THE RELIABILITY OF
A THREE-DIMENSIONAL CEPHALOMETRIC TECHNIQUE

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The most rewarding aspect
of my efforts in writing this paper
has been the opportunity to work closely with
two unique and inspiring individuals:

I wish to express my gratitude to

Dr. Ernest H. Hixon

whose insights and concepts provided the foundation for this work;

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who demonstrates the value of dedication to an idea

and irresistable perseverence in bringing forth its fruit.

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INTRODUCTION

A continuing challenge to dentistry has been the difficulty of measuring orthodontic tooth movement. Part of the difficulty results from the fact that this tooth movement is taking place in growing patients. Thus, tooth movement change from growth may be greater than the tooth movement achieved by the orthodontic treatment, particularly given the minute increments in which the latter occurs. In fact, the movement achieved by orthodontic treatment might be even smaller than the errors made in measurement of this movement!

In using standard radiographic technique, the greatest source of measurement error results from the difficulty of precisely locating landmarks.[1,2] A major step in overcoming this problem was Bjork's[3] development of the use of metallic implants. These provide well-defined fixed landmarks, considerably reducing measurement error.

A remaining source of measurement error is the problem of representing the three-dimensional subject on a two-dimensional film. Thus, the two dimensions recorded on film are distorted by the unmeasured third dimension.

The limitations of two-dimensional representation have also made it impossible to superimpose implants perfectly in subsequent films when there is any variability in repositioning the patient during subsequent exposures. And variability of repositioning almost always occurs, due to the lack of any head-holding device which permits precise repositioning when the periods of time between films are of any length. This is particularly true when growth is occurring in the patient between exposures.

The repositioning problem has been partially overcome by Bjork[4], by simply using a cephalostat with a builtin image-intensifier that permits television monitoring of the implants before exposing the films. However, this requires equipment not readily available in most dental schools.

The problem of representing landmarks in a three-dimensional system has also been largely resolved by Schwartz[5], Savara[6], and Dehan[7]; Schwartz and Savara using Broadbent cephalometers, and Dehan using three x-ray machines. These techniques have proven reliable in cross-sectional research. Nixon and Cruikshank[8] subsequently devised a potential system utilizing only one film and two concurrent exposures.

Believing that the Nixon-Cruikshank one-film technique possessed certain advantages over its predecessors, we determined to develop it into a useful clinical tool for longitudinal research. We have now established a system which, with readily available equipment, provides a solution to the repositioning problem, and permits representation of orthodontic treatment changes in a valid three-coordinate system, all while maintaining a high degree of reliability.

This paper will attempt to evaluate the reliability of this system.

REVIEW OF THE LITERATURE

The longitudinal study of cephalometric data has made very evident the significance of reliability. In longitudinal studies, errors in measurement are doubled, since error affects the measurement both of the starting point and of the point marking the amount of change. As Hixon[9] pointed out, if the measurement error is only ± half a mm and, in fact, a one mm change has occurred, the apparent change may range from no change at all to a change of two mm.

With this problem in mind, we investigated the literature in an attempt to ascertain which techniques might reduce measurement error, and what standards the developed technique would be measured against.

In using the standard radiographic technique, it has been demonstrated the standard error of measurement may be limited to ± 0.4 mm using two independent measurers. However, this study, by Potter and Meredith[10], attempted to measure only biparietal and bigonial diameters, both exceptionally easy landmarks to identify. Bjork[1] on the other hand, found that other landmarks were not nearly so reliably located. He, by a process of double determination, carried out by two independent investigators, marked 29 different landmarks, and determined the accuracy of 73 different linear measurements and 55 different angular measurements. This investigation showed considerable difference in the reliability with which various landmarks could be located on the films. The errors in linear measurements varied from 0.3 to 2.84 mm, and the errors of the angular measurements varied from 0.3 to 2.4°.

Hixon[11] with nine different people independently tracing three headplates found that the range of interincisal angle for the three patients was 12-13½°. The maximum difference of lower incisor-to-mandibular plane for the three patients was 5.5 - 7.5°, obviously not reliable landmarks.

