Oak Ridge

Radiology
12/76

MASTER

CONF-761153--2

Application of Longitudinal Magnification Effect to Magnification Stereoscopic Angiography: A New Method of Cerebral Angiography[1]

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Presented at the 62nd Scientific Assembly and Annual Meeting of the Radiological Society of North America, Chicago, Illinois, November 14-19, 1976.

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ABSTRACT

We have developed a new method of stereoscopic cerebral angiography which employs 2X radiographic magnification. In order to obtain the same depth perception in the object as with conventional contact stereoscopic angiography, one can make the x-ray exposures at two focal spot positions which are separated by only 1 inch, whereas the contact technique requires a separation of 4 inches. The smaller distance is possible because, with 2X magnification, the transverse detail in the object is magnified by a factor of two, but the longitudinal detail, which is related to the stereo effect, is magnified by a factor of four, due to the longitudinal magnification effect. The small focal spot separation results in advantages such as improved stereoscopic image detail, better image quality, and low radiation exposure to the patient.

INDEX TERMS: Cerebral angiography, Stereoscopy, Magnification technique, Image quality

INTRODUCTION

The history of stereoscopy in diagnostic radiology goes back to 1898. By 1930, the popularity of this technique reached its peak and then gradually diminished due to disadvantages such as expense and high patient exposure, despite its unique advantage of giving a three-dimensional display of radiologic patterns. An excellent review of the technical problems in stereoscopy may be found in a textbook by Christensen, Curry, and Nunnally (1).

We have developed a new method of stereoscopic angiography which employs the radiographic magnification technique and which is based on the "longitudinal magnification effect" (2). The method may be described as an "integrated" stereo system, which produces serial stereo angiograms similar to conventional angiograms, without additional exposure to the patient. When stereo views are required, any consecutive pair of films can be used. This method provides several advantages compared to the conventional "contact" stereo angiography. The physical principle of the method and preliminary experimental results on test objects and phantoms are described in this study.

ESSENCE OF MAGNIFICATION STEREOSCOPIC ANGIOGRAPHY

The distance between the focal spot and the film is 40 inches, and the object is placed halfway between the focal spot and the film, giving a geometric magnification of 2X. The focal spot size has to be small enough to produce magnification radiography. A practical example of the focal spot size is given later. To obtain the same depth perception in the object with magnification stereoscopic angiography as with contact stereo angiography, one can make the x-ray exposures at two focal spot positions separated by only 1 inch, whereas contact angiography usually requires a separation of 4 inches. The smaller separation is possible because, with 2X radiographic magnification, the transverse detail in the object is magnified by a factor of two, but the longitudinal detail, which is related to the stereo effect, is magnified approximately by a factor of four due to the longitudinal magnification (2). Therefore, the 1/4 reduction of the focal spot separation used in contact stereo angiography gives the same stereo effect with the magnification technique. This small separation results in several practical advantages.

THEORY

The basic geometric arrangements for the exposing and viewing procedures in the contact stereo technique are shown in Fig. 1. We assume that a portion of a thick object (small scale Z) which is related to the depth of the object, is radiographed by two exposures from two focal spot positions which are separated by the distance S. In practice, two radiographs are made for two exposures; for simplicity, both x-ray image formations are shown in Fig. 1-(A) by superposition of the two images. The scale Z is located at distance R from the center of the radiation field. The distance between the focal spot and the recording system is D. The two exposures create a discrepancy in the images, i.e., a slight difference in the two radiographs, which is the essential feature of stereoscopy. The size of the discrepant image is X, as shown in Fig. 1-(A). From similar triangles, we have the simple relationship

$$X = \frac{S\ Z}{D - Z} . \qquad (1)$$

This equation indicates two important results; namely, the size of the discrepant image is proportional to the focal spot separation and is independent of the position of the radiation field.

When a three-dimensional display of radiologic patterns is required, a stereo viewer or a cross-eyed method is usually employed. The essense of reconstructing the depth information in the object is shown in Fig. 1-(B), where the two radiographs are again superimposed for convenience. It is assumed that the left eye views only the radiograph made with the left focal spot and the right eye that made with the right focal spot. The image of scale Z is then recognized as scale Z_v, the tip of which is a cross-point of lines connecting vantage points and the corresponding images. The distance between the eye and the film is D_v, and the interpupillary distance is S_v. From similar triangles, we obtain the height of the reconstructed scale as

$$Z_v = \frac{D_v\ X}{S_v + X} . \qquad (2)$$

When the tube shift, S, is different from the interpupillary distance, distortion of the stereoscopic image occurs, so that the recognized small scale may not be perpendicular to the film plane. The magnitude of the distortion depends on parameters such as the location and size of the small scale. We ignore this distortion effect in the following discussion, because our stereoscopy provides only "relative" depth information and because this distortion is probably unimportant in practice (1).

Since the size of the discrepant image is usually small compared to the interpupillary distance ($S_V >> X$), we have approximately, from equation (2),

$$Z_V \simeq \frac{D_V X}{S_V} . \tag{3}$$

The relationship indicates that the depth perception is approximately proportional to the size of the discrepant image. This implies, in conjunction with the result of equation (1), that the larger the focal spot separation, the greater the depth perception will be, as is well known.

