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Image Quality in Mammography

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ABSTRACT

In mammography, image quality is a function of the shape, size, and x-ray absorption properties of the anatomic part to be radiographed and of the lesion to be detected; it also depends on geometric unsharpness, and the resolution, characteristic curve and noise properties of the recording system. X-ray energy spectra, modulation transfer functions, Wiener spectra, characteristic and gradient curves, and radiographs of a breast phantom and of a resected breast specimen containing microcalcifications are used in a review of some current considerations of the factors, and the complex relationship among factors, that affect image quality in mammography. Image quality and patient radiation exposure in mammography are interrelated. An approach to the problem of evaluating the trade-off between diagnostic certainty and the cost or risk of performing a breast imaging procedure is discussed.

INTRODUCTION

The recent emphasis on early detection of breast cancer has led to an accelerated interest in mammography. Recent studies on the question of benefit versus risk in routine mammography and in mammography associated with breast screening programs have become quite controversial and, to some degree, quite confusing (1, 2). There is agreement that radiation exposure to the patient must be minimized. Image quality and patient exposure in mammography are interrelated, however (3, 4). For example, reduction of patient radiation exposure can be achieved in mammography simply by use of the highest-speed recording system available, but the use of such a system may result in degradation of the radiologic image and thus in reduced diagnostic certainty, so that the reduction of patient exposure is of no value to the patient. It is therefore timely and important that the factors affecting image quality in mammography be discussed and understood.

In essense, image quality is a function of the shape, size, and absorption properties of the anatomic part to be radiographed and of the lesion to be detected; of the geometric unsharpness; and of the recording system in terms of its resolution, characteristic curve, and noise properties. Sufficient image quality is required so that the mammogram contains adequate information for interpretation and evaluation. Figure 1 shows the various factors, and the complex interrelationships among these factors, that affect image quality in mammography or breast imaging. Each factor is a major topic within itself. It is the purpose in this presentation, therefore, to review some current considerations of these factors as they affect image quality in terms of object contrast, geometric and recording system unsharpness, the recording system characteristic curve and noise properties, and image evaluation.

OBJECT CONTRAST

Molybdenum and tungsten target tubes are presently used for film and screen-film mammography and xeroradiography. The relative usefulness of these tubes depends upon the thickness and composition of the breast (5, 6, 7). Determining the optimal tube in terms of image quality and patient exposure is complicated by factors such as the x-ray energy spectrum emitted, the filtration used, attenuation properties of structures within the breast, scatter, and the energy response of the recording system (8, 9).

The x-ray spectra emitted by a molybdenum anode tube and by a tungsten anode tube at 40 kVp are shown in Figure 2 (10). These spectra were measured with an intrinsic germanium detector and a 4096-channel pulse height analyzer (11) and have been corrected for the energy dependence of the detector efficiency. The rather intense spectral lines at 17.9 and 19.5 keV from the molybdenum anode tube are due to the characteristic $K\alpha$ and $K\beta$ radiation of molybdenum. The spectrum from this tube is strongly suppressed at photon energies above 20 keV by inherent filtration and by the standard additional 0.03 mm molybdenum filter, because of the K-shell absorption edge of molybdenum at that energy. The tungsten spectrum, on the other hand is smoothly continuous. Because of the relative concentration of x-ray energy in the 17.5 and 19.5 keV lines of the molybdenum-anode spectrum, molybdenum is superior to tungsten for imaging of low-contrast detail in soft tissue. Greater attenuation of low-energy x-rays causes greater subject contrast. Figure 3 shows the x-ray spectra from both tubes, transmitted through 5 cm of fat (left) and through 5 cm of water (right). In the calculation of these spectra from the measured incident spectra, the energy dependence of the attenuation coefficient of fat and water was taken into account (10, 12). These materials were chosen because the breasts of older women are composed primarily of fat, whereas those of younger women contain a considerable fraction of fibrous and glandular (water-equivalent) tissue.

The characteristic lines in the molybdenum spectrum carry a significant portion of the total x-ray intensity transmitted through the fat. The relative strength of the characteristic lines is decreased considerably in passage through the 5 cm of water because of the even stronger preferential absorption of low-energy photons by water. These spectra suggest, therefore, that the contrast of small objects such as microcalcifications in mammograms of fatty breasts approximately 5 cm thick should be greater with the molybdenum anode tube, but that the contrast of details in breasts of the same size, but of higher density would be nearly equal.

These predictions are confirmed in radiographs (Fig. 4) of a 1.5 cm thick section of resected breast tissue superimposed with 3.5 cm of lard (left) and 3.5 cm of water (right) which simulate 5-cm-thick fat- and water-equivalent breasts. The radiographs show that: (a) through fat, the molybdenum tube image has much greater contrast than the tungsten image; (b) the molybdenum tube image through water has significantly less contrast than that through fat; and (c) for the dense or water-equivalent breast, the images with molybdenum and tungsten are quite similar. Regarding the latter observation, the tungsten image is obtained at a lower patient exposure because, when the molybdenum target is used, a high percentage of low-energy components is absorbed in the patient and thus does not contribute to formation of the image. For increasing thicknesses of dense, water-equivalent breasts, contrast differences between tungsten and molybdenum tubes become smaller, but patient exposure increases relatively faster with the molybdenum tube.

Therefore, the effect of breast tissue on the transmitted x-ray spectrum, and hence on radiographic contrast, depends upon the amount of fat relative to fibrous and glandular tissue present. Breasts composed primarily of fat yield images of higher radiographic contrast when imaged with the molybdenum rather than the tungsten anode tube at the same kVp, although the patient exposure required with molybdenum increases relatively faster with breast thickness. When the breast is very thick or contains a large percentage of fibrous and glandular tissue, the contrast obtained with the molybdenum anode tube will be similar to that obtained with the tungsten anode tube, but patient exposure will be greater.

For Xeroradiography, emphasis has recently been placed on the use of tungsten target tubes at higher kVp settings, and with increased aluminum filtration to harden the beam further and thus reduce the radiation dose. This approach should be taken with caution because, at some point