Baumrind[2] has further demonstrated that there is not only considerable difference in the variances of location of the commonly used landmarks, but that the distribution of the variance is not random, but affected by the nature of the landmark being located. He graphically represented the distribution of landmark location, using automatic coordinate-localizing equipment and a specially-designed computer program, and found that the standard deviation of landmarks ranged from .53 mm (for porion) to 5.21 mm (for gonion).

Hatton and Granger[12] found that independent investigators using independent films taken on the same day had more error between films than they had from tracing and measuring technique. They measured the distance between three sets of landmarks. They were: bolton point and nasion; distal margin of the first molar crypt to mesial border of cuspid crypt; and lower border of the mandible to a point midway between the two highest cusp tips of the first molar. The films were of fifteen three-year old children. The variance due to tracing and measurement technique was $(0.500)^2$ mm, $(0.126)^2$ mm, and $(0.249)^2$ mm, while the variance for between-film measurements was $(0.539)^2$ mm, $(0.243)^2$ mm, and $(0.279)^2$ mm.

Bjork[2] has suggested that metallic implants would solve the problem of locating landmarks, and states that, as a result of using implants, he can measure growth changes within limits of ± 0.5 mm.

McDonald[13] described a technique for studying tooth movement using an oblique x-ray beam angulated 25°, which was considered a reasonable approximation of half the posterior arch divergence. Thus, measurements made on the head film would coincide more closely to the same measurements made on the same side of the jaws than would be possible with an ordinary head film in which the midsagital plane was parallel to the film. He used implants as reference points to superimpose subsequent films. He found that the standard error of the measure

$\text{SEMeas} = \sqrt{\frac{\Sigma d^2}{2n}}$ was .21 mm.

One problem in using implants as reference points to superimpose subsequent films is that any change in head position between films would alter the relative position of the implants on the films. Stackler[14] demonstrated that a change in angulation of only 5° would result in considerable variation in apparent landmark change ranging from none to as much as 4.5 mm depending on the position of the landmark and direction of the movement.

Kaaber[15] used implants and a modified Evald cephalostat, in an attempt to overcome the repositioning problem. The position of the head was controlled by adjustable stabilized nose and neck rests. Rotation was prevented by strengthening the vertical arms, using individual acrylic ear plugs, adjustable chin rest, and an individual acrylic base plate between the jaws. All of the adjustable elements had millimeter scales in order to reproduce the position of the rests. Exposures were made 8 - 14 days apart. He indicated the errors in the method to range from 0.106 mm - 0.334 mm. Although Kaaber demonstrated that he could quite reliably reposition the head of his patients, it must be remembered that they were repositioned by the same man, and within two weeks. Nor did he have to contend with growth of his patients' heads. With a growing patient, long time periods between films and different operators between films would greatly decrease the reliability of head positioning.

Bjork's solution[4] to the repositioning problem has been the incorporation in the cephalostat of an image intensifier so that he may monitor the position of the implants before exposing the film.

A third method for contending with implant superimposition is to quantify the position of the implants in space. Schwartz[5] described a method by which he established a Cartesian coordinate system using the intersection of the central rays of the two x-ray heads of the Broadbent and Bolton cephalostat as the reference point.

Miller, Savara, Singh[16], and Savara, Tracy, and Miller[17] analyzed the reliability of such a system by analysis of variance technique. The variability was divided into four factors: between, and within locators; and between, and within measurers. They found that between measurers, the variance was $(.08)^2$ mm and $(.06)^2$ mm respectively, and within measurers, it was $(.123)^2$ mm and $(.09)^2$ mm. Landmark location error was five times as large as measurement error.

Dehan[7] also developed a three-dimensional technique utilizing three x-ray machines, each perpendicular to the others. He used a phantom with small steel balls evenly spaced at 6 mm imbedded in the mandible. The variance of the distance between the balls on any one film is about $(.48)^2$ mm and the variance of the three films combined was reduced to approximately $(.25)^2$ mm.

