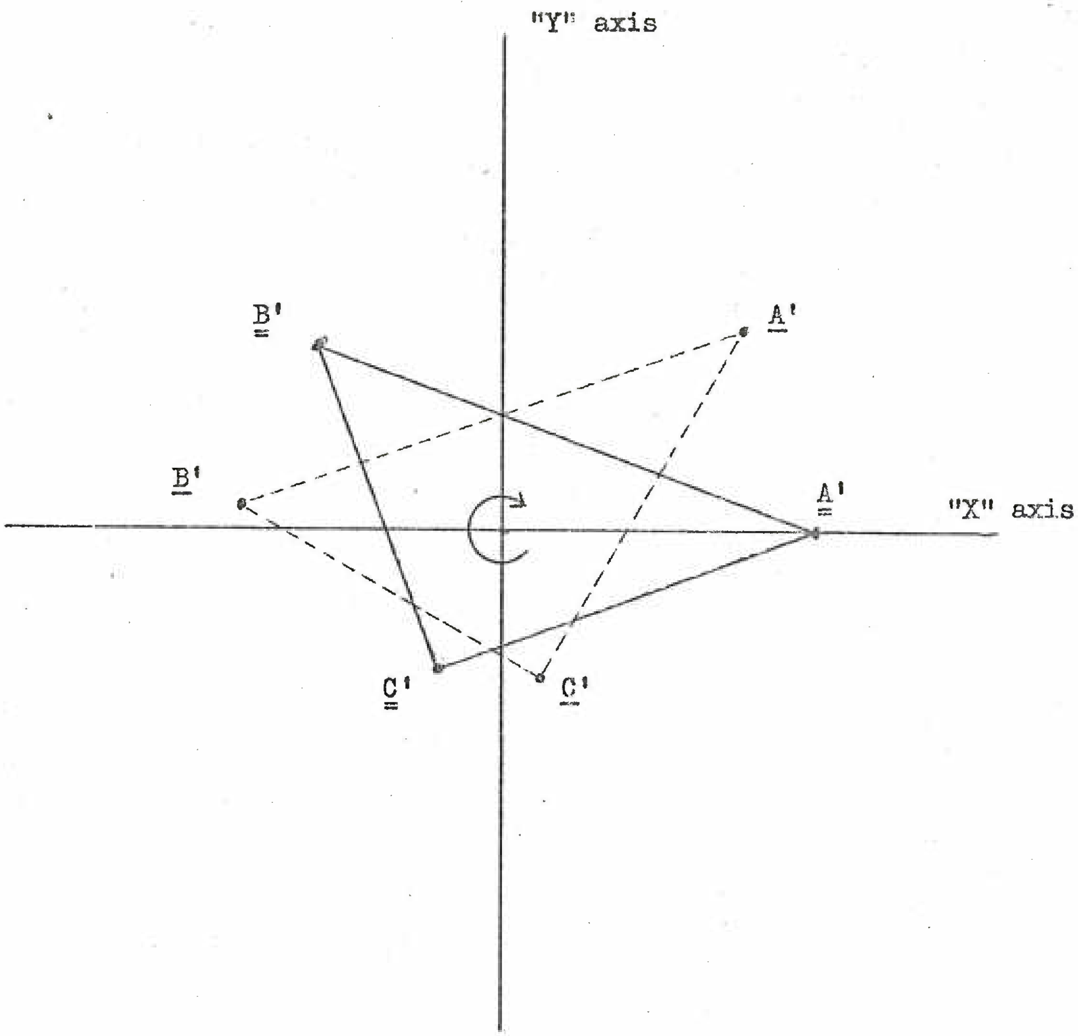


Figure c   Rotation about the "Z" axis.