Geometries for exposing and viewing procedures in the magnification stereoscopic technique are shown in Fig. 2. The object is placed closer to the x-ray tube, and the distance between the focal spot and the distal surface of the object is D_1, giving the magnification $M = D/D_1$. Other geometric factors remain the same as for the contact stereo technique. With x-ray exposures from the two focal spot positions, the images of scale Z are formed as AB and A'B', which correspond to the right and left focal spots, respectively. The center or the frame of the two radiographs is shifted with the magnification stereoscopic technique; therefore, for the viewing procedure, the centers of two radiographs, C and C', are superimposed as shown in Fig. 2-(B), with the result that, during viewing, points A and A' overlap at the same position. The size of the discrepant image for the magnification technique, X_M, is equal to the distance BB' in Fig. 2-(B). A magnified stereo image is then formed in the same manner as for the contact stereo technique. Therefore, the height of the reconstructed image, Z_{VM}, is given approximately by

$$Z_{VM} \approx \frac{D_V X_M}{S_V} ; \qquad (4)$$

the derivation is similar to that for equation (3).

Now we shall consider the size of the discrepant image obtained with the magnification technique compared to that with the contact technique. We have shown previously from studies of the longitudinal magnification effect (2) that, with the magnification technique, the image size of a longitudinal object located in a plane perpendicular to the film plane is enlarged approximately by the square of the magnification compared to that obtained with the conventional contact exposure. Therefore, the sizes of AB and A'B' are greater by a factor of M^2 than the corresponding image sizes obtained with the contact stereo technique. This leads to an important result--that the size of the discrepant image for the magnification stereoscopic technique is greater by the same factor M^2 than that for the contact stereo technique. If we introduce this result and equation (1) into equation (4), we obtain

$$Z_{VM} \approx M^2 S \frac{D_V Z}{S_V (D - Z)} . \qquad (5)$$

The factor M^2S provides the basis of the new magnification stereoscopic angiography method, since it implies that the depth perception of a stereoscopic image obtained by the magnification technique is approximately proportional to the square of the magnification and to the focal spot separation. Therefore, at 2X magnification the same depth perception as that with the contact stereo technique is obtained with 1/4 the focal spot separation of the conventional stereo technique, or at 3X magnification, with 1/9 the focal spot separation.

The experimental verification of this theoretical result is illustrated in Fig. 3, which shows two pairs of radiographs for a stereo test object. The test object is composed of steps, the height of which changes in 20 mm increments. One pair of radiographs, made by the conventional contact stereo technique, employs a 4-inch tube shift and a 40-inch FFD. The other pair of radiographs, which were made with 2X magnification, uses a 1-inch tube shift, with the same FFD. When these two pairs of radiographs are viewed with the stereo viewer or by the cross-eyed method, the depth perceptions of the test object obtained with these two techniques are comparable, although the transverse detail of the magnified radiograph is enlarged. Therefore, this experimental result is in good agreement with the theoretical prediction which is the basis of the new magnification stereo technique.

IDEAL SYSTEM FOR MAGNIFICATION STEREO ANGIOGRAPHY

Magnification stereo cerebral angiography can be performed in principle with a conventional x-ray tube having a small focal spot, if two angiograms are taken for two injections, provided that the x-ray tube is shifted 1 inch in a direction parallel to the film changer for the second injection. Another possibility is to employ a mechanical procedure (3) to shift the x-ray tube by 1 inch between the exposures. However, the ideal system for this method would include a new x-ray tube having two small focal spots separated by 1 inch. We hope that such an x-ray tube can be developed.

With such a special tube, the following system for cerebral angiography should be arranged: The patient is placed halfway between the tube and the conventional rapid film changer. Following injection of the contrast medium, the patient is exposed alternately to x-rays from the two small focal spots in the x-ray tube. Every exposure should be synchronized with the change of films. Thus a set of serial angiograms is prepared, but the radiographs are made by alternating exposures from the two focal spots.

TECHNICAL ADVANTAGES

Magnification stereo angiography has three potential advantages.

(a) Integrated stereo system. When stereo examination is not required, the system can be used as a unit that generates serial cerebral angiograms which are the same as conventional magnification angiograms, except that exposures are made alternately with the two focal spots which are separated by 1 inch. When stereo views are required, a pair of angiograms made in two consecutive exposures is used. Thus, this stereo technique can be integrated into routine angiography procedures without the need for additional injection, radiation, or film consumption, and may be regarded simply as a special feature of the procedure.

(b) Better image quality. Visibility of small blood vessels is improved because of the sharpness, noise, and visual effects associated with the magnification technique (4,5,6,7,8,9), if technical parameters such as screen-film system, focal spot size, and magnification are selected properly.

(c) Low patient exposure and low tube rating. The skin dose to the patient in this technique is about equal to or less than that in conventional cerebral angiography, because (i) a faster screen-film system can be used without impairing the overall image quality of angiograms and (ii) the air gap effect eliminates the need for a grid. Therefore, a very low radiation output from the x-ray tube is required compared to the output of the conventional tube; i.e., a tube with a low power rating can be employed.

