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BIOSTEREOMETRICS

by

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THESIS

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Special thanks is due to the following who's participation in this project made it all possible. Dr. John Gibbs who was gracious enough to offer the records of his treated patients for case analysis.

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INTRODUCTION

According to one historian of Science (Kuhn, 1970), two important conditions are always found to have been satisfied in research areas in which work is proceeding well. The first is that there is a common research paradigm- a consensus as to the nature of the central problems of the field. The second is that there is a shared research model or milieu. Orthodontic and Clinical Craniofacial research does not measure up in comparison to such standard as well as one might wish (Baumrind, 1991)! As in most clinical fields, it is relatively easy for us to identify the central problems of clinical interest. They are the characterization of the anomalies we wish to correct and the quantification of the short- and long-term effects of our therapeutic interventions. There is even some degree of consensus as to which types of record contain the information of main interest to investigators. These include x-ray images of various sorts, plaster casts, photographs, and written records. However, there is no common or shared theory on how to investigate these records and more importantly, there is no common set of records for all investigators to examine (Baumrind, 1991).

In order to speed information transfer in our field and to make the results of clinical studies credible, conditions must be created in which all qualified investigators have easy access to true copies of the records and data from which publishing authors make their inferences. Experience has shown that disembodied sets of numerical values are of greatly reduced usefulness when one lacks the ability to relate them to the particular images from which they were derived. Yet it is also clear that original records belong in the possession of the clinicians who generated them. The ability to produce high quality copies of physical and written records therefore becomes a necessary first step in the information acquisition chain (Baumrind, 1980; Baumrind, 1991).

During the past 15 years, Baumrind et al (1980,1991) has worked toward remedying these deficiencies. He proposed a flow chart for the organization of clinical information acquisition and described a specialized photographic system for producing sharable images of physical records. In our nomenclature, the term "records" refers to durable physical representations or transforms made directly from the subject, (e.g. study casts, cephalograms, photographs, panoramic X-ray images, etc.).

Furthermore, at present, there exist no efficient methods for quantitatively evaluating treatment results in 3-dimension from study casts in occlusion. Thus, the purpose of this paper is two fold. First, we will propose a solution to the problem of duplicating study casts and produce a reservoir of information that can be shared with all qualified investigators in the field. Concurrently, we will develop a 3-dimensional imaging system of not only quantitatively assessing the upper and lower casts separately but also in occlusion. Subsequently, we will report on the initial practical tests of system performance. These tests were performed using twenty-four study casts with a number of small radiopaque targets attached. Both stereo digital and stereo x-ray images were taken, and the 3-dimensional coordinates of each images were computed.

BACKGROUND AND SIGNIFICANCE

Study casts are used to make qualitative and quantitative assessments of the goodness of treatment. Intra-arch measurements are made using simple measuring tools such as flexible rulers, dividers, and calipers (Walter, 1953; Nance, 1947; Nef, 1957; Bolton, 1958; Cooper,1960; Huckaba, 1964; White and Hobbs, 1977). However, these simple measurements although made in three planes of space cannot be seen in anyway as being three dimensional (Jones, 1991). These direct measurements made on three dimensional objects are merely measurements of a linear distance between pairs of surface points. When several such measurements are made on the same object at the same time, it is usually impossible to relate them meaningfully to each other since the several line segments do not lie in the same plane. Instead of acquiring an integrated data set which gives a coherent impression of the three dimensional form of the object measured, one obtains a number of discrete and unrelated values (Baumrind, 1975; Baumrind and Moffitt, 1972; Baumrind, Moffitt, and Curry, 1983). For example, knowledge of both the canine to canine distance on a study cast and of the molar to molar distance on the same cast still give us no clue as to the associated canine to molar distance. This situation can be remedied by acquiring three dimensional coordinate information about the set of landmarks in which we are interested. Once three dimensional coordinates are known for any landmark with sufficient accuracy, that point can be related to all other similarly known landmarks unambiguously by simple mathematical calculations. Additionally, because it is so much easier to measure 2-Dimensional surfaces than 3-Dimensional structures, clinical orthodontists have tended to content themselves with the study of 2-Dimensional photographic projections of the irregular three dimensional objects in which they are really interested. For example, photographs of the occlusal surfaces of study casts are being substituted for direct measurements formerly made on the casts themselves. These 2-Dimensional projective transforms are certainly easier to measure than the original 3-Dimensional objects they represent. But while they are adequate for many research and clinical purposes, they do incorporate into the measurement process irrecoverable errors due to the projective displacement of all points not on the principal axis of the camera or x-ray system and they also lose all sense of asymmetry except for that around the principal axis of the camera or x-ray system (Baumrind, 1983). Furthermore, inter-arch measurements which is to say measurements between the upper and lower study casts are difficult to make with acceptable accuracy and reproducibility using available physical methods of measurement because they cannot be made with the cast in physical apposition to each other. Therefore, the accurate and precise measurement of irregular three dimensional structures of a study cast involves technical problems which make it a difficult task to perform efficiently on a routine basis. Since changes in the dentition as a result of treatment through time are 3-Dimensional in nature, optimal evaluation of treatment results using study casts depend in large measure on our ability to conceptualize and perceive changes in three dimensions.

True three dimensional measuring techniques have been applied including the Optocom (Van der Linden et al., 1972; Van der Linden, 1978), stereophotogrammetry (Savara, 1965; Berkowitz, 1971), the Optical Profilometer (Berkowitz et al., 1982), and Image Analysis (Brook et al., 1983) but the techniques are usually cumbersome and are rarely performed. One of the most promising instruments for the measurement of casts to be developed in recent years has been the Reflex Metrograph, both its precision and accuracy have been tested (Butcher and Stephens, 1981; Takada and Lowe, 1982; Richmond, 1984, 1987; Jones, 1987). However, images and data obtained from this method are not shareable and not as efficient as the present method. More highly advanced and sophisticated softwares using high end computer processing units can be utilized but would be impractical due to its excessive operating cost .

A thorough search of the literature has shown that there is no science for the measurement of surfaces comparable to that of stereophotogrammetry, whether the subject be of microscopic dimension or the macroscopic sweep of the earth's surface or the ocean's bottom (Berkowitz, 1971). Baumrind et al (1972,1975,1983,1985), has been conducting studies involving stereo photogrammetry for a number of years. Specialized stereo cameras for 3-D biometric assessment of the upper and lower study casts separately has been designed and constructed (Baumrind, Moffitt, and Symes, 1978; Baumrind et al, 1978). Tests were performed in order to investigate the accuracy of the stereo coordinates obtained from this system (Curry and Baumrind , 1985). However, implementation had to await the availability of more sophisticated equipments at reasonable costs that would ideally have the following characteristics: Ease of image acquisition and display, relatively modest storage requirements, amenable to quantitative evaluation in 2-D and 3-D, quantitative acquisition as undemanding of the clinician as possible, and generate data to reflect inter-arch as well as intra-arch relationships. That time has now arrived.

PRINCIPLES OF STEREOPHOTOGRAMMETRY

The methods of three dimensional measurement which we are developing are adaptations of standard aerial mapping techniques which have a history of seventy years of effective application in civil engineering. We are attempting to apply these principles in a simplified form to the specific tasks of measuring study casts. Photogrammetry is a specialty devoted almost entirely to solving the problems of making accurate 3-Dimensional measurements from paired 2-Dimensional projections (Moffitt and Mikhail, 1979). A very brief examination of basic photogrammetric principles is a prerequisite to an understanding of our own method. The Broadbent method is an x-ray variant of one such photogrammetric system in which two film surfaces lie at right angles to each other and areas between the viewing stations lie at 45 degrees angle to the basic reference plane of the structure being observed (Broadbent, 1931). The Broadbent method is conceptually extremely sound but is in practice somewhat more difficult to use and less reliable than desired (Baumrind, 1975). An alternative to the Broadbent method which has several advantages for our purposes is the stereo-system. In this case, the two film surfaces lie parallel or almost parallel to each other and at the same elevation above the focal points of the stereo camera or x-ray system. This system is typically used in aerial photography (Baumrind and Moffitt, 1972). A camera mounted in an aircraft takes a picture of the terrain from exposure station 1 and then flies on to exposure station 2 at which point another picture is taken. The films are processed and, by one of a variety of systems, the parallactic angle "A" between intersecting rays from each exposure station to the point is computed. If the height above the datum plane (H) and the distance between exposure station 1 and exposure station 2 (termed "base"), and the focal length of the camera are known, sufficient information is at hand to compute the elevation of the object by simple algebraic calculations (fig 1). This set of condition can readily be simulated in the case of x-ray or video camera as shown in (fig 2). Here, two x-ray films are exposed from position 1 and 2. From a geometric point of view, figures 1 and 2 are equivalent. The only difference is that in fig.2, the focal length of the "camera" is equal to the focal spot to film distance (H). As in the aerial case, if the height (H) and base (b) are known, the 3-D position of the point can be calculated quite simply.

In general, our method involves examining a pair of two dimensional digital images taken of the upper and lower study casts separately from slightly different perspectives, (just as, for example, the two eyes of a human being view an object in space from slightly different perspectives). The advantages of the digital image display method include rapid access to images, compactness of storage, and the fact that the information is readily available for various kinds of computer-aided image manipulation. Duplicates of images and data for investigation by other researchers can then be accessed through the network.

Subsequently, each of the pair is digitized individually and the digitized data from each pair of images is integrated using common control points to produce a single three dimensional map by means of a relatively simple set of computer calculations. The back of the upper and lower casts are aligned carefully and clear scotch tape was used between them to maintain their relationship. A stereoradiograph pair of the casts in occlusion are then taken from which the relationship of the two casts in 3-dimensions are determined.

Both the precision and accuracy of this method will be tested as well as the determination of the validity of data collected. Analysis and minimization of the errors inherent in the system will be reported. This includes the theoretical limits of accuracy of the method in general, the physical limits of our own apparatus as used, and landmark location errors in three dimensions.

SPECIFIC AIMS

1. To develop a 3-Dimensional imaging system for measuring study casts that combines stereophotogrammetric and stereoroentgenographic records for the purposes of locating the relationship between the upper and lower study casts in occlusion.

2. Concurrently, to develop a system that will generate a reservoir of information that can be share with other qualified investigators in the field.

3. To report on the initial practical tests of system performance. This includes:

a. determining the reliability of locating landmarks within image.

b. determining the reliability of locating the landmarks between images.

c. comparing 3-Dimensional distance measurements of various pairs of "tiepoints" made from direct physical measurement of study casts with divider and ruler, and computed 3-Dimensional distance measurements from stereo video/x-ray images with an existing software for analysis of stereo x-rays and photographs.

d. determining whether both systems produce coordinate sets of comparable accuracy to fit the 3-Dimensional coordinates from x-rays and video with some confidence.

4. To utilize this method to test a clinical hypothesis that study casts of "well treated" cases will have a larger number of cusp-fossa contacts than cases that were not "well treated" where "well treated" is defined by the consensus of five independent assessments by expert clinicians. Subsequently, this method will be employed for the integration of data from different types of craniofacial record.

MATERIAL AND METHODS

SAMPLE SELECTION

The study casts used in this study are from patients who received orthodontic treatment from a single university trained orthodontic expert. The requirement for classification as an expert was that the clinician satisfy at least four of the following criteria:

1) more than 10 years of clinical experience,

2) certification by the American Board of Orthodontics,

3) membership in the Edward H. Angle Orthodontic Society,

4) more than 5 years as an orthodontic instructor at an American Dental Association approved orthodontic department,

5) publication of one or more original papers in a peer-reviewed orthodontic journal.

Dr. John Gibbs of San Mateo, who provided the cases for this study, is a clinical professor of Orthodontics at the University of the Pacific and met the other requirements above.

For this study, pre- and post-treatment study casts of twelve cases were selected for a total of 24 study casts. All study casts were obtained from the orthodontic office of the treating clinician.