Nixon and Cruikshank[8] developed a technique in which two x-ray machines were used, angulated only about 30° from each other, allowing them to have both images on one film, in an effort to minimize the measurement error still further. They found that between independent investigators the SEMeas was .09 mm and that they could calculate the distance between implants between films with an average variance of $(.160)^2$ mm.

MATERIALS AND METHOD

A cephalometer was constructed similar to the one described by Nixon and Cruikshank; two heads set equidistant from the plane of the film and horizontal in relation to each other. One machine was set so that the central ray was perpendicular to the film and so that it passed through the center of the earposts of the head positioner. Its distance from the film was 241.65 cm. The second machine was set 180 cm from the first machine, in such a mannner that its central ray intersected the central ray of the first machine at an angle of approximately 32°, 80.75 mm from the film plane which approximately coincides with the center of the subject's head. This resulted in producing two separate images on one x-ray film. (Figure 1.)

A phantom was then used with three metallic implants (A, B, and C) spaced approximately as they would be in a subject. Two other implants were placed in the phantom. One (i) within the triangle that would be formed by constructing lines joining the three implants (A, B, and C), and in the same plane as A, B, and C. A fifth implant (I), in seven of the films, was placed outside the area of the triangle and not within the plane of the three implants (A, B, and C).

Ten films were exposed, and developed, each with the phantom placed in differing positions and attitudes to represent variation in head positioning within the head-holder. Using a millimeter rule marked at 0.5 mm intervals, and a ten diopter (2½ magnification) magnifying glass, two independent investigators measured directly on the film the distance between the image of each implant and the image of the constructed grid. These measurements were estimated to the nearest .05 mm. The measurements were next averaged. By simple geometry, they were then reduced for each point to X, Y, and Z coordinates, with X representing the horizontal on the plane of the film, Y the vertical on the plane of the film, and Z the perpendicular to the plane of the film.

The X, Y, and Z coordinates on nine of the ten films were then by geometric methods transposed to the coordinate system of the remaining film.

This transformation was made with these considerations: that A, B, and C represented implants in a common bone in the mandible or the maxilla, and are stable in relation to each other; that implants i and I represented landmarks which were expected to move in relation to implants A, B, and C; that the implants A, B, and C on the two films would not fit perfectly because of measurement error; that the transformation of the coordinates of the second film would be transposed specifically to the coordinate system of the first film, not to an average coordinate system of the two films.

The transformation was accomplished by geometrically superimposing the geometric center of the second triangle (represented by the implants A, B, and C at the apices) to the geometric center of the first; then by requiring one point (A) of the second film to lie on the line that passes through the common geometric centers and point A of the first film; and finally by rotating the second triangle so that it occupies the plane of the first triangle.

In order for this technique to produce the best fit, instead of merely a "good fit" as was the case in this study, the chosen apex which is to lie on the line through the common centers must be the apex furthest from the geometric center of the triangle.

As a result of the geometric transformation, all of the coordinates of the implants could be directly compared. Because there was no movement in the position of landmarks i and I, any variation in their coordinates between the films represents the error inherent in the method.

FINDINGS

The findings are summarized in Tables One through Five. It was found that the SEMeas = $\sqrt{\frac{\Sigma d^2}{2n}}$ resulting from two independent measurements by different investigators was ± .06 mm. This figure represents only measurement error. Because the centers of the implants were marked with a pinprick by one or the other of the investigators, landmark location error is not represented. It was felt that establishment of the amount of error in landmark identification would not be useful because of the large size of the round steel balls used for implants in the phantom, compared to the significantly smaller size of the implants used in subjects.

An evaluation of the error introduced by the various manipulations of the averaged measurements was then calculated. It was found that the errors in the X, Y, and Z axes were not symmetrical (i.e. did not correspond). Table Three indicates that the variance on the X axis was approximately $(.077)^2$ mm, the Y axis $(.084)^2$ mm, and the Z axis $(.156)^2$ mm.