EXPERIMENTAL RESULTS

In order to demonstrate the advantages of magnification stereo angiography, we prepared radiographs of a skull phantom by both conventional contact and magnification techniques, as shown in the diagrams of Fig. 4. In the contact technique, the skull phantom was placed in a lateral position above a grid with a medium-speed screen-film system (DuPont Par Speed screens with Kodak RP film). Two radiographs were made at two positions of the x-ray tube, the tube being shifted by 4 inches in a direction parallel to the plane of the cassette. Test objects, such as plastic tubes (approximately 0.3 mm and 0.8 mm in diameter) filled with Renografin-60 and steel wire meshes (approximately 1, 2, 3, and 4 cycles/mm), were placed at various levels in the skull phantom, which had been cut sagitally into 1-inch slices. The nominal focal spot size was 1 mm, and the distance between the focal spot and the film was 40 inches. The x-ray tube used was a Siemens Bi 125/3/50 RG.

For the magnification technique, the skull phantom was placed half-way between the focal spot and the film, the magnification being 2X. The nominal focal spot size was 200 microns, and a fast screen-film system (Radelin TF2 screens with Kodak RP film) was employed. The same kVp and the same exposure time are used for both techniques, whereas the tube current is reduced to approximately 1/4 with the magnification technique; this verifies one of the technical advantages for the new technique, namely, low patient exposure and low tube rating. Further reduction of radiation exposure is possible by use of a faster screen-film system, as discussed later.

The quality of single-plane radiographs and stereoscopic images was compared in radiographs of the skull phantom. In addition, for comparison of the transfer characteristics of these techniques, the MTFs of geometric unsharpness and of screen-film systems were measured (10,11); the results are given in Figs. 5-7. For the contact exposure technique, the MTFs of the Par-RP system and of geometric unsharpness, as well as the total MTF, are shown in Fig. 5. The magnification factor for the average distance of radiologic structures in the skull was estimated as 1.1. The MTF of geometric unsharpness is derived from the Fourier transformation of slit images obtained in a direction perpendicular to the cathode-to-target axis. At low spatial frequencies, the total MTF is close to the MTF of Par-RP; as the frequency increases, the total MTF quickly approaches zero due to the MTF of geometric unsharpness. The MTFs for the 2X magnification technique are shown in Fig. 6, where the MTFs are displayed in terms of the spatial frequency in the object plane. Since the effective unsharpness of the TF2-RP system is reduced by the magnification of the input x-ray pattern, the MTF of TF2-RP at 2X magnification is improved compared to that for contact exposure, with the result that it is even better than the MTF of Par-RP for contact exposure. The MTF of the 200 μ focal spot at 2X magnification is also slightly better than that of geometric unsharpness for the contact exposure technique. Fig. 7 shows a comparison of the total MTFs for the two techniques. It is apparent that the magnification technique provides better transfer characteristics in radiologic image formation.

Parts of skull radiographs made with the two techniques are shown in Fig. 8. For the comparison, the magnified radiograph is reduced photographically to the size of the contact radiograph. For single radiographs made by contact exposure, two wire meshes up to 2 cycles/mm were resolved, whereas three wire meshes up to 3 cycles/mm were easily resolved by the magnification technique. Detail visibility of plastic tubes filled with the contrast medium was better in the magnification than in the contact technique. For example, some irregular shapes of plastic tubes and the resulting non-uniform distribution of the contrast material were observed in the magnified radiograph, but it was not possible to recognize the same pattern in the conventional radiograph. Some of the small plastic tubes (0.3 mm in diameter) were not visible with the contact technique, but were detected with the magnification technique.

Stereoscopic images were observed with a stereo viewer. The depth perception was considered comparable for the two techniques, again in agreement with the prediction. Transverse detail by the magnification technique is, of course, recognized as magnified. The overall effect, combined with these two observations and with the difference in qualities of single radiographs, was that the detail visibility of the magnified stereoscopic image was overwhelmingly superior to that of the conventional stereoscopic image. For example, without prior knowledge most observers could not recognize the

0.3 mm plastic tubes in the conventional stereoscopic image, whereas all observers easily recognized all of the tubes in the magnification stereo technique. Therefore, the magnification stereo technique provides superior image details for both single-plane radiographs and stereoscopic views.

DISCUSSIONS AND CONCLUSION

Several technical parameters are involved in the magnification stereo technique; their proper selection is crucially important.

(a) Area to be recognized as stereoscopic image. If we use a 14" by 14" format for the rapid film changer, the area in the patient recognized as a stereoscopic image is calculated from simple geometry as being approximately 6.5" by 7.0", for 2X magnification and 1 inch separation of the focal spot positions. This size has been designated by a radiologist as satisfactory for cerebral angiography. As the magnification or the focal spot separation increases, the size of the stereoscopic image is reduced.

(b) Focal spot separation. Slight variation in the focal spot separation has no serious effect on the advantages of this technique. However, the smaller the separation, the less the stereoscopic effect for recognizing the depth information will be. We have tried 2-inch separation and found that, although the depth perception increased, the adjustment for stereo vision became somewhat difficult and the area in the object for using the stereoscopic image was reduced. With 2X magnification and 1-inch separation, the three-dimensional image appears to be deformed compared to that with the contact technique and 4-inch separation. This is because the transverse detail is magnified by a factor of two, whereas the longitudinal detail is the same as that with the contact technique. When 2X magnification with 2-inch separation is employed, however, the shape of the three-dimensional image appears similar to that with the contact technique, except that both transverse and longitudinal details are magnified by a factor of two. It is known for the conventional stereo technique that the slight change in the tube shift does not critically affect the quality of stereoscopic images. The 4-inch separation at a 40-inch FFD, namely, the 1:10 ratio for these distances, was chosen by trial and error (1). We have not challenged this criterion in the present investigation and have tried to keep the same depth perception with the new magnification technique. Therefore, the optimal focal spot separation with the magnification technique might differ slightly from 1 inch and might be determined in future investigations.