DEMOGRAPHICS OF THE SAMPLE

All of the 12 patients in this study were adolescent patients between the ages of 7.59 to 15.39 years (mean = 10.94 ± 1.76) at the time of pre-treatment records, and between the ages of 12.54 to 18.04 years (mean = 14.92 ± 1.50) at the time of post-treatment records. Females outnumber males by a count of 29 to 19. The proportion of Class I and Class II patients, and extraction and non-extraction patients was equal. The ethnic mix of the population was similar to other practices sampled by our research group in the San Francisco Bay Area.

IMAGE ACQUISITION

A. KEY SYSTEMS PARAMETERS

The key system parameters (Baumrind, 1983) of a dedicated coplanar stereometric system are the relationships between the focal spots of either cameras or x-ray tubes and the film surface. These parameters are used in the geometric computation of the 3-D coordinates of each landmark of interest on the study casts. The key measurements and the relationships among them are illustrated in (fig3):

(1) The distance between the focal spots of the two x-ray tubes---termed "B" (for base).

(2) The distance from the focal spots of the tubes to the film plane---termed "H" (for Height). (In this case it is further assumed that the distance between the film surface and each of the tube focal spots is the same)

(3) The point of contact of the perpendicular ray (also called "central ray" or "principal ray") from each x-ray tube upon the film surface. This point of normal contact is called the "principal point."

Calibration of the system to determine the system parameters prior to acquiring images to specify the relationships between the x-ray tubes and the film surface is possible by direct measurements; however, if key parameters cannot be known with sufficient accuracy (equal or better than $\pm$ 0.5 mm) in advance, as the case in this study, the parameters are treated as unknowns to be determined at the time the films are exposed. This is accomplished by installing within the photographic field an array of artificial control points (fiducials) designed for the specific purpose of facilitating the computation of the key system parameters. Such an array consists in principle of a set of unambiguously identifiable points whose precise relationships to each other are known in advance of image generation. The calibration cage used in this study holds both the points of the array in appropriate relationships and the individual study cast (fig. 4). The precise coordinates of the fiducials were measured by a milling machine located in the mechanical engineering department at the University of California, Berkeley. This defined object space is fabricated from plexiglass. The study cast is placed in the box and with a slight pressure, the glass cover is shut and the gray foam on the bottom keeps the occlusal surface of the cast directly against and parallel to the glass cover that defines the focal plane.

B. RADIOPAQUE MARKERS

Prior to acquiring an image, each upper and lower study cast was labeled by four widely spaced radioopaque 1/8 oz. #11 shotshells from Omark industries. These markers are termed "Tiepoints" and they will relate the upper and lower casts and thus allow merging together of the 3-D coordinates of the same upper and lower casts that were computed separately. The shotshells were superglued on 1/4" color coding avery labels. In order to decrease ambiguity in locating the tiepoints on the monitor by increasing the contrast between the shotshell and its shadow, tiepoints were spray painted canary yellow by Zynolyte #22008 and the inner 3mm of the label was colored black using a black permanent marker.(fig. 5)

C. PHYSICAL MEASUREMENT OF "TIEPOINTS"

The distances between tiepoints of all forty-eight upper and lower study casts were physically measured twice using a divider and a flexible metric ruler estimated to 0.1 mm precision.

D. STEREOMETRIC DIGITAL CAMERA SYSTEM

The function of the stereo digital camera system is to generate a pair of two dimensional digital images taken of the upper and lower study cast separately from slightly different perspective (fig. 24). Digitized data from each pair of images are integrated using common corner fiducials to produce 3-dimensional coordinate data of each landmarks of interest.

The stereo digital images of the 24 pre- and post- treatment upper or lower casts are taken separately using two Pulnix TMC-74 digital video cameras which uses a high resolution solid state image sensor (CCD). The lenses of the cameras are of an offset architectural type as schematically shown in fig 6. This arrangement involves a somewhat higher initial cost but allows the cameras to be moved closer to the study cast than would be possible if the center of the lens were perpendicular to the center of the film. And the closer the camera is to the cast, the better will be our resolution, a factor which is important when working with relatively low resolution computer monitors. The two stereo cameras are connected directly to a Macintosh Quadra 610 and are mounted on a photographic stand looking directly down on the study cast (fig. 7). Adobe photoshop was used to acquire image on the screen. Two images (images A and B) of the same cast taken from slightly different perspective will be acquired and the use of a switch box to switch from one camera to the other is employed. A ComputerEyes/RT SCSI Video Frame Grabber is utilized to capture the images on the screen to be further enhanced and subsequently stored in diskettes.

E. STEREO X-RAY SYSTEM

The purpose in acquiring stereoradiographs of the casts in occlusion is to determine the relationship of the upper and lower casts (via "tiepoints") and thus allow merging together of the 3-D coordinates of the same upper and lower casts that were computed separately.

The upper and lower casts are occluded by aligning the back of both casts. 3M clear scotch tape was used to secure and stabilize the casts during exposure. The stereoradiograph of the study casts in occlusion were exposed with a dedicated coplanar craniofacial x-ray system (fig. 8) located at the University of California School of Dentistry. It was formerly located in the sixth floor x-ray facility in the science building. At that time, it was fully calibrated, but because of the departmental relocation, the device was moved and reassembled twice. Since it has not been possible to recalibrate the system, it should be recognized that the present data are raw and are reported prior to recalibration. (See discussion)

A spring loaded cassette changer is used to change films between exposures from the centered and offset tubes (fig. 9b). There is an elapsed time of 1 to 2 seconds between exposures. Two pairs of study casts in occlusion are placed in a foam shelf and are exposed simultaneously (fig. 9a). Fig. 9c shows a schematic illustration of the stereo x-ray system showing study cast in position.

All images are exposed with rare earth screens on standard 8-inch by 10-inch (203.2-mm by 253.0-mm) x-ray films. A fiducial array consisting of four small lead spheres in the plate holding the film cassettes is exposed on each film. The fiducial marks are used in subsequent processing to control film distortions and to align the images. Various studies (i.e., Veress and Lippert, 1977) have examined the effects of x-ray film distortion and of the finite size of the x-ray focal spots on computed coordinate values. We reduce the effects of film distortions by transforming the image coordinates into the coordinate system of the fiducial array with a four parameter transformation. Errors due to the size of the focal spot are ignored.

Fig. 10. consists of a sample stereopair from this system. Note the radiopaque "dots" on each upper and lower cast on the centered film, and the amount by which they are displaced in the offset member of the pair. These are the tiepoints, and they are useful illustration of the amount of image displacement between the two films.

DATA ACQUISITION AND PROCESSING

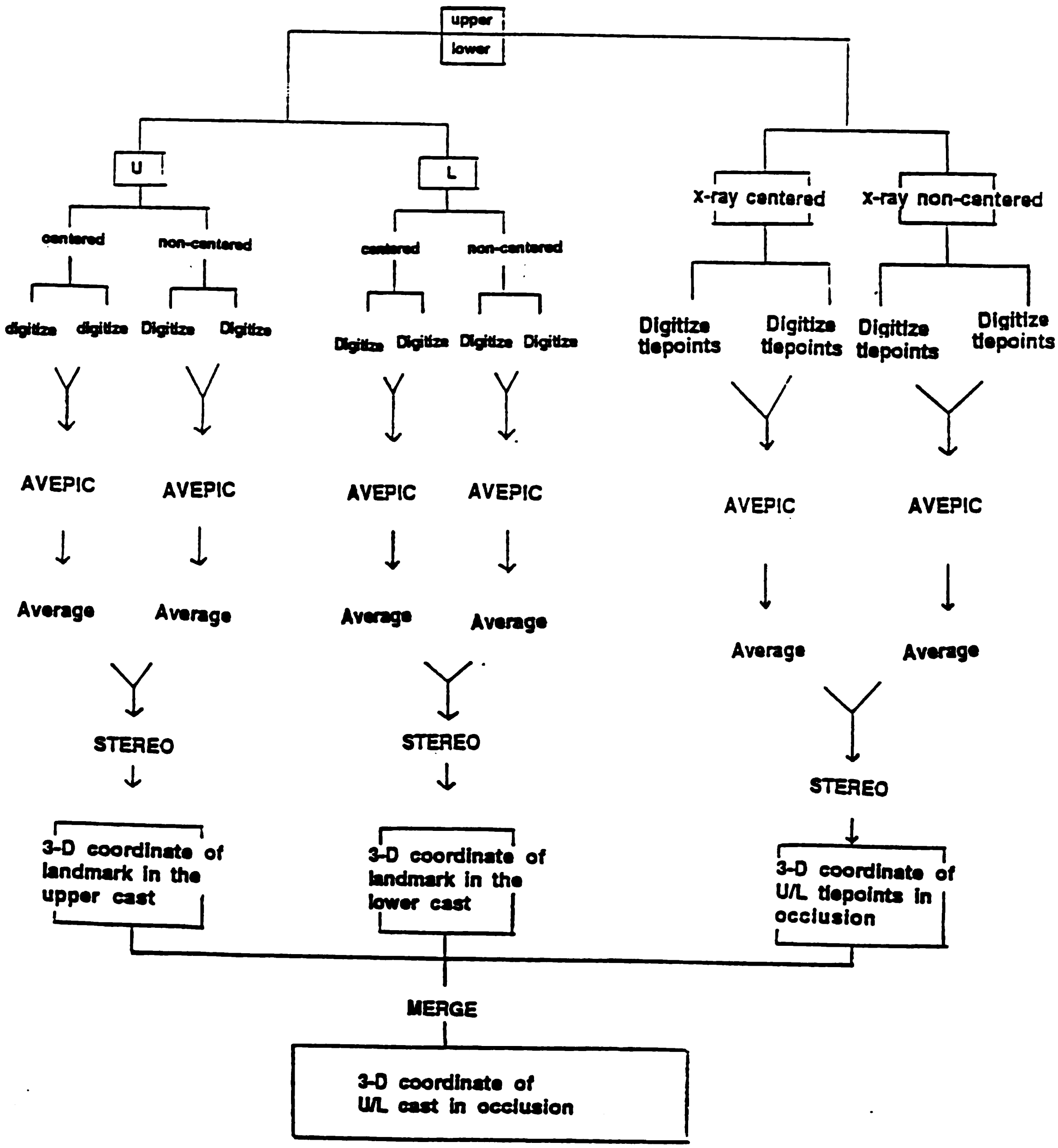
The digitizing of stereo digital images was done using a specially written digitizing program called cranioimage 2.2 which adapts the earlier system of the UCSF Craniofacial software package (Baumrind, 1980) to use on a Macintosh computer monitor software. The dental landmarks, fiducial array, and "tiepoints" on each member of the stereoimage pairs were digitized directly on the screen by pointing the cursor. The images are then stored in floppy disks. The data generated are then transformed into a format readable by an IBM compatible computer where they are subsequently processed as will be described below. Fig. 11 shows the landmarks located.

The general procedure for digitizing stereoradiographs also followed The University of California San Francisco method (Baumrind, 1980); however, it differs with the above in that only the upper and lower radiopaque "tiepoints" on each member of the pairs of stereo x-ray images were digitized using a SAC GP3 graf/pen acoustical digitizer linked to the IBM compatible computer by a conversational mode program called DIGITIZ (fig. 12).

All data are processed using an interactive package developed by CRIL. The software, originally written in FORTRAN 77 for use on a VAX 11-750 in a UNIX environment has been rewritten to run on any IBM compatible PC using a 286 or subsequent processing chip. Each image is digitized twice, and the files of digitized coordinates are then passed to an averaging and checking program called AVEPIC. Because the fiducials are also digitized and included in each file, additional digitizings of the same frame can be added at a later time and transformed to the system of fiducial coordinates. This allows for error correction and the addition of new points.