Table Four reveals that the variances of the X, Y, and Z axes for the points A, B, and C were homogeneous, and that the X and Z axes of i and I were homogeneous with respect to each other and to A, B, and C. However, the Y axis variance of both i and I demonstrated significantly more variance than the Y axis of the points A, B, and C, but were homogeneous with each other. Table Four also reveals that the largest error introduced for the situations tested was:

$$X = (.0730)^2 \text{ mm}$$
$$Y = (.1504)^2 \text{ mm}$$
$$Z = (.1714)^2 \text{ mm.}$$

DISCUSSION

The unusual variance in the Y coordinate would make one suspicious that unique features exist in the measuring of Y which contribute to the increased measurement error. In calculating the X, Y, and Z coordinates of each point in one film, four measurements were used. (Figure 2.) They are indicated as α, β, γ, and δ. α and β were directly measured on the film. γ was the calculated difference between those two. δ was also measured directly on the film, but was measured to the X axis, not to the Y axis as were the others. Further, it was noted that there were at all times two images of each point which were horizontal. This meant that when the α and β measurements were made, the ruler was aligned on the two images and would then necessarily be perpendicular to the Y grid. However, when the measurements for δ were made, no such mechanism was available to insure that the measurement was made at right angles to the X grid. It was done by visual alignment. It also became apparent that the angulation of the phantom may in some films introduce an optical illusion effect which would affect the measurer.

In an effort to establish the validity of this seemingly reasonable explanation for the increased variance of Y for i and I, the SEMeas of all i measurements was calculated, and found to be = ± .06 mm. Failing to demonstrate this to be a source of increased variance, the i measurements were re-done, after marking the point of intersection of the perpendicular from the landmark. The SEMeas of the new measurements were compared with the original measurements: SEMeas = .055 mm. Then assuming the error might have been systematic as a result of optical illusion, the means of the original group of measurements was compared with the improved measurement technique group. It was found that the means were 10.48 for the original group and 10.51 for the improved technique group.

F ratio was 1.002

$$T = \sqrt{\frac{\bar{x}_1 - \bar{x}_2 + (\mu_1 - \mu_2)}{\frac{1 + 2}{n}}} = .05$$

with df. = $(n-1) + (n' - 1) = 18$.

The probability of the means being the same is greater than 90+ %. Therefore, we were not able to identify the source of the increased variance of Y for i and I as variation in measurement reliability.

The variance of Y for implants A, B, and C was much smaller than was expected. It would be expected to at least approximate the SEMeas ± .06 mm. Therefore, an F Max test between the variance of Y for A, B, and C, and SEMeas ± .06 mm was conducted. At α .05, the null hypothesis was rejected. (Table Four.) It was further noted that the average variance of Y was $(.84)^2$ mm which corresponded quite well to the SEMeas. Therefore, it was hypothesized that the source of the large variance of Y in i and I must have been contained in the transformation of the coordinate systems. It was then recognized that the transforming of the two triangles to the same plane would be accomplished without regard to measurement error because only three points were used, and three points define a plane. The measurement error was still there, but not expressed until the fourth point (i or I) was calculated. To overcome this problem, one need only use four reference points instead of three.

This delayed-expression of measurement error would increase the apparent measurement error of X, Y, and Z to varying degrees, depending on the attitude of the plane of the implants A, B, and C. The only way it could be recognized in this situation was by significant reduction of the variance in X, Y, or Z or A, B, and C. In this situation, the significant reduction apparently occurred in the Y coordinate.

SUMMARY AND CONCLUSION

A useful clinical tool for longitudinal research was developed by utilizing a three-dimensional radiographic technique projecting two images on one film, in conjunction with an implanted subject. Three of the subject's implants were in a fixed relationship to each other, to act as a point of reference from which it would be possible to state the position in space of a fourth implant or other landmark. The landmark's position was stated in reference to the three fixed implants so that it would be possible to directly compare the position of the landmark at subsequent times with that position recorded at the time of the first film.

By eliminating the need for accurate repositioning of the subject for subsequent x-rays, and by eliminating the distortion caused by representing a three-dimensional subject in two dimensions, it was expected that this method would make possible a significant reduction of measurement error.