(c) Magnification. In order to obtain even better images than those with the present magnification technique, it is possible to apply higher magnifications than 2X in conjunction with a micro-focal spot. However, although this would permit a smaller separation which may make it easier to develop a special x-ray tube with two focal spots, the area seen as a stereoscopic image becomes smaller, and the skin dose to the patient increases. Therefore, it may not be practical to employ very high magnification with micro-focal spots except for some special purposes.

(d) Screen-film system. A very fast screen-film system such as the rare-earth screens can be used for this technique; this will reduce the patient dose, but slightly degrade the image quality. We have tried Kodak Lanex Regular screens with Kodak Ortho G film. Radiographs of the skull phantom were made with 32 mA tube current, which is a considerable reduction compared to the 60 mA used with the TF2-RP combination.

We have also examined 3M Trimax Alpha 8 screens with XD film for cerebral angiography in monkeys. Preliminary results were encouraging, as demonstrated in Fig. 9. The angiogram of a monkey by the contact technique (A) was made with the Par-RP system at 65 kVp, 200 mA, and 0.1 sec, whereas the magnified angiogram (B) was made with the Alpha 8-XD system at 65 kVp, 25 mA, and 0.1 sec. The tube current is reduced to 1/8 with the magnification technique. It is obvious from Fig. 9 that the detail visibility of small vessels is far superior with the magnification technique. In addition, it has been confirmed that the stereoscopic images obtained with the magnification technique yield a superb three-dimensional display of small vessels compared to the conventional contact technique.

(e) Focal spot size. Small focal spot size is one of the most important factors for the successful application of the magnification technique. The actual size of the "200 μ" focal spot used for the demonstration of this technique was 250-280 μ according to our measurement on the rms equivalent uniform focal spot size (12). (The size varied slightly in the directions measured.) We consider such a size to be satisfactory for this technique; however, if it is increased to twice the present size, it is likely that the image quality for this technique will not be acceptable, because the total MTF will be considerably degraded to a level comparable to or less than the total MTF of the conventional technique.

We have shown theoretically and experimentally that the new magnification stereoscopic technique with small separation of two focal spot positions provides the same depth perception as that with the conventional stereo technique. With the magnification technique, image qualities of both single-plane radiographs and stereoscopic images are superior to those obtained with the contact technique. The radiation exposure to the patient with the new technique is comparable to or can be less than that with the present technique, and x-ray tubes with a low rating can be used. For application of this new stereo technique to routine clinical examinations in cerebral angiography, it will be necessary to devise a mechanical device for shifting the x-ray tube, or to develop a new x-ray tube with two focal spots. With this arrangement for alternate x-ray exposures at two focal spot positions with 1-inch separation, the new method can be regarded as an integrated stereo system, which produces serial stereo angiograms similar to conventional angiograms, without additional injection, patient exposure, or film consumption. When stereoscopic views are required, any consecutive pair of films can be used.

Acknowledgments. The authors are grateful to Mrs. Elisabeth Lanzl for improving the manuscript and to Mr. Edward Kucinsky for technical assistance.

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FIGURE CAPTIONS

Fig. 1. Geometries for exposing and viewing procedures in the contact stereo technique. For simplicity, two image formations in exposing (A) and two radiographs in viewing (B) are shown schematically by superposition.

Fig. 2. Geometries for exposing and viewing procedures in the magnification stereo technique.

Fig. 3. Comparison of stereoscopic images of test object by conventional contact technique with 4-inch tube shift, and by 2X magnification technique with 1-inch tube shift. FFD is 40 inches.

Fig. 4. Exposure condition and geometric setup for contact stereo cerebral angiography and magnification stereo cerebral angiography with skull phantom.

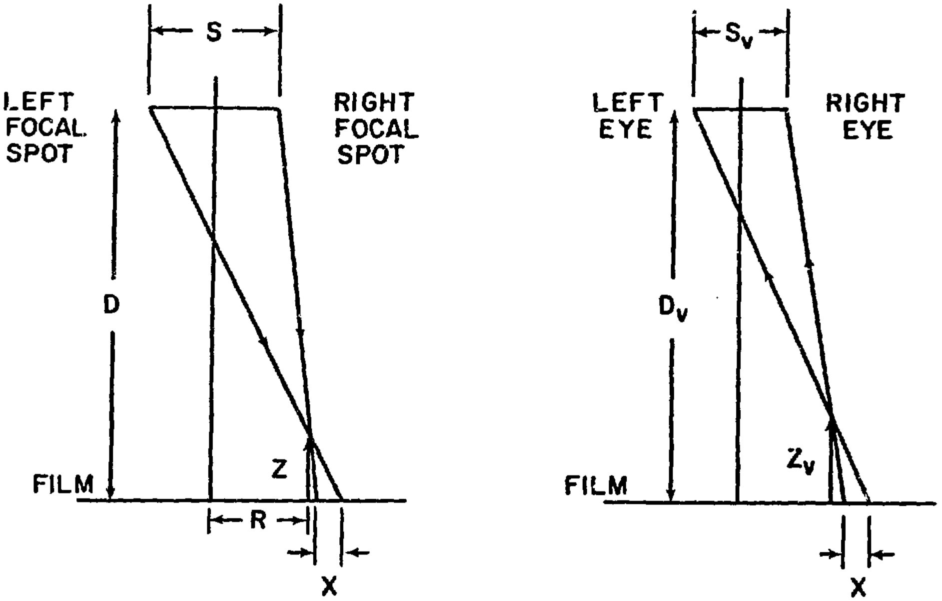
Fig. 5. MTFs for contact exposure technique in conventional cerebral angiography.