Each member of the pair of both type of images (digital and radiograph) were digitized twice; and, the averaged coordinates for pairs of images are passed to a general 3-dimensional computation program called STEREO. The program determines which camera or x-ray device was used for image acquisition and refines the image coordinates appropriately. Digitized coordinate values are fit to the calibrated fiducial values using a four parameter transformation. All coordinates are then transformed to a principal point coordinate system and, in the case of the digital camera, corrected for lens distortions. Three-dimensional coordinates are computed from the intersections of conjugate rays, and the residual parallaxes are reported.

The flow chart below summarizes the protocol used: (fig. 13)



DATA ANALYSIS

Direct Physical Measurements of distance between "Tiepoints":

All physical measurements of the study casts were determined twiced by one of the investigators in the same day. The size of the combined method error (ME) was calculated using the formula $ME = \pm \sum\sqrt{d^2 / 2n}$ (Jones, 1991), where d is the difference between two registration of a pair of "tiepoints" and n is the number of duplicate registrations. Method error of 3 cases are presented in table 1 on page 48.

The reliability of the estimates of the various landmarks within image:

After all the video and x -ray images for a given case have been digitized successfully, the data are passed to a batch program called AVEPIC. The rigid matrix of digitized values for each tracing of a given image or x-ray film is rotated and translated mathematically to best-fit registration upon the program's built-in representation of the relative positions of the selected four corner fiducials. The optimal mathematical registration on corner fiducials is accomplished by a least-squares subroutine which analogizes mathematically the physical operation represented schematically in fig. 14.

The computer calculates the linear distance (hypotenuse) between the built-in values for the "known" positions of the corner fiducials and the digitized values for each corner fiducial for each tracing and then computes the mean of the four hypotenuse for each tracing.

If , for any tracing, the hypotenuse values exceeds 1.0 mm or if among the several tracings for any given film the range among hypotenuse values exceeds 0.3 mm, then processing for that film ceases and the fiducials are redigitized. If all tracings for the film stack properly, processing proceeds. The coordinate values for all points on each stereo video tracing have been expressed in terms of the coordinate system used when it was measured by a milling machine at the University of California, Berkeley. The value of points on the stereo x-rays were expressed in terms of an orthogonal system based on two of the corner fiducials.

Since errors for the unambiguous fiducial points will usually be much smaller than the errors for the more ambiguous anatomic structures (fig. 14), the program then proceeds to check the reliability of the estimates of the various landmarks for the several tracings within each video or x-ray image. Since there are no previously known characteristic envelope of error of different study cast landmarks, the envelope of errors for each landmarks on the study casts were set within

1 mm or less depending on how ambiguous the point is. Assuming that the estimate on each tracing were equally valid, the computer will calculate the best estimate to be the mean value among the two tracings. If one of the two or three digitized value for example was grossly different from the other value, this outlier will be discarded based on the "set" envelope of error for that landmark. A process which is the precise mathematical equivalent of this averaging operation is built into the program AVEPIC and is used for each landmark located.

The AVEPIC output file contains in its first two columns the best estimates of the X and Y coordinates of each landmark, tiepoints, as well as data as to how good those best estimations for that particular point or landmark in the form of the sums of squares in X and Y and the sum of the cross products XY for the replicate tracings, thus, indicating the reliability of locating landmarks within images.

a. Fig. 15 shows four TRACING files created from a pair of digital images (centered and oblique) of case #114. The upper and lower left tracing files represents the exact locations of the points which were digitized from the centered image of the pre-treatment upper cast at time point 1, while the upper and lower right tracing files represents the points from the oblique image of the same upper cast. A tracing file is uniquely determined by study number, film number, and point sequence. The file consists of four main columns that represents the point name, point number, x coordinate, and y coordinate respectively starting from the left.

b. Fig. 16 shows two AVEPIC files made from the previous TRACING files (fig. 15) of case #114. It contains the averaged point coordinates, plus some simple statistical measures of how well the different digitized estimates of each point agreed among themselves. The file on the left is the averaged point coordinates of the centered image of the pre-treatment upper cast at time point 1, while the right one is from the oblique image of the same upper cast. The file consists of seven main columns representing the point number, point name, x coordinate, y coordinate, sum of squares of x residuals, sum of squares of y residuals, and sum of (x residual times y residuals).

c. Fig. 17 shows TRACING files of upper and lower tiepoints from pair of x-ray images of timepoint 1 upper and lower cast #114 in occlusion.

d. Fig. 18 shows the two AVEPIC files of the same tiepoints made from the tracing files shown in fig 17.

The reliability of the estimates of the various landmarks between images (images A & B):

The AVEPIC files generated previously are required input file for the program called STEREO. The STEREO program is used to compute the 3-Dimensional coordinates (x, y, z) of landmarks which have been digitized on pairs of films (created using the "avepic" program) from the stereo video or x-ray devices. The subsequent stereo file generated by the STEREO program not only contains the x, y, and z coordinates of each landmarks; but also more importantly, the residual parallaxes are reported for each point which is a determination of the reliability of the estimates of landmarks between images A and B of an upper or lower casts or x-ray film. If they are small, and randomly plus and minus, the run is likely good. If they are small for the fiducials, but large for other points, then the casts may have been moved within the calibration cage prior to acquiring the second image or the patient moved prior to exposing the second x-ray film. If the parallaxes are large for all points, there may be a digitizing error, the film may be reversed, or an incorrect camera file may be specified in an input file called CHECK.DAT. The parallax is simply the amount by which the two rays of light from each film do not intersect in space. In a perfect system, they would intersect exactly, but an acceptable value would be $\pm$ 0.2 mm.

a. Fig. 19 shows a STEREO file from the joint processing of the two avepic files, representing a stereo pair of films from fig. 16. The first five columns represents the point names, x coordinates, y coordinates, z coordinates, and y parallax value (smaller is better) respectively.

b. Fig. 20 shows a STEREO file from the two "tiepoint" avepic files from fig. 18.

Comparison of 3-Dimensional distance measurements between various pairs of tiepoints on the upper and lower casts made by the three different method of measurements:

In our system, we can measure the "tiepoints" (in each upper and lower cast separately) and teeth on digital images, but we can only measure "tiepoints" (in the occluded upper and lower study cast) in the x-ray images. The question becomes how much confidence can we have that these things are comparable. The minimum requirement to determine this would be by computing the distances between several two points and comparing them. If the distances between several two points measured the same for all methods (digital image, x-ray image, and direct physical measurement of tiepoints), we can have confidence in the results. Calculation of the Root- Mean-Square (RMS) errors for the stereo video and x-rays were done to determine whether the level of system performance is acceptable.

a. Table 2 shows comparison of data generated by the three different method of measurements taken from the pre-treatment (timepoint 1) and post-treatment (timepoint 2) upper and lower casts of case #210.

Determining whether both systems produce coordinate sets of comparable accuracy to fit the 3-Dimensional coordinates from x-rays and video with some confidence:

The merge program merges two 3-Dimensional coordinate maps (stereo files generated by stereo program) together. It needs at least three common points in the two systems (tiepoints), and fits them together by rotating, translating, and scaling the second file to fit the first as nearly as possible. The output MERGE file consists of the transformation parameters, and the coordinate values of points in both systems.

a. Fig. 21 shows a MERGE output file generated by superimposing the stereo file (3-D map coordinates) of the upper cast computed from the pairs of digital images on the stereo file of the same upper cast computed from the pairs of x-ray images via the common "tiepoints". This data was taken from case #114 at timepoint 1.

FINDINGS

1. The reliability (reproducibility) of the measurement of the physical distances between "tiepoints" using calipers compared favorably with the reports of others (Walter, 1953; Nance, 1947; Nef, 1957; Bolton, 1958; Cooper,1960; Huckaba, 1964; White and Hobbs, 1977). The method error for paired measurements for all "tiepoint" pairs of the final twelve case sample was 0.11 ± 0.11 mm. In evaluating this finding, it should be remembered that the conceptual and difinitial problems in locating "tiepoints" are minimal since they are simple metal spheres.

2. The reliability of landmark location on the individual digital images of study casts was also quite good, the reliability being on the order of 0.3 mm for most landmarks. This indicates that we are fairly confident in our ability to locate the same landmark repeatedly on the centered image and on the oblique image considered separately.

3. The test of how well we locate the same anatomical point on the centered and oblique films of each film pair involves analyzing the relationship between the paired images of the point on the centered and oblique films. As was explained previously, the change in the residual y parallaxes for each point indicates the reliability of locating the landmarks between centered (image A) and non-centered (image B) digital or x-ray images. Once the two principal points O and O' are located (fig. 3), and if both images are superimposed together on the common reference points, removing extraneous rays, the situation can be illustrated schematically in fig. 22. We will observe that the base distance (B) between cameras or x-ray source must be precisely the same as that between the datum plane representations of the two principal points O and O'. The line between P1 and P2 of the image (P) should be parallel to the

line O and O'.

The mean of the between image mean residual y parallax between the upper stereo digital image pairs was -0.02 mm $\pm$ 0.08. The analogous error for the lower stereo digital pairs was -0.01 $\pm$ 0.07.

However, because of inadequate system calibration, we observed a "warping" of the relationship between the two images of each stereopair of digital photographs. This twisting is represented schematically in figure 23 which departs from the ideal case of figure 22 in that the line (B) between the focal spots of the two cameras is <u>not</u> parallel to the line between the two principal points on the film plane (represented as O and O') and is also not parallel to the conjugate points P1 and P2 which represent the film plane projection of a typical anatomical dental landmark.

4. The experience with the x-ray stereopairs was precisely analogous to that with the photographic stereopair. The individual "tiepoints" on both the centered and the oblique film were located with high reliability but the relationship between the images on the centered and oblique films of each pair showed a warpage greater than that for the photographic system. This is explained by the fact that resources had not been available for the recalibration of the stereo x-ray machine following its three moves from its original highly calibrated site in S616. (First it was dismantled and stored for over a year in the Department of Orthopedic Surgery's research laboratory in HSW. Then it was moved and reassembled in D1118. Finally it was taken apart again, moved and reassembled in room D1102. Because appropriate resources were unavailable, proposed recalibration at the new site which had been intended as a prelude to the present study was never performed.)

5. The implications of the lack of calibration became apparent when we

attempted to merge data from the three sets of "tiepoints" measurements. (Direct physical with calipers, sterephotogrammetrically from digital images and stereoradiographically from x-ray stereopairs). Note that in order to fit these stereopairs, it was necessary to rotate and translate the three dimensional digital maps from both the stereo x-rays and sterephotographs. These displacements and transformations cause the errors of measurements to propagate dramatically. the result of this propagation may be seen in table 2. Thus for most case we were unable to merge the x-ray and photograph maps together.

DISCUSSION

As noted earlier, the immediate purpose of this project was to obtain quantitative answers to a set of specific clinical questions. These questions concern measuring the linear distances between teeth in the opposing arches measured in occlusion. Later, we intend to utilize the method developed here to document spatial changes between teeth within and between the upper and lower arches in 3-dimensions. This long range goal will involve the integration of measurements made on cephalograms, study casts, and facial photographs into a single 3-dimensional map of the face.

The rationale for our long range goal is as follows: orthodontists have traditionally analyzed physical changes in treatment and growth by capturing data from (1) x-ray films of the skull and teeth; (2) study casts of teeth, and (3) photographs of face and mouth. Each of these types of physical record allows us to examine a portion of the total variability in the growing face but none by itself allows us to access all the information needed for the understanding of growth and treatment changes. In fact, each type of record sharpens our understanding of some aspect of physical change by discarding information about other aspects of physical change. Unfortunately, the dissection of the face into three separate types of physical record inevitably involves the lost of information about the interactions between the records. The use of 3-dimensional mapping methods has the potential of allowing us to reintegrate information from all three types of record to yield a single integrated and coherent picture.

To date, clinicians and craniofacial investigators integrate the information from different records conceptually. This is to say, they usually examine study casts, x-ray films, and photographs and merge information from them as a mental operation. While clinicians have become very adept at this process, it does not permit quantitation of the interactions between records of different types and it does not permit averaging across subjects.