It was found that measurement error compared advantageously with that presented in the orthodontic literature, in that changes in landmark position between subsequent films which are greater than:

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

would represent real change, with α = .01 level of confidence. (Table Five.)

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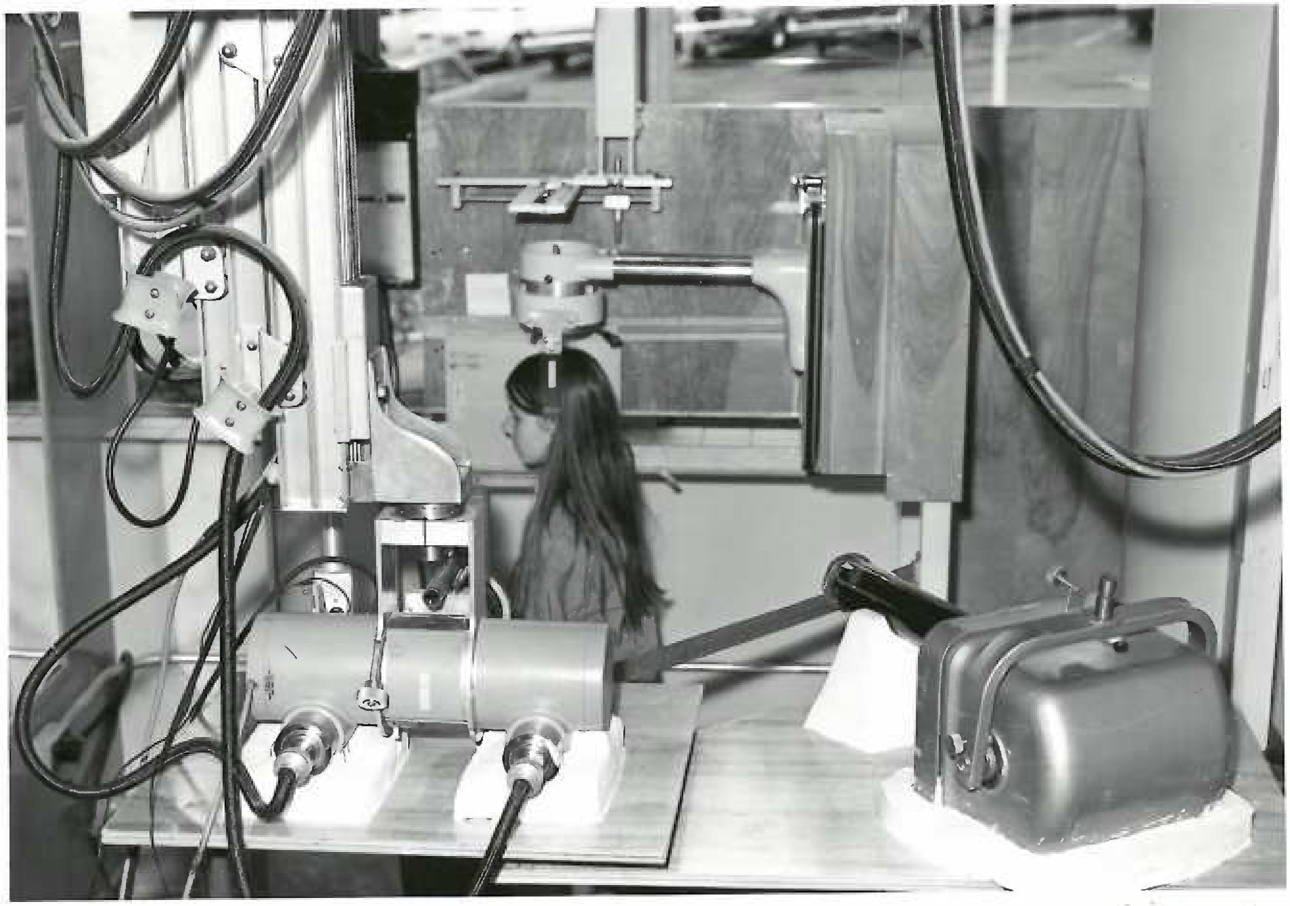

FIGURE 1.