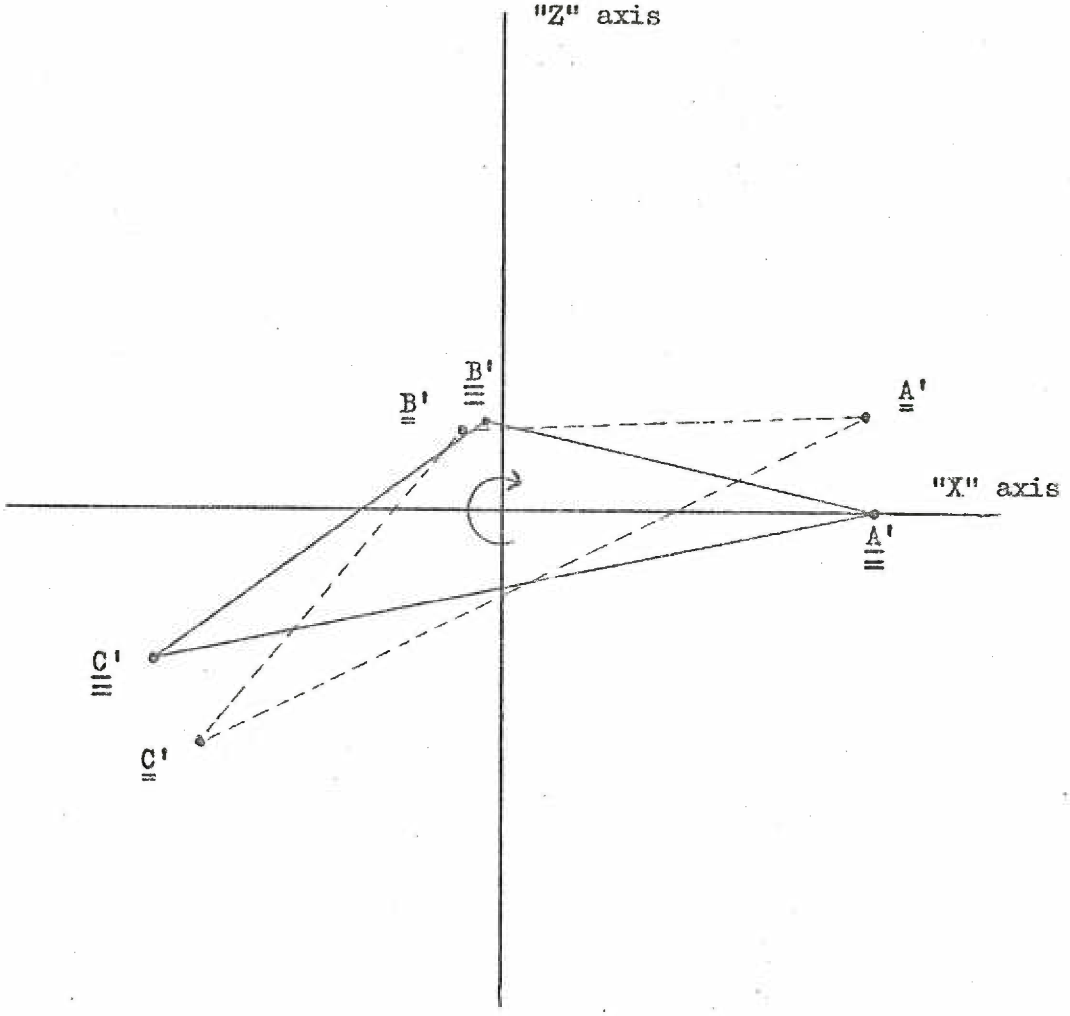


Figure d   Rotation about the "Y" axis

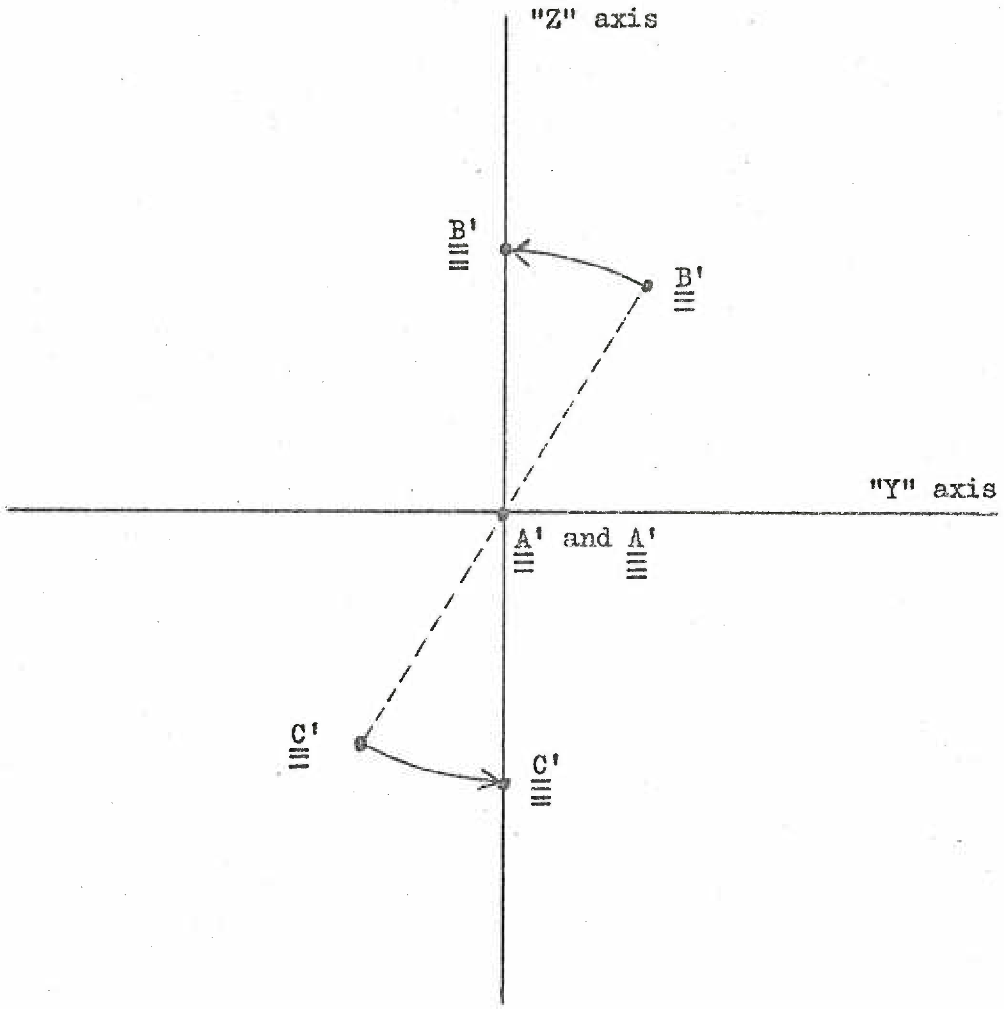


Figure e   Rotation about the "X" axis