The system we are utilizing that is capable of accomplishing the above objectives employs the principles of stereophotogrammetry (Baumrind, 1975). This method involves computing 3-dimensional coordinates from pairs of 2-dimensional overlapping camera images taken under properly defined conditions, and by using four common merge points, which we call "tiepoints" with previously determined coordinates, data from two different 3-dimensional transforms (digital photographs and analog x-ray images) could be merged into a single integrated map with extreme accuracy.

No other previously developed system has had the potential for integrating information from different types of craniofacial image into a single coherent 3-dimensional map. Other 3-dimensional systems such as CT and MRI have been proposed for 3-dimensional measurements of the study of craniofacial growth and orthodontic treatment. MRI is intrinsically attractive because it involves no known radiation hazard. However, MRI is notoriously poor for imaging calcified structures and is best for the observation of subtle differences in soft tissue density. CT is far better for analyzing hard tissue but involves considerable radiation doses, streak artifacts from metal appliances and fillings, poor resolution in the axial direction, and relatively high economic cost. For these reasons, despite its apparent attractiveness, it has never been utilized for orthodontic records keeping and, indeed, is used only rarely in routine maxillo-facial surgery.

The underlying purpose of the project was to test the merging and integrating capability of the stereo method as applied to a craniofacial problem. But in order to test the logic and implementation of the stereo method without subjecting living subjects to non-diagnostic radiation, we developed a surrogate experiment in which study casts were substituted for living patients. As explained in the introduction, the findings from this surrogate experiment will themselves be useful for the evaluation of occlusal development and orthodontic treatment. The ultimate test for the goodness of calibration was the correspondence among distances between "tiepoints" measured by the three different method. Examination of the comparison of values in table 2 shows that the errors in the system are too large for it to be practical to test the original hypotheses satisfactorily at the present time.

Despite the short range failure of our clinical application, much has been learned in the process of developing the system. We were able to develop the apparatus for acquiring stereo digital images of study casts in a usable configuration. The only shortcoming of this part of the system has been our inability thus far to calibrate the control cage which contains the study cast with sufficient accuracy and precision. The mechanism for offsetting the camera lenses so as to permit the use of the full format of the digital camera chip was successfully completed. The previously existing CRIL digitizing program was successfully rewritten to function on the Macintosh using images imported from the NIH Image 1.45 program. A successful protocol for enhancing the captured images was established. We were able to generate 3-dimensional photographic coordinates of points on the individual upper and lower study casts. Finally, the stereo x-ray machine was reassembled to approximate closely its original configuration in room S616. We were also able to obtain 3-dimensional measurements of the upper and lower "tiepoints" from the stereo x-rays. But because of limitations in the accuracy of our calibration, the system errors are still too great to answer clinical questions we had previously proposed to answer.

Fortunately, there are strong internal indications that our raw digitizing data is both reliable and accurate. The evidence for this statement is that these data passed the reliability checks of our tracing-averaging program called AVEPIC. Thus we feel justified in asserting that when resources become available at a later date to calibrate our x-ray and photographic systems better, we will be able to use the data already gathered to test the original hypothesis.

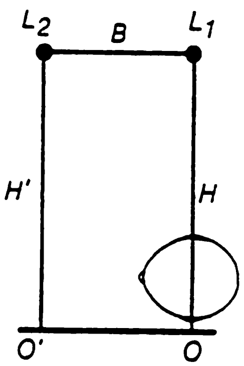


Fig. 3

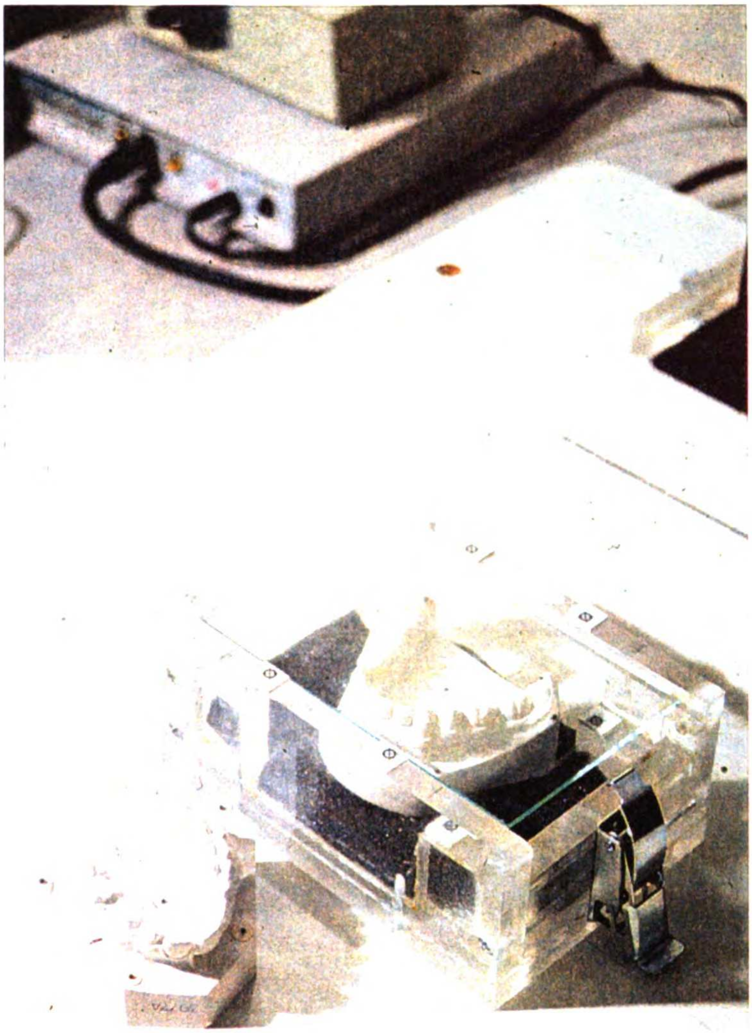


Fig. 4

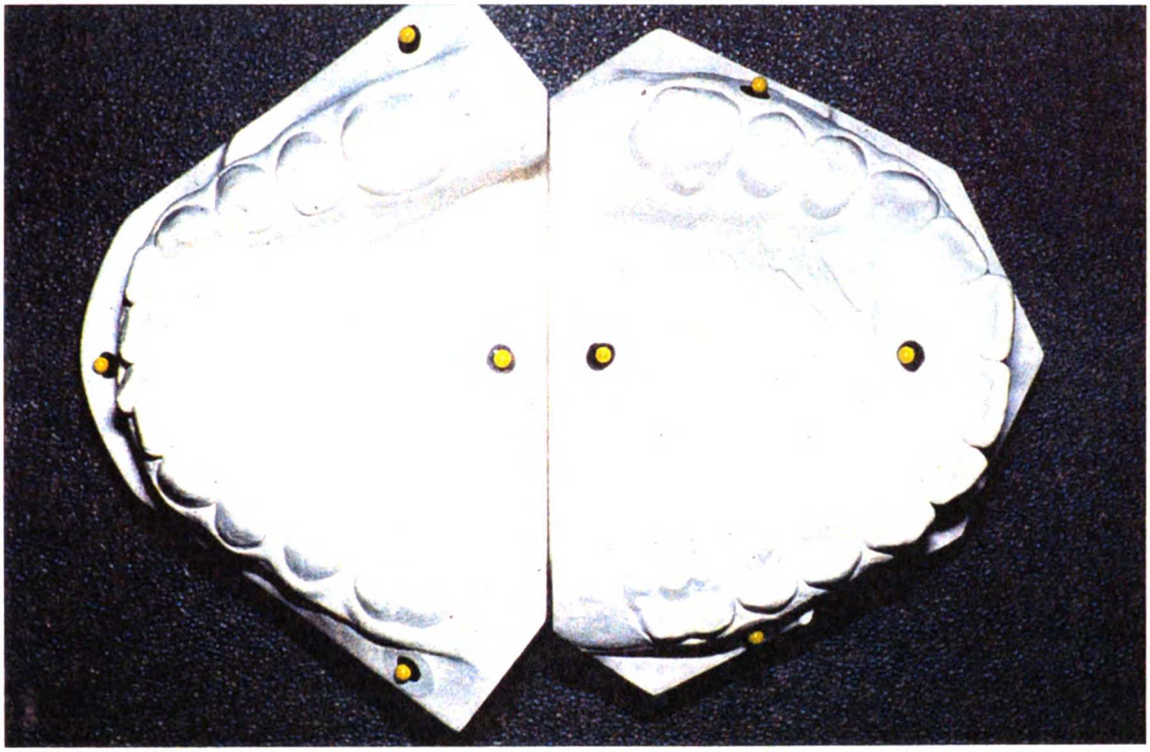
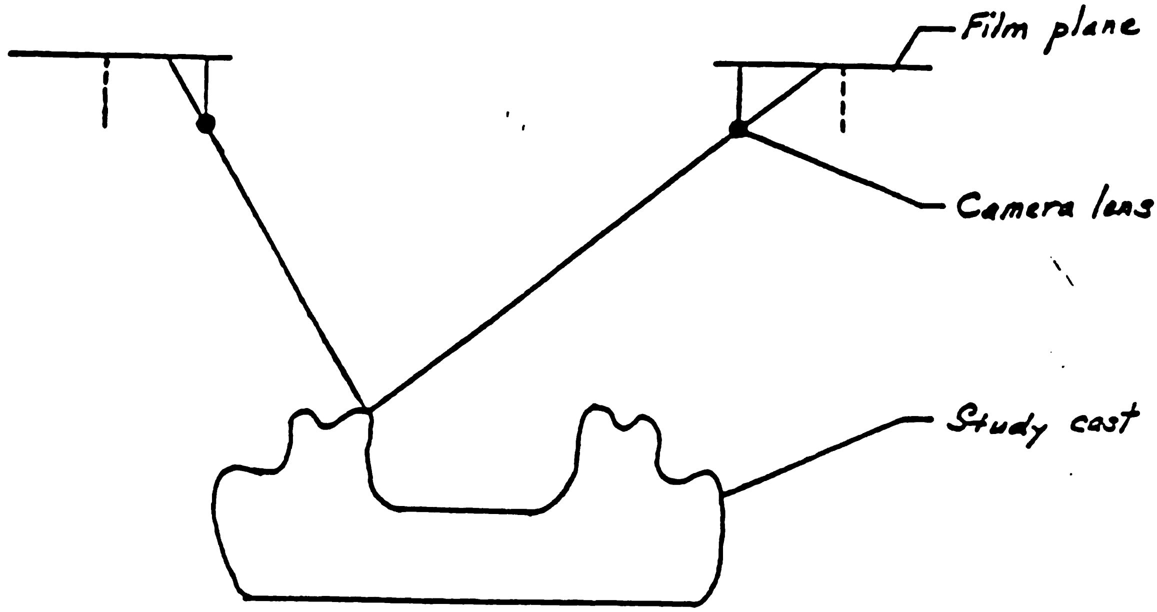


Fig. 5



Center of the lens is offset from the center of the film. If the center of the lens were in the center of the film (as shown by the dotted line), then the image of the part of the study cast would fall either medial or lateral to the film surface. This could also be controlled by having the camera axes converge-- but in that case the film surfaces would no longer be co-planar and the geometry would become more complicated.