Photograph of the two x-ray heads
and their relation to the subject and film holder.

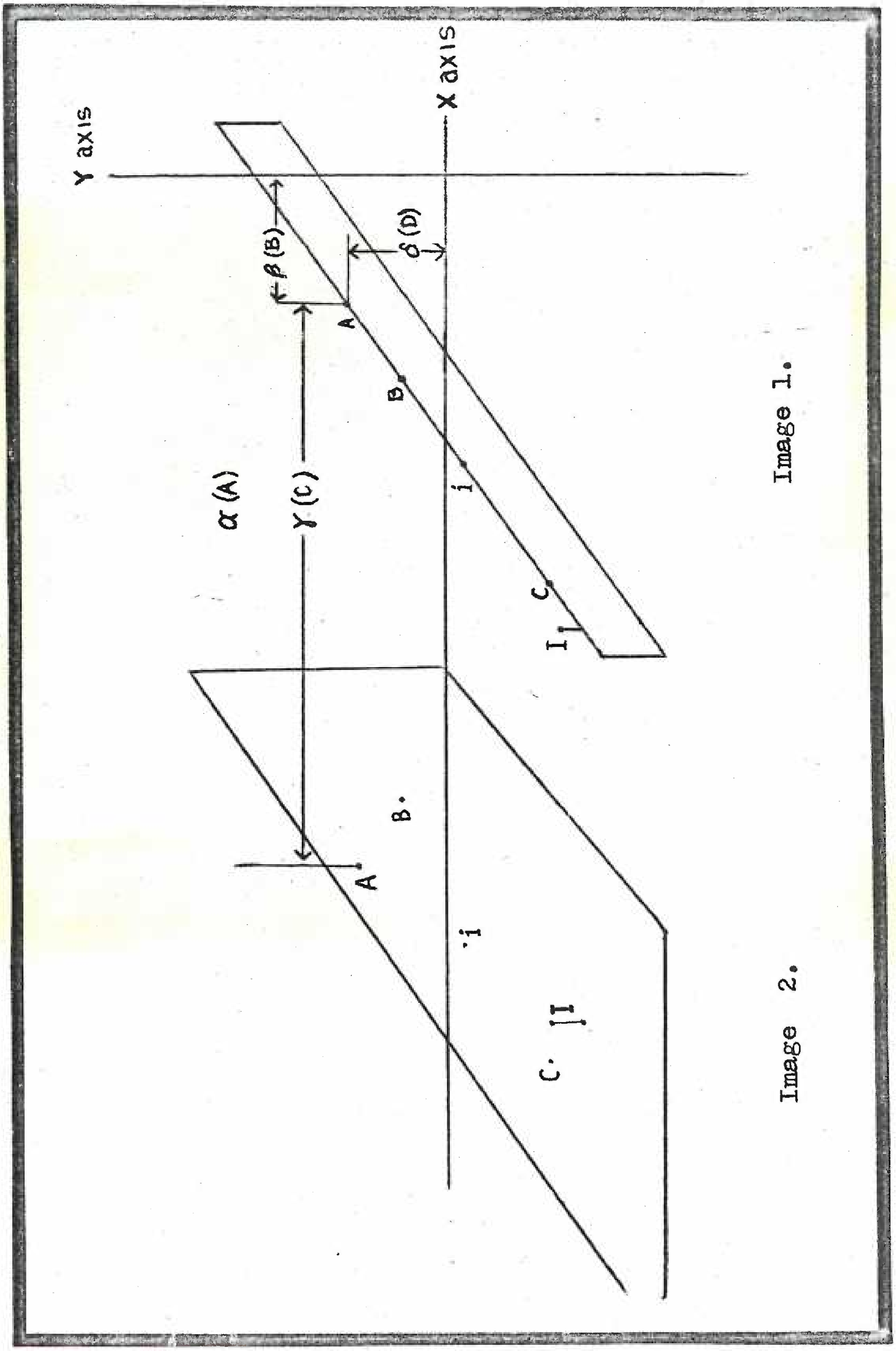

FIGURE 2.