Fig. 6. MTFs for cerebral angiography with 2X magnification.

Fig. 7. Comparison of total MTFs for contact and magnification cerebral angiography.

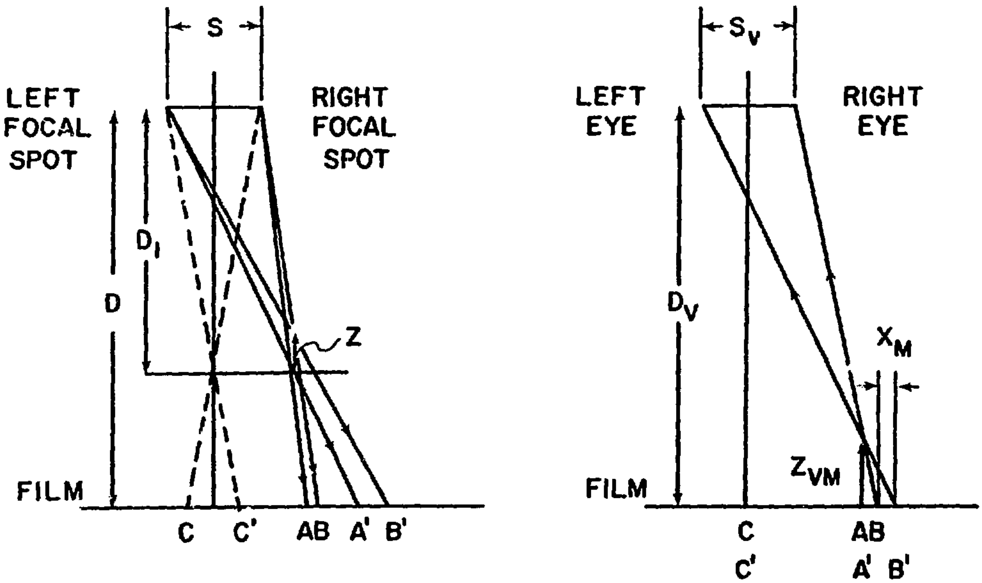
Fig. 8. Comparison of skull phantom radiographs made with contact (A) and magnification (B) techniques. Contact radiograph is enlarged photographically to the same size as magnification radiograph, for ease of comparison.

Fig. 9. Comparison of cerebral angiograms of a monkey made with contact (A) and magnification (B) techniques. Contact radiograph is enlarged photographically for ease of comparison.