Fig. 6

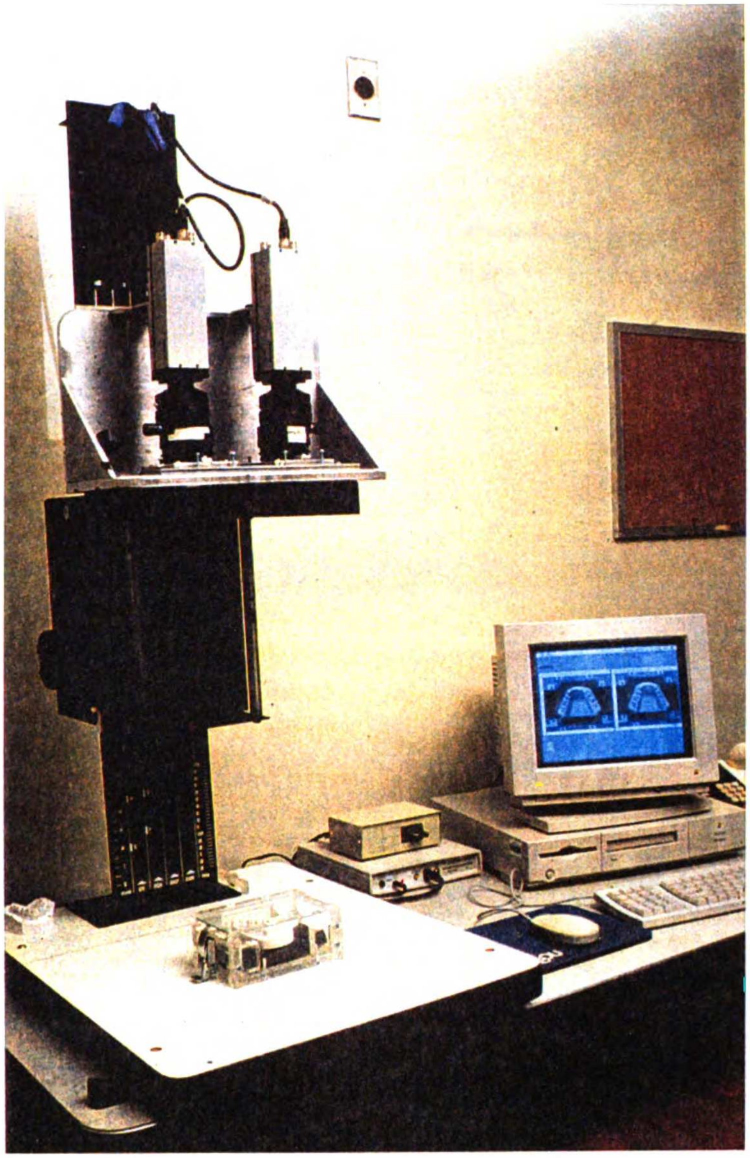


Fig. 7

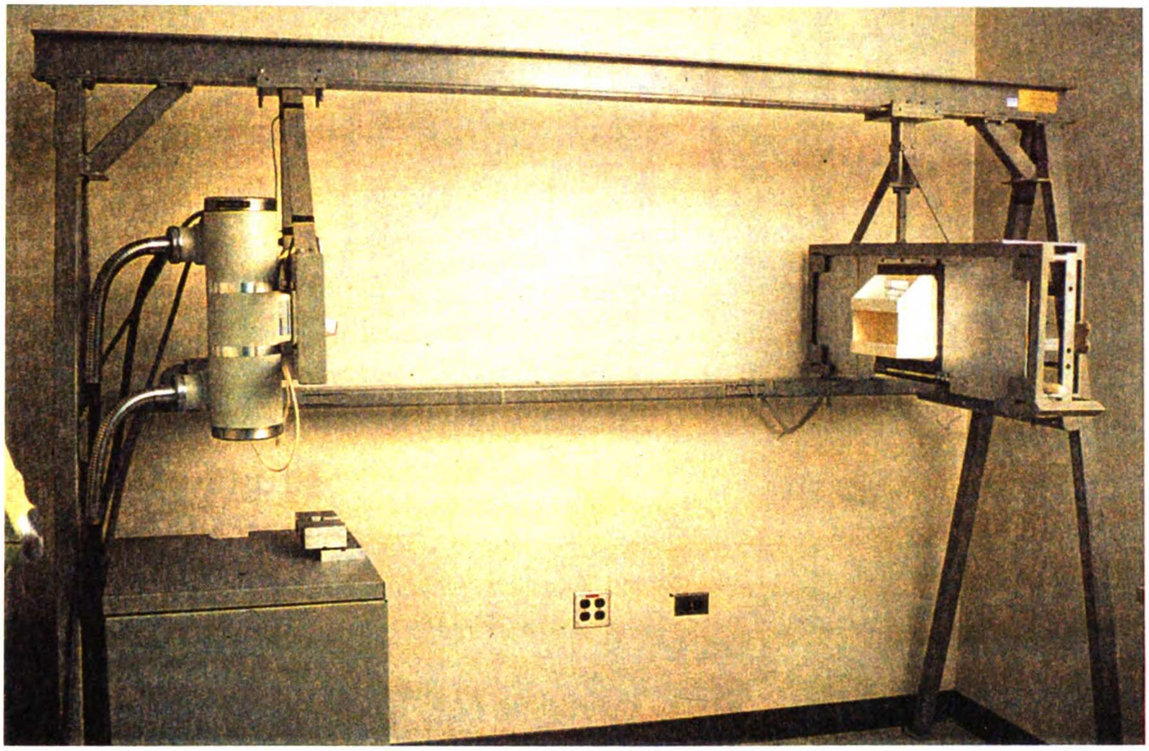


Fig. 8

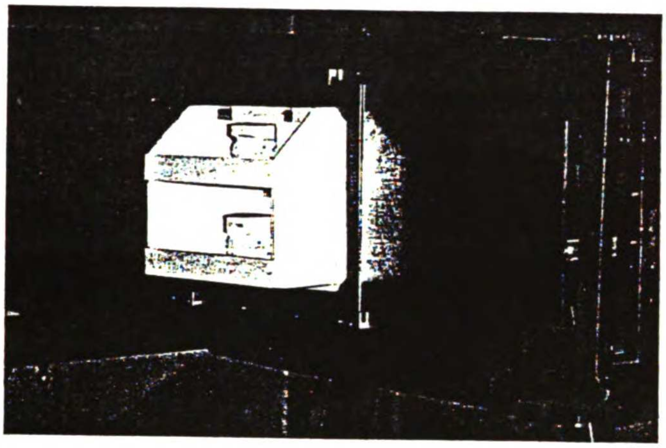


Fig. 9a

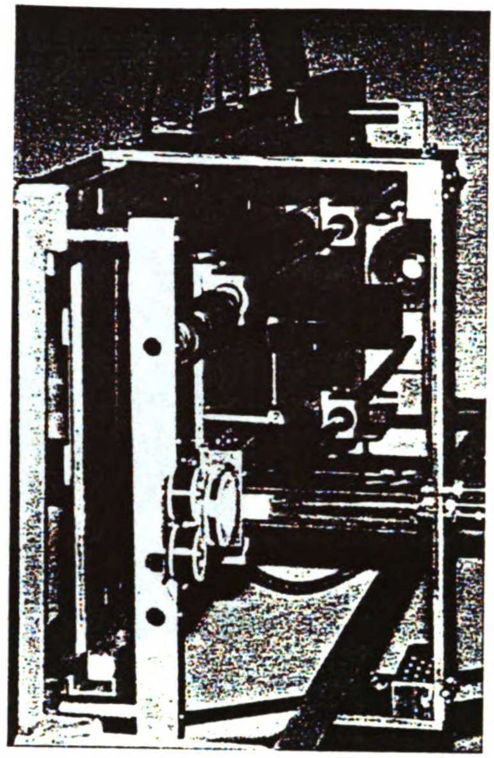


Fig. 9b

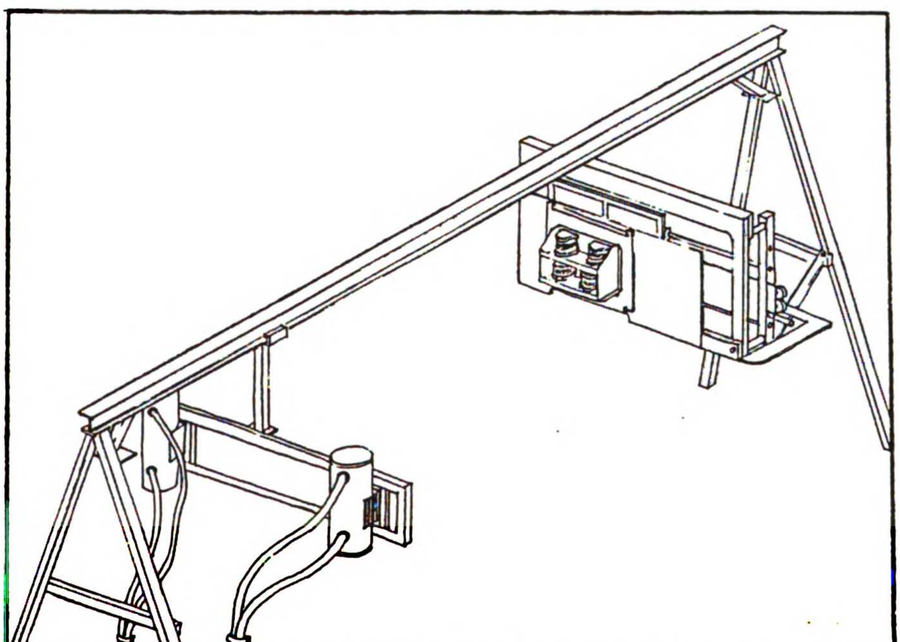


Fig. 9c

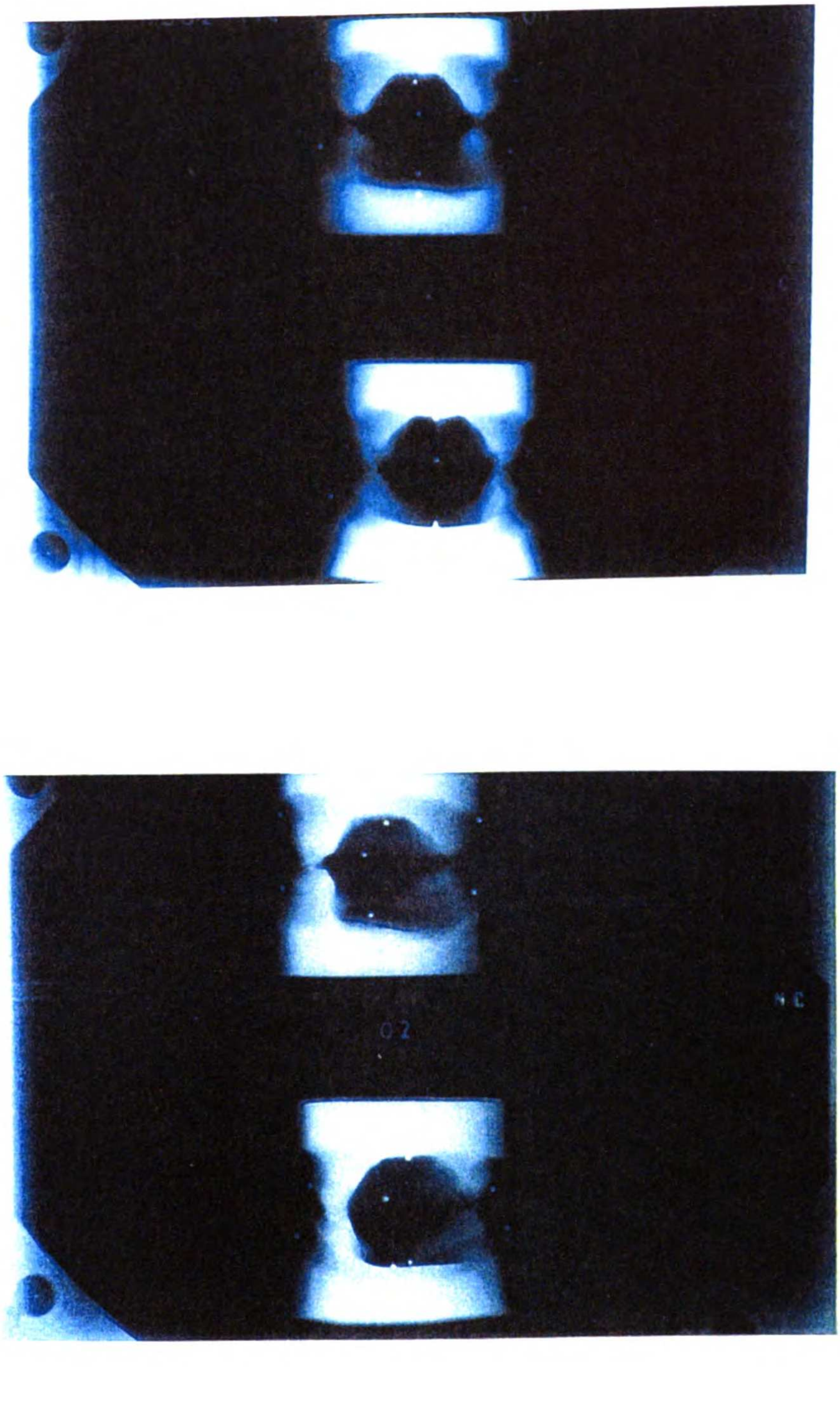


Fig. 10

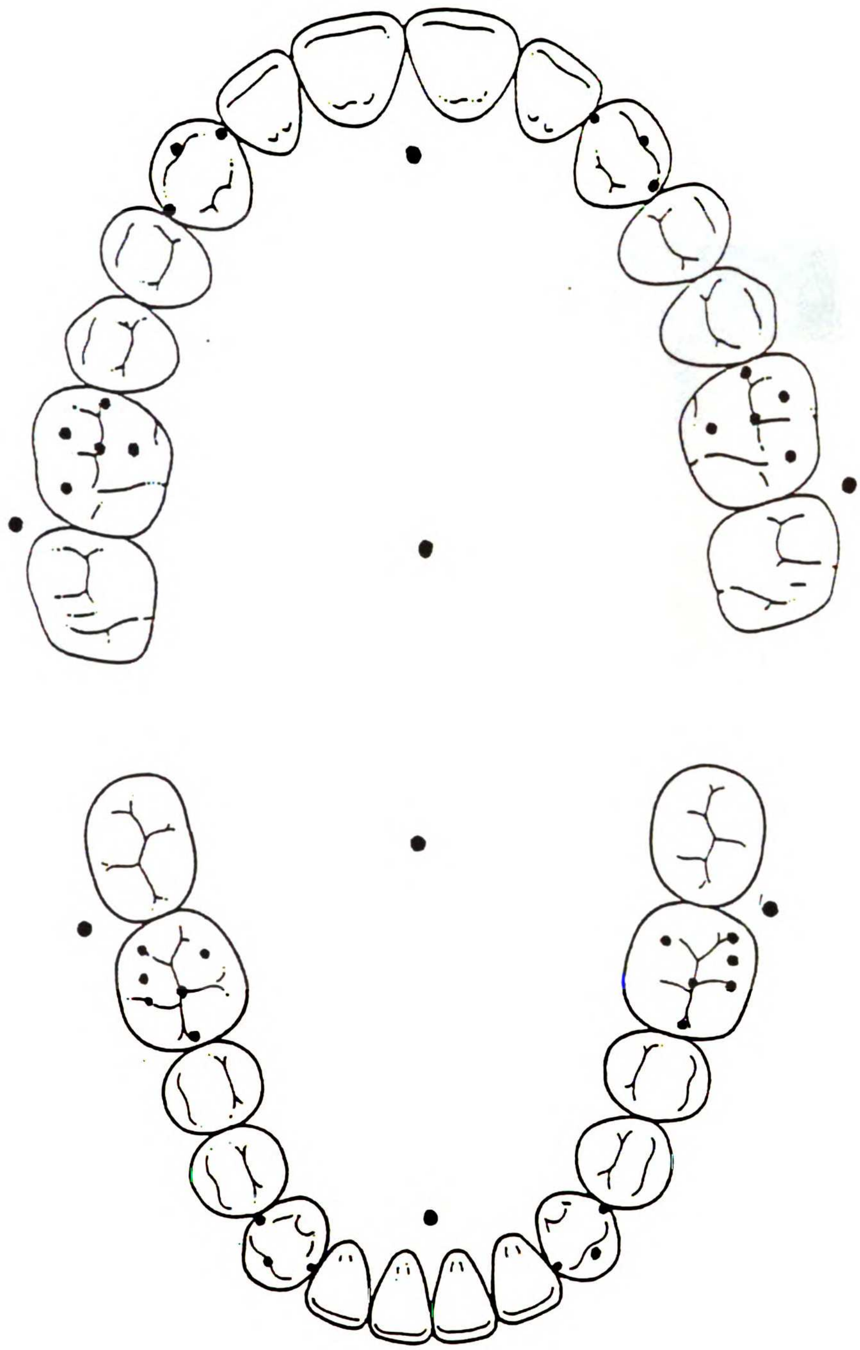


Fig. 11

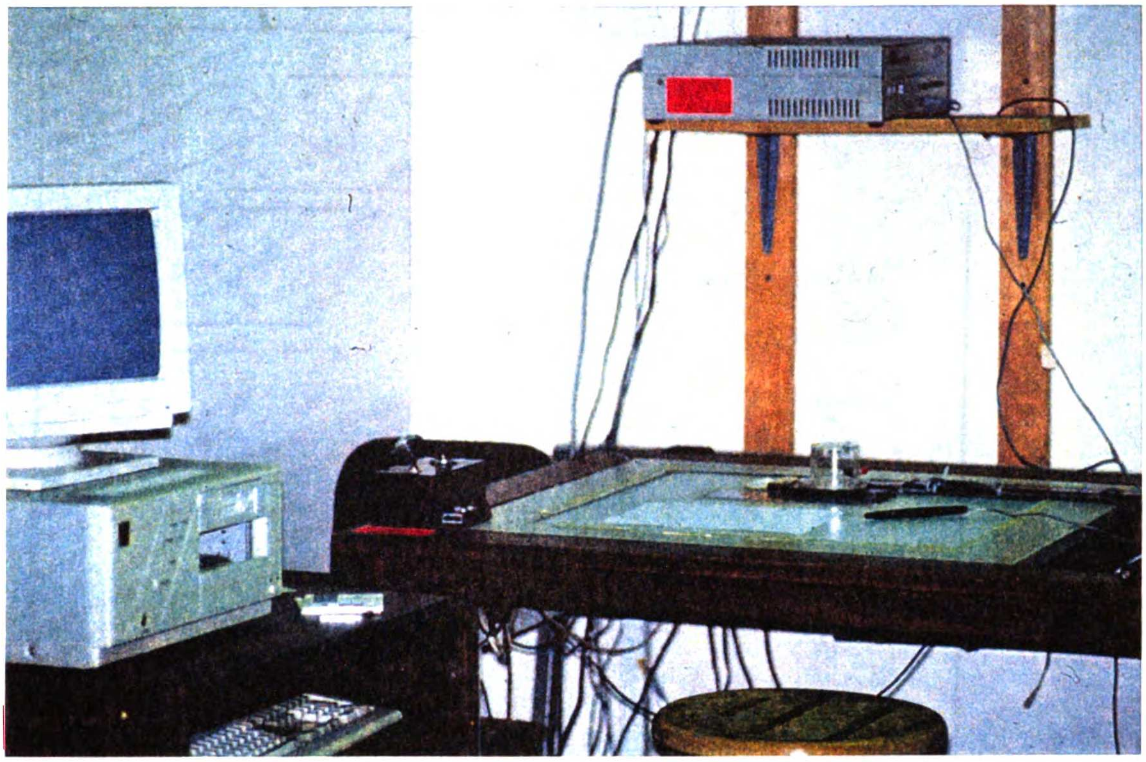