Schematic Drawing of Developed Film
Of the Phantom With Implants

Table 1.

(See FIG. 2) (Measurements made on the films by two investigators.)

INVEST-IGATOR	MEASURE-MENT	A	B	C	i	I
FILM 1:						
1:	a	176.60	205.90	234.35	204.80	234.60
2:		176.40	205.80	234.30	204.90	234.75
1:	b	48.60	43.70	92.10	61.15	83.80
2:		48.40	43.60	92.05	61.15	83.90
1:	d	-7.40	+0.65	-11.60	-6.30	-5.35
2:		-7.35	+0.60	-11.45	-6.30	-5.40
FILM 2:						
1:	a	177.10	204.70	234.60	204.90	233.60
2:		177.10	204.75	234.50	204.80	233.55
1:	b	49.30	42.60	92.40	61.15	82.70
2:		49.20	42.50	92.25	61.10	82.75
1:	d	6.40	12.60	14.40	10.80	17.75
2:		6.40	12.60	14.35	10.80	17.80
FILM 3:						
1:	a	170.00	208.65	225.25	200.40	229.40
2:		170.05	208.75	225.30	200.40	229.35
1:	b	46.90	51.25	92.65	63.20	87.10
2:		46.90	51.25	92.60	63.20	87.00
1:	d	3.25	2.40	-6.20	0.00	-2.05
2:		3.15	2.30	-6.00	0.00	-2.00
FILM 4:						
1:	a	181.10	196.40	181.00	205.10	234.10
2:		181.00	196.45	181.10	205.15	234.25
1:	b	47.80	30.00	47.60	54.50	73.60
2:		47.60	29.95	47.80	54.45	73.55
1:	d	16.60	15.25	16.70	17.10	21.85
2:		16.70	15.30	16.60	17.05	21.90

Table 1. (Continued)

INVEST-IGATOR	MEASURE-MENT	A	B	C	i	I
FILM 5:						
1:	a	170.05	208.90	226.40	200.80	229.85
2:		170.00	209.00	226.45	200.75	229.90
1:	b	46.05	50.70	92.70	62.70	86.70
2:		45.95	50.60	92.55	62.60	86.70
1:	d	10.30	10.50	8.80	9.80	11.75
2:		10.45	10.50	8.90	9.75	11.90
FILM 6:						
1:	a	192.00	215.60	250.70	218.80	248.60
2:		192.05	215.60	250.60	218.80	248.60
1:	b	60.40	49.90	102.30	70.65	92.00
2:		60.45	49.90	102.45	70.60	92.00
1:	d	19.60	25.35	23.60	22.75	27.65
2:		19.70	25.40	23.60	22.75	27.65
FILM 7:						
1:	a	168.40	197.05	224.10	195.90	225.10
2:		168.45	197.10	224.10	195.75	225.05
1:	b	38.10	31.95	79.25	49.50	71.35
2:		38.20	31.90	79.20	49.40	71.30
1:	d	-0.10	2.25	-14.15	-4.10	-8.55
2:		-0.05	2.45	-14.25	-4.00	-8.55
FILM 8:						
1:	a	178.00	206.70	236.10	206.25	161.85
2:		178.00	206.80	236.25	206.35	161.90
1:	b	48.90	43.80	92.85	61.60	37.20
2:		49.00	43.75	92.90	61.60	37.20
1:	d	12.25	2.60	13.10	9.20	14.25
2:		12.30	2.55	13.20	9.20	14.35

Table 1. (Continued)

INVESTIGATOR	MEASUREMENT	A	B	C	i	I
FILM 9:						
1:	a	(178.00	206.65	236.10	206.35	161.90
2:		(178.05	206.75	236.20	206.40	162.00
1:	b	(48.80	43.80	92.85	61.60	37.15
2:		(48.95	43.70	92.90	61.70	37.25
1:	d	(12.30	2.75	13.10	9.30	14.35
2:		(12.40	2.75	13.20	9.40	14.50
FILM 10:						
1:	a	(185.70	209.90	243.95	212.65	169.60
2:		(185.75	209.95	244.00	212.70	169.75
1:	b	(56.20	46.20	98.20	66.70	45.20
2:		(56.20	46.20	98.15	66.75	45.10
1:	d	(12.90	15.60	18.75	19.55	13.40
2:		(12.80	15.55	18.75	15.65	13.50