(A) EXPOSING (B) VIEWING

fig 1



(A) EXPOSING (B) VIEWING

fig 2

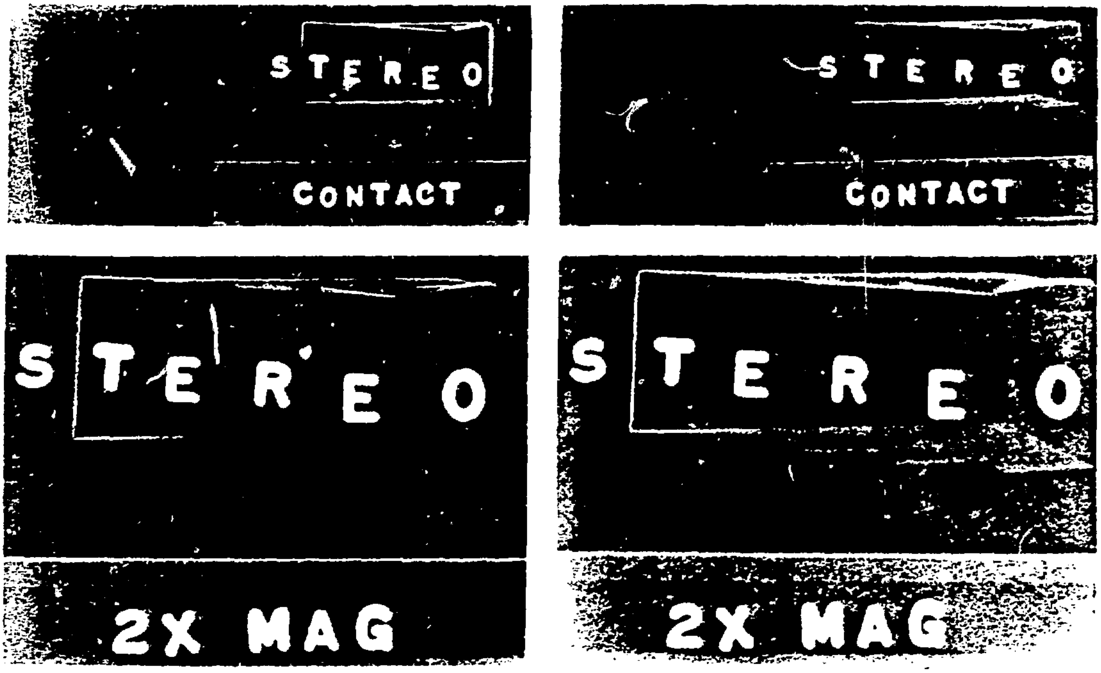

STEREO
CONTACT
STEREO
CONTACT
STEREO
2X MAG
STEREO
2X MAG

fig 3

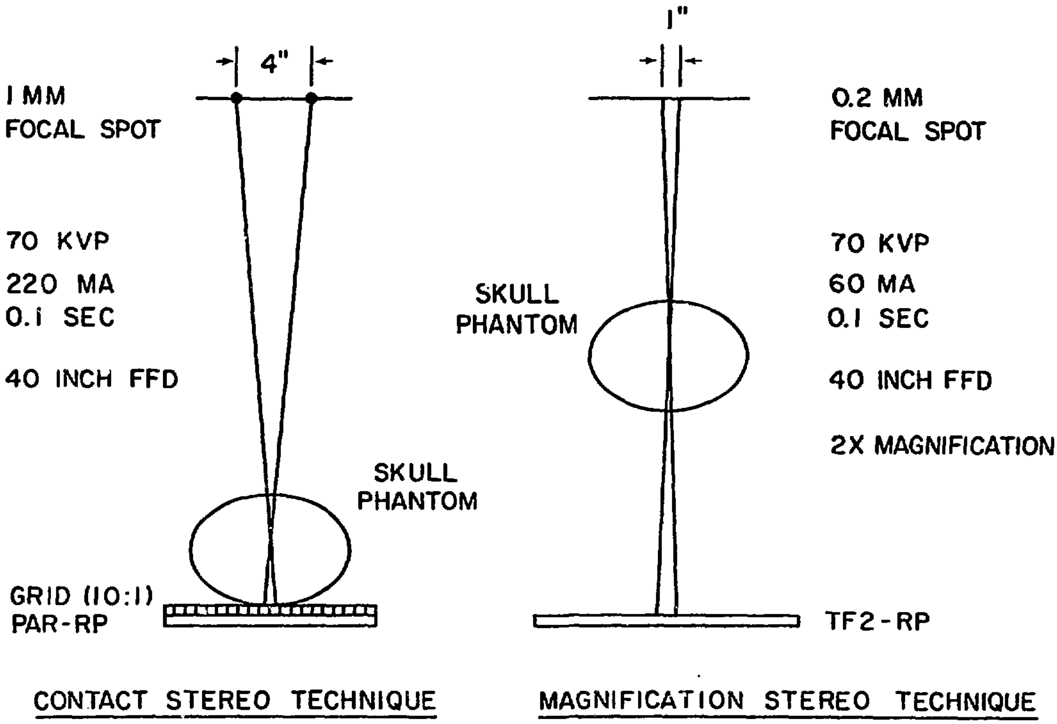

4"
1 MM
FOCAL SPOT
70 KVP
220 MA
0.1 SEC
40 INCH FFD
SKULL
PHANTOM
GRID (10:1)
PAR-RP
CONTACT STEREO TECHNIQUE
1"
0.2 MM
FOCAL SPOT
70 KVP
60 MA
0.1 SEC
40 INCH FFD
2X MAGNIFICATION
SKULL
PHANTOM
TF2-RP
MAGNIFICATION STEREO TECHNIQUE

fig 4

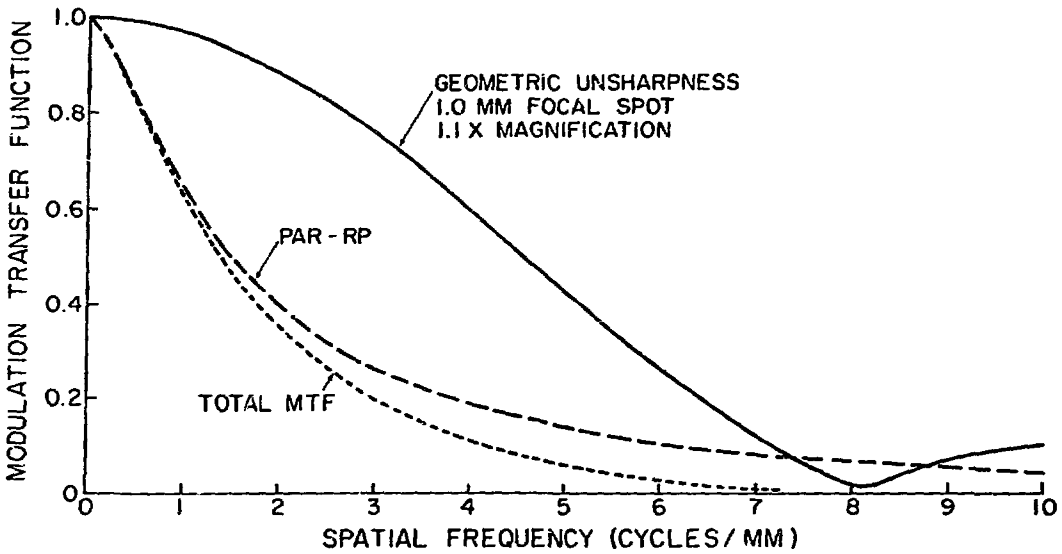

MODULATION TRANSFER FUNCTION
1.0
0.8
0.6
0.4
0.2
0
GEOMETRIC UNSHARPNESS
1.0 MM FOCAL SPOT
1.1 X MAGNIFICATION
PAR - RP
TOTAL MTF
0 1 2 3 4 5 6 7 8 9 10
SPATIAL FREQUENCY (CYCLES/ MM)