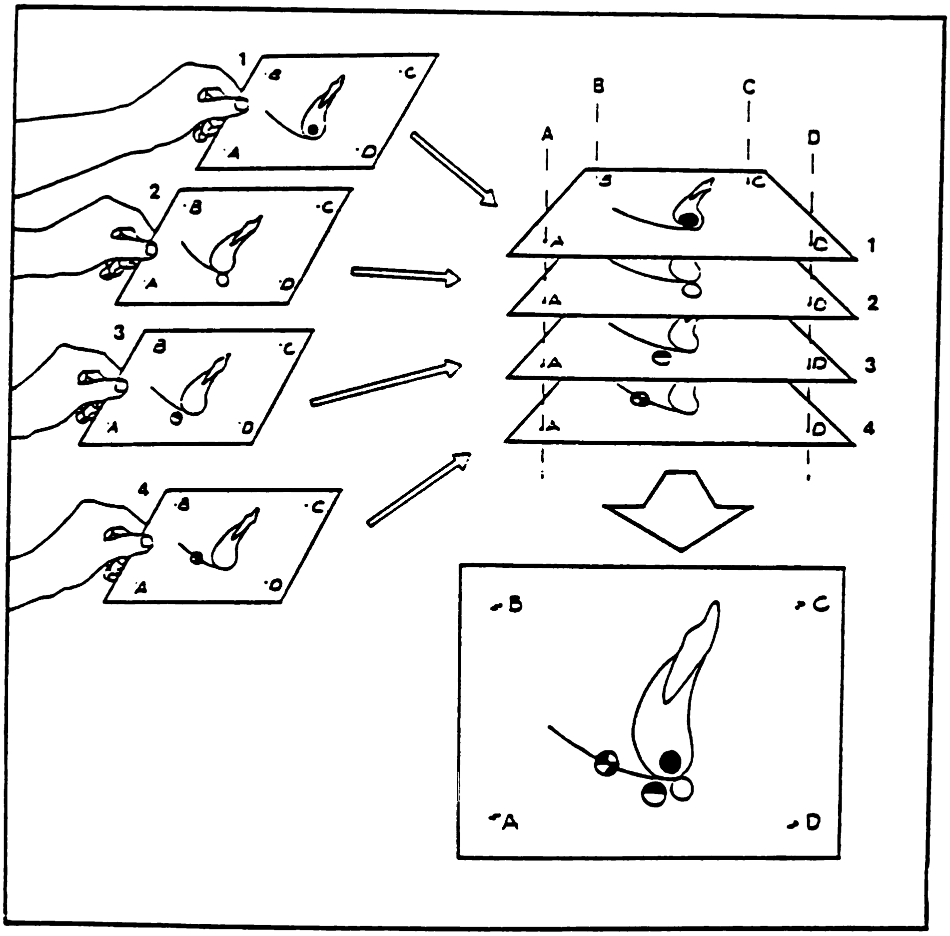


Fig. 12



Fiç. 14 Schematic representation of the physical operation of stacking fo.ır independent tracings of the same head film on the corner fiducials A.3,C, and D. Note that the errors for the fiducial points themselves will be much snaller than the errors for the more ambiguous structures. This figure was used with permission from Dr. Sheldon Baumrind.