FILM No.	IMPLANT A	IMPLANT B	IMPLANT C	LANDMARK i	LANDMARK I
x AXIS					
1	40.686	42.926	79.526	54.069	74.126
2	40.620	43.003	79.516	54.024	74.063
3	40.695	42.888	79.556	54.002	74.006
4	40.669	42.935	79.535	54.158	74.034
5	40.659	43.027	79.453	53.972	74.180
6	40.605	43.028	79.507	54.047	74.145
7	40.606	43.099	79.434	54.033	73.992
8	40.716	42.827	79.596	54.028	
9	40.767	42.739	79.633	54.113	
10	40.503	43.013	79.622	54.022	
y AXIS					
1	2.779	1.959	-5.233	-0.231	-1.713
2	2.793	1.943	-5.231	-0.282	-1.874
3	2.777	1.967	-5.239	0.000	-1.722
4	2.783	1.958	-5.236	-0.389	-1.948
5	2.785	1.940	-5.220	-0.203	-1.507
6	2.796	1.939	-5.231	-0.142	-1.815
7	2.796	1.922	-5.213	-0.242	-1.903
8	2.773	1.980	-5.248	-0.274	
9	2.761	1.999	-5.255	-0.240	
10	2.818	1.943	-5.256	-0.368	
z AXIS					
1	212.858	262.571	226.992	233.818	240.931
2	212.756	262.617	227.049	233.955	241.032
3	212.872	262.534	227.016	233.672	241.093
4	212.831	262.412	227.179	234.148	241.262
5	212.817	262.313	227.292	233.610	240.916
6	212.732	262.452	227.239	233.977	241.193
7	212.733	262.784	226.904	233.943	240.767
8	212.904	262.415	227.102	233.924	
9	212.985	262.304	227.134	233.912	
10	212.574	262.361	227.486	233.072	

Table 2. Corrected x y & z coordinates for A B C i I for each film.

		Standard Deviation	Variance
I:	x	.0730	.0053
	y	.1504	.0226
	z	.1714	.0294
i:	x	.0528	.0028
	y	.1106	.0122
	z	.1681	.0282
A:	x	.0732	.0054
	y	.0157	.0002
	z	.1138	.0130
B:	x	.1081	.0117
	y	.0226	.0005
	z	.1509	.0228
C:	x	.0662	.0044
	y	.0140	.0002
	z	.1689	.0285
I:		.0738	.0055
i:		.0998	.0096
A:		.0668	.0045
B:		.0574	.0033
C:		.0927	.0046

TABLE THREE

Standard Deviation and Variances
in Calculated Positions of A, B, C, I, i,
in Both XYZ Coordinates and in Linear Distance.

F.MAX			CRITICAL VALUE[18] α.05
for A B C:	x	2.66	5.34
	y	2.50	5.34
	z	2.19	5.34
for i A B C:	x	3.77	6.31
	y	61. *	6.31
	z	2.17	6.31
for I A B C:	x	2.21	6.31
	y	103. *	6.31
	z	2.26	6.31

F TEST			CRITICAL VALUE[19] α.05
for i I	x	1.66	3.37
	y	1.85	3.37
	z	1.04	3.37

F MAX		CRITICAL VALUE[18] α.05
SEMeas y of A B C	18.*	6.31

TABLE FOUR

Various F Tests and F Max Tests

		S		2.576.S = .01 level of confidence
I:	x	.0730	=	.1880
	y	.1504	=	.3876
	z	.1714	=	.4415
i:	x	.0557		
	y	.1106		
	z	.1681		

TABLE FIVE

Larger Standard Deviation
Of XYZ Coordinates of I and i
At .01 Level of Confidence