fig 5

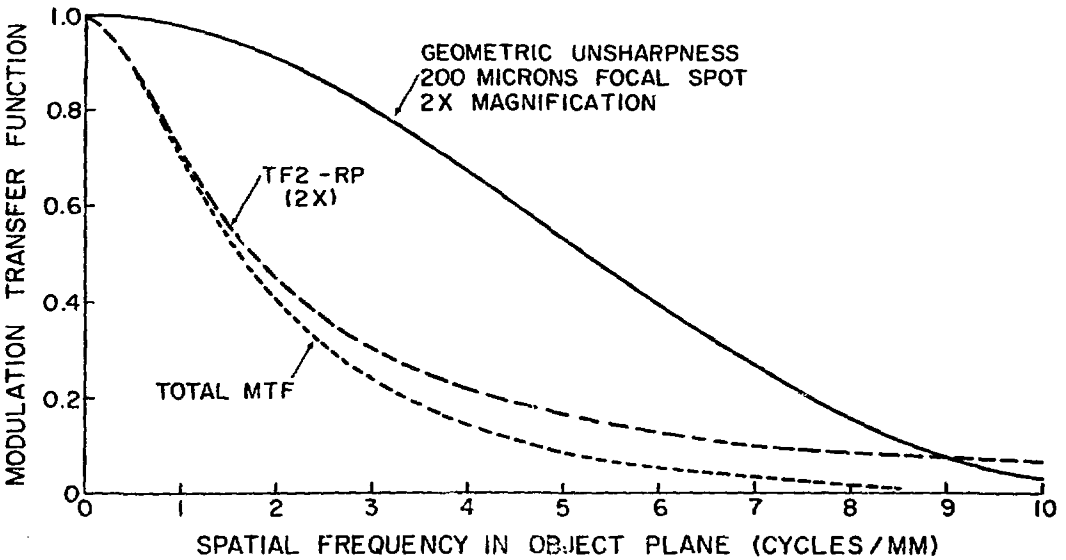

MODULATION TRANSFER FUNCTION
1.0
0.8
0.6
0.4
0.2
0
GEOMETRIC UNSHARPNESS
200 MICRONS FOCAL SPOT
2X MAGNIFICATION
TF2 - RP
(2X)
TOTAL MTF
0 1 2 3 4 5 6 7 8 9 10
SPATIAL FREQUENCY IN OBJECT PLANE (CYCLES/MM)