Fig. 14

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Fig. 15

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-77

9502 1.01636 3 7 96
11411 R 10/30/87 / / F LUTT,BETT 12/30/75 .UC

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-77

Fig. 16

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  0 1 :UTIP1      581  147.40  208.70
  0 2 :UTIP2      582  183.40  196.60
  0 3 :UTIP3      583  216.90  209.90
  0 4 :UTIP4      584  181.40  207.60
  0 1 :LTIP1      587  215.90  185.20
  0 2 :LTIP2      588  184.30  175.90
  0 3 :LTIP3      589  149.60  183.30
  0 4 :LTIP4      590  184.10  168.40
 -7
H               DATE FILE CREATED =  4/ 3/80   BY moses
9502LATSKX  11482     MERGE
  1 N
  0 A :LL_REG     821   65.80   40.10
  0 B :UL_REG     822   57.80  220.00
  0 C :UR_REG     823  280.90  228.30
  0 D :LR_REG     824  309.40   36.50
  0 1 :UTIP1      581  153.30  209.50
  0 2 :UTIP2      582  189.30  197.20
  0 3 :UTIP3      583  222.70  210.00
  0 4 :UTIP4      584  187.60  208.00
  0 1 :LTIP1      587  222.10  185.60
  0 2 :LTIP2      588  190.10  176.80
  0 3 :LTIP3      589  155.60  184.60
  0 4 :LTIP4      590  190.20  169.10
 -7
```

Fig. 17

9502	.99336	3 7 96						
11481 R	10/30/87	/ /	F LUTT,BETT				12/30/75	.MER
821 A	:LL_REG	.89	-178.48	.021	.019	-.020		
822 B	:UL_REG	.00	.00	.006	.060	.019		
823 C	:UR_REG	221.79	.00	.050	.000	-.004		
824 D	:LR_REG	242.81	-191.09	.000	.016	-.001		
581 1	:UTIP1	86.75	-13.75	.037	.003	-.011		
582 2	:UTIP2	115.46	-27.19	.021	.002	-.006		
583 3	:UTIP3	155.12	-15.61	.001	.002	.002		
584 4	:UTIP4	122.92	-16.65	.002	.000	-.001		
587 1	:LTIP1	153.53	-40.05	.008	.035	-.017		
588 2	:LTIP2	117.38	-47.99	.111	.000	.006		
589 3	:LTIP3	87.37	-38.78	.037	.000	.001		
590 4	:LTIP4	124.21	-55.37	.094	.000	-.005		
-77								

9502	.99337	3 7 96						
11482	10/30/87	/ /	F LUTT,BETT				12/30/75	.MER
821 A	:LL_REG	1.25	-178.76	.001	.000	.000		
822 B	:UL_REG	.00	.00	.000	.002	.000		
823 C	:UR_REG	221.70	.00	.003	.000	.000		
824 D	:LR_REG	242.82	-191.34	.000	.001	-.001		
581 1	:UTIP1	94.34	-13.77	.002	.049	-.009		
582 2	:UTIP2	129.58	-27.33	.005	.038	-.014		
583 3	:UTIP3	163.31	-15.72	.008	.157	.034		
584 4	:UTIP4	128.18	-16.44	.053	.127	-.082		
587 1	:LTIP1	161.52	-40.06	.099	.036	-.059		
588 2	:LTIP2	129.59	-47.76	.011	.001	.004		
589 3	:LTIP3	95.56	-38.82	.057	.022	.035		
590 4	:LTIP4	129.24	-55.30	.118	.012	-.038		
-77								

Fig. 18

LATSKX 9502 11411 11412 123075 103087 F 3/96/ 7
LUTT,BETT UL_REG UR_REG LR_REG
1109.61 1169.04 -61.76 41.66 1103.42 144.21 39.83 1163.22

LL_REG	1.12	-57.43	.14	-.07	811	2	2
UL_REG	.00	.00	.00	.07	812	2	2
UR_REG	88.41	.00	.00	-.05	813	2	2
LR_REG	87.50	-56.58	.00	.13	814	2	2
LL_ROD	18.27	-72.76	-26.27	-.13	701	2	2
UL_ROD	17.93	15.70	-26.27	.09	702	2	2
UR_ROD	68.20	15.94	-26.36	-.08	703	2	2
LR_ROD	69.43	-72.10	-25.91	.04	704	2	2
UTIP1	3.99	-36.83	.35	-.09	581	2	2
UTIP2	38.43	-12.09	-12.84	.03	582	2	2
UTIP3	72.69	-35.92	-2.16	-.09	583	2	2
UTIP4	37.85	-45.80	-3.10	.07	584	2	2
UR6_DBCT	11.14	-32.62	-18.94	-.01	1001	2	2
UR6_MBCT	12.23	-28.54	-18.26	-.38	1002	2	2
UR6_MLCT	16.85	-32.11	-18.30	.46	1003	2	2
UR6_COP	14.74	-31.12	-17.28	-.23	1004	2	2
UR6_MMR	14.99	-27.87	-13.94	-.16	1005	2	2
UR3_DCON	19.76	-13.74	-17.22	-.13	1006	2	2
UR3_LCT	20.33	-8.67	-19.19	-.22	1007	2	2
UR3_MCON	22.79	-7.88	-13.36	.04	1008	2	2
UL3_MCON	54.59	-9.15	-14.18	.38	1009	2	2
UL3_LCT	57.21	-10.40	-17.11	-.43	1010	2	2
UL3_DCON	58.11	-14.00	-16.24	-1.43	1011	2	2
UL6_MBCT	64.56	-30.44	-18.33	.21	1012	2	2
UL6_DBCT	65.29	-35.12	-18.98	-.05	1013	2	2
UL6_MLCT	59.77	-33.59	-21.36	.58	1014	2	2
UL6_MMR	61.52	-30.25	-17.71	-.05	1015	2	2
UL6_COP	62.21	-34.03	-17.26	-.02	1016	2	2

Fig. 19

```
LATSKX    9502      11481 11482        123075 103087  F 3/96/ 7
LUTT,BETT                     UTIP1      UTIP2      UTIP3
 1704.00 1684.00   64.04    93.19 1704.00  500.27  114.29 1684.00
 LL_REG       -17.90  101.21  155.78   -.30        821   2  2
 UL_REG       -84.93   38.93    2.11    .00        822   2  2
 UR_REG        69.57 -120.15     .38    .00        823   2  2
 LR_REG       154.62  -68.66  165.10   -.25        824   2  2
 UTIP1           .00     .00     .00   -.42        581   2  2
 UTIP2         43.03     .00     .00   -.90        582   2  2
 UTIP3         50.90  -47.72     .00   -.54        583   2  2
 UTIP4         20.59  -30.93    6.21   -.06        584   2  2
 LTIP1         58.35  -38.40   21.80   -.43        587   2  2
 LTIP2         47.03    1.22   21.69   -.42        588   2  2
 LTIP3         11.36    9.89   20.95   -.47        589   2  2
 LTIP4         35.28  -18.82   40.48   -.20        590   2  2
```

Fig. 20

```
                    COORDINATES FOR TRANSFORMED POINTS
                    IMAGE "LUTT,BETT          " FIT TO "LUTT,BETT

 POINT        X         Y         Z        ID


LL_REG     -17.90    101.21    155.78     821   ONLY IN FILE 1
UL_REG     -84.93     38.93      2.11     822   ONLY IN FILE 1
UR_REG      69.57   -120.15       .38     823   ONLY IN FILE 1
LR_REG     154.62    -68.66    165.10     824   ONLY IN FILE 1
LTIP1       58.35    -38.40     21.80     587   ONLY IN FILE 1
LTIP2       47.03      1.22     21.69     588   ONLY IN FILE 1
LTIP3       11.36      9.89     20.95     589   ONLY IN FILE 1
LTIP4       35.28    -18.82     40.48     590   ONLY IN FILE 1

UTIP1        -.85      -.08      4.30     581   FILE 2
UTIP1         .00       .00       .00     581   FILE 1

UTIP2       43.88     -3.26     -1.80     582   FILE 2
UTIP2       43.03       .00       .00     582   FILE 1

UTIP3       52.07    -46.00      4.01     583   FILE 2
UTIP3       50.90    -47.72       .00     583   FILE 1

UTIP4       19.42    -29.31      -.30     584   FILE 2
UTIP4       20.59    -30.93      6.21     584   FILE 1

LL_REG     -16.57    -13.29      -.96     811   ONLY IN FILE 2
UL_REG      20.51     29.90     12.72     812   ONLY IN FILE 2
UR_REG      87.24    -30.58     15.27     813   ONLY IN FILE 2
LR_REG      49.22    -71.73      1.59     814   ONLY IN FILE 2
LL_ROD      -8.91    -32.11    -30.30     701   ONLY IN FILE 2
UL_ROD      49.20     33.43     -8.98     702   ONLY IN FILE 2
UR_ROD      87.32      -.77     -7.56     703   ONLY IN FILE 2
LR_ROD      30.07    -66.68    -28.31     704   ONLY IN FILE 2
UR6_DBCT    10.85      1.23    -13.57    1001   ONLY IN FILE 2
UR6_MBCT    14.24      3.38    -11.88    1002   ONLY IN FILE 2
UR6_MLCT    15.38     -2.41    -12.65    1003   ONLY IN FILE 2
UR6_COP     14.25      -.39    -11.46    1004   ONLY IN FILE 2
UR6_MMR     15.98      1.30     -7.37    1005   ONLY IN FILE 2
UR3_DCON    29.50      8.99     -7.07    1006   ONLY IN FILE 2
UR3_LCT     33.64     12.66     -7.78    1007   ONLY IN FILE 2
UR3_MCON    34.95     10.63     -1.75    1008   ONLY IN FILE 2
UL3_MCON    58.27    -11.93     -1.95    1009   ONLY IN FILE 2
UL3_LCT     59.95    -14.18     -5.07    1010   ONLY IN FILE 2
UL3_DCON    58.10    -17.59     -5.06    1011   ONLY IN FILE 2
UL6_MBCT    52.50    -33.81    -10.90    1012   ONLY IN FILE 2
UL6_DBCT    50.08    -37.66    -12.66    1013   ONLY IN FILE 2
UL6_MLCT    47.36    -32.37    -14.80    1014   ONLY IN FILE 2
UL6_MMR     50.22    -31.69    -10.33    1015   ONLY IN FILE 2
UL6_COP     48.16    -35.02    -10.78    1016   ONLY IN FILE 2
Stop - Program terminated.