fig 6

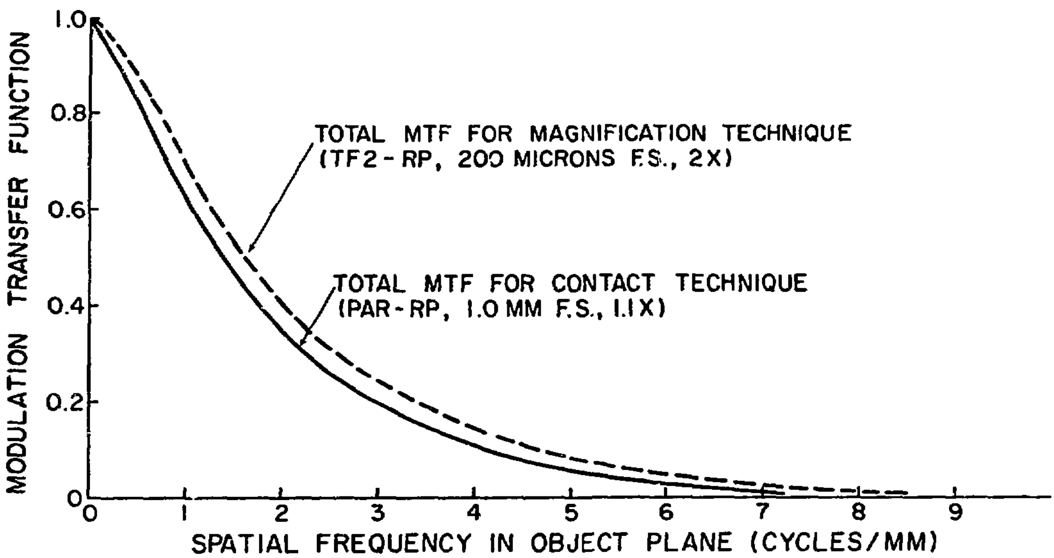
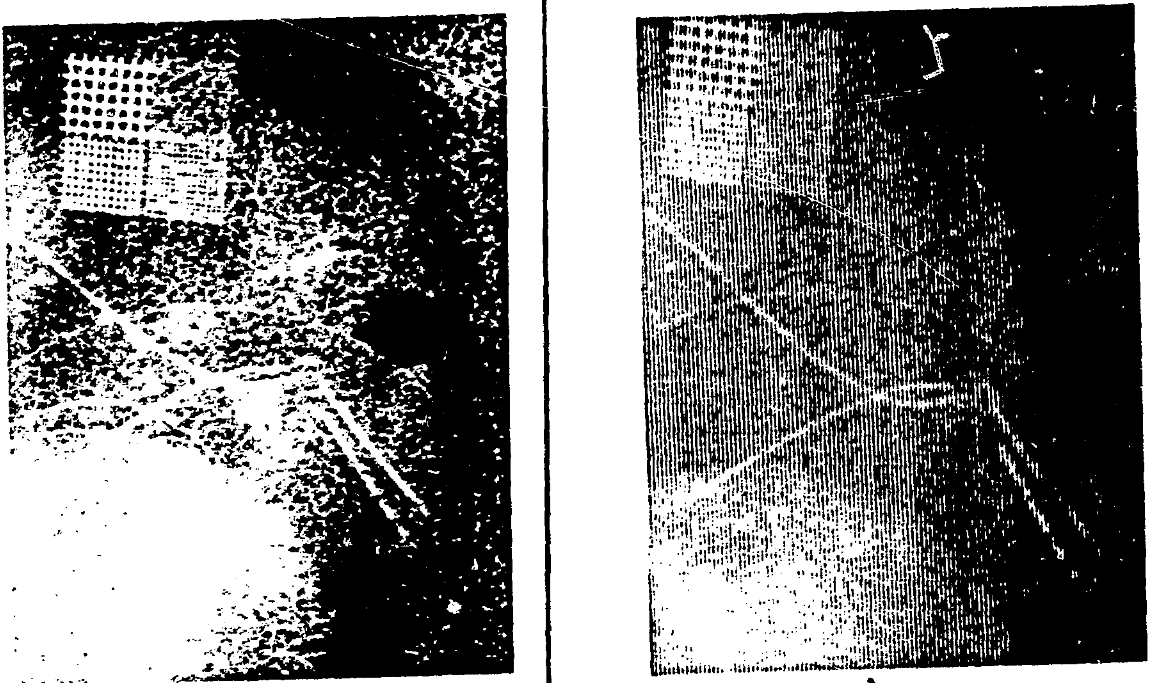
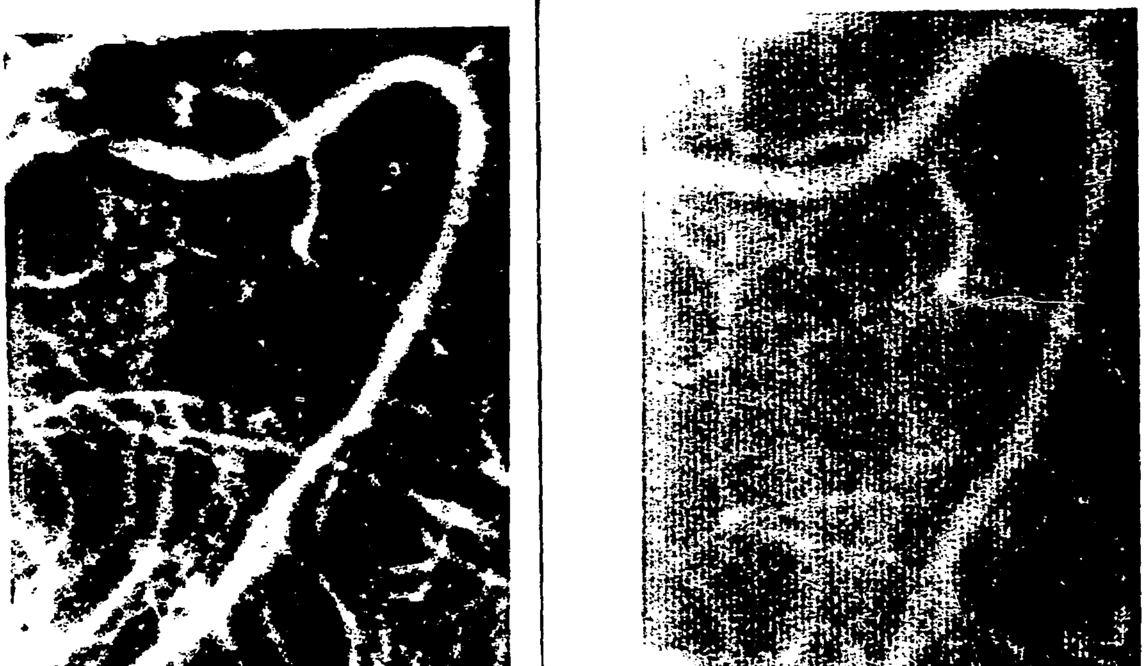

TOTAL MTF FOR MAGNIFICATION TECHNIQUE
(TF2-RP, 200 MICRONS F.S., 2X)
TOTAL MTF FOR CONTACT TECHNIQUE
(PAR-RP, 1.0 MM F.S., 1.1X)
MODULATION TRANSFER FUNCTION
1.0
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
SPATIAL FREQUENCY IN OBJECT PLANE (CYCLES/MM)

Fig 7



B A

fig 8



B A

fig