[2]s 0;65H 19:16:17 u c:/cril_dat/9502>
```

Fig. 21

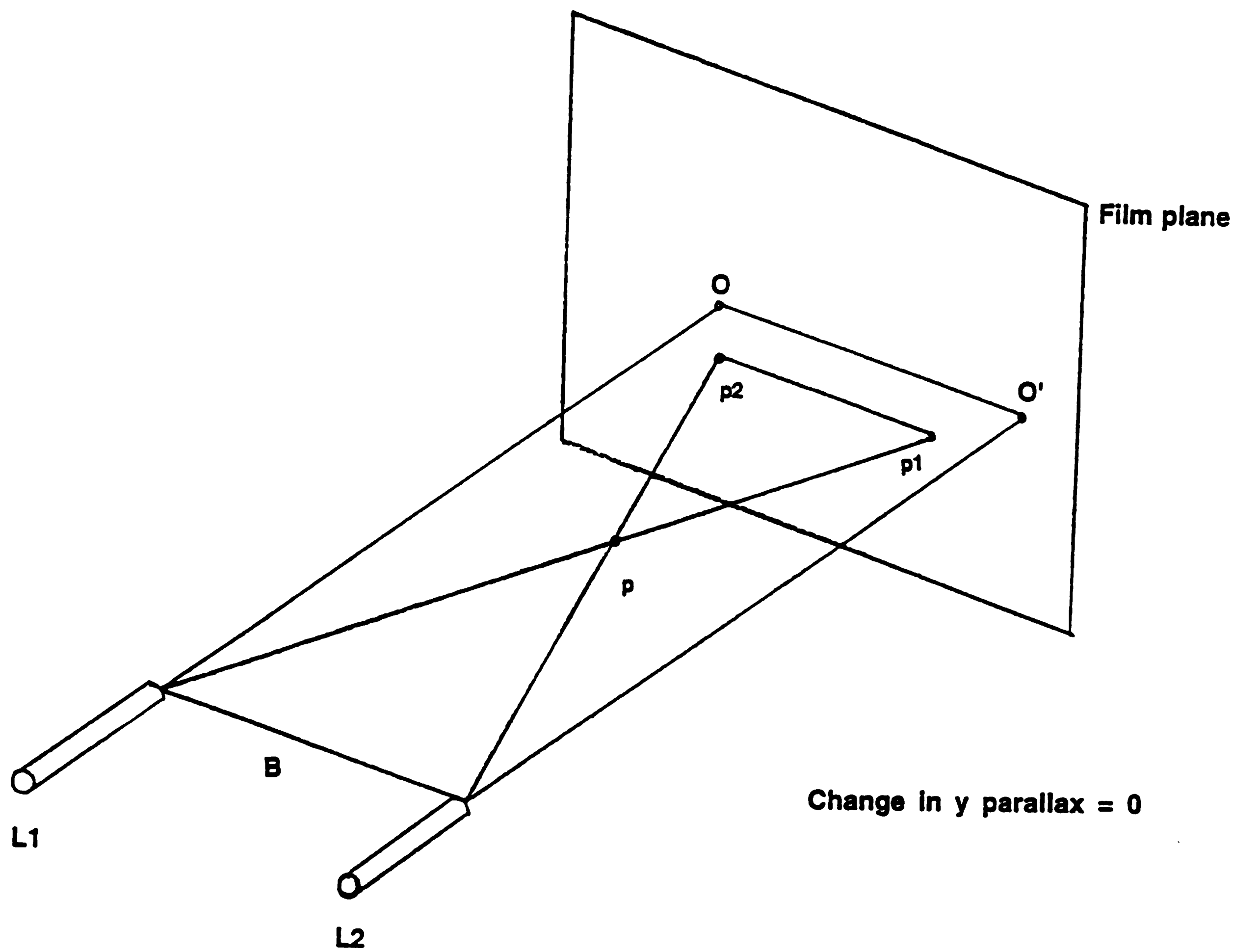

Fig. 22

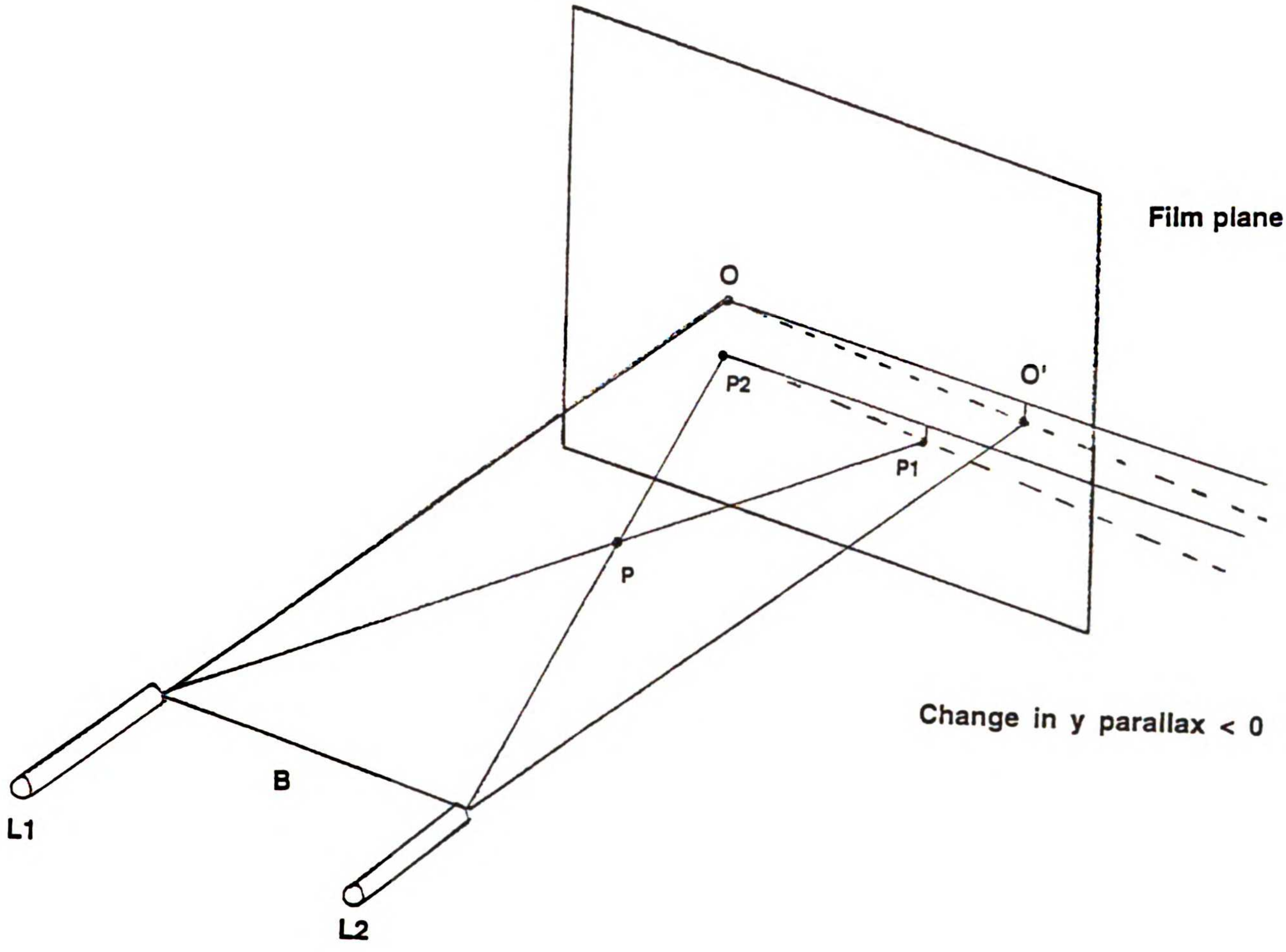

Fig. 23

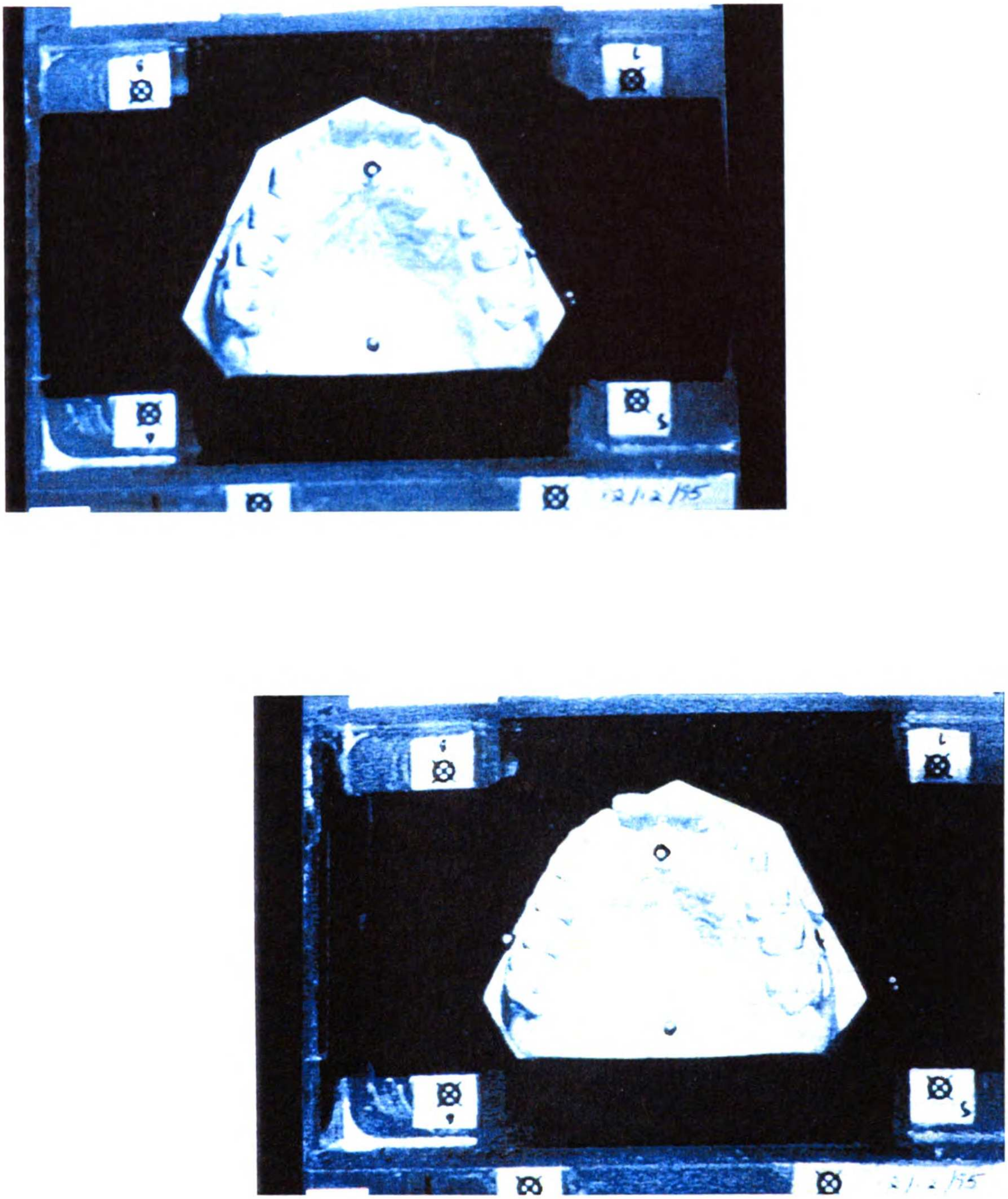

Fig. 24

case #	timepoint	cast	points	ME
103	1	U	12	0.2
			13	0.05
			14	0.2
			23	0.1
			24	0.05
			34	0.1
		L	12	0.3
			13	0.15
			14	0
			23	0.1
			24	0.05
			34	0.05
113	1	U	12	0.15
			13	0.05
			14	0.35
			23	0
			24	0
			34	0
		L	12	0.25
			13	0.4
			14	0.05
			23	0.2
			24	0.05
			34	0.2
114	1	U	12	0
			13	0.05
			14	0.05
			23	0
			24	0
			34	0
		L	12	0.05
			13	0.2
			14	0.25
			23	0.1
			24	0.25
			34	0

12 = distance between tiepoints 1 and 2.
13 = distance between tiepoints 1 and 3.
14 = distance between tiepoints 1 and 4.
23 = distance between tiepoints 2 and 3.
24 = distance between tiepoints 2 and 4.
34 = distance between tiepoints 3 and 4.

ME = method error for paired tiepoint measurements.

Table 1

CASE #	TIMEPOINT	METHOD	1 to 2	1 to 3	1 to 4	2 to 3	2 to 4	3 to 4
210	TP1	M	29.30	53.00	29.55	31.20	28.50	30.75
		U	29.67	54.49	30.45	31.76	28.14	31.73
		X	28.12	55.72	34.14	36.20	32.46	30.52
		M	36.15	61.05	32.05	36.65	29.30	33.05
		L	36.88	63.07	32.89	36.94	29.50	34.12
		X	40.82	63.59	31.29	34.31	29.90	35.53
	TP2	M	32.95	57.45	32.10	33.90	30.00	32.00
		U	33.59	58.88	33.08	34.24	30.38	32.37
		X	32.63	59.91	36.66	39.73	35.88	31.90
		M	30.95	58.95	32.70	37.00	30.00	33.10
		L	31.74	60.57	34.57	37.90	31.39	34.21
		X	35.74	61.02	30.75	36.58	29.70	35.32

M = Direct physical measurements of tiepoints.
U = Computed distance measurements of tiepoints in the upper cast from stereo digital images.
X = Computed distance measurements of tiepoints from stereo x-ray images
L = Computed distance measurements of tiepoints in the lower cast from stereo digital images.

1 to 2 distance value between tiepoints 1 and 2.
1 to 3 distance value between tiepoints 1 and 3.
1 to 4 distance value between tiepoints 1 and 4.
2 to 3 distance value between tiepoints 2 and 3.
2 to 4 distance value between tiepoints 2 and 4.
3 to 4 distance value between tiepoints 3 and 4.

Table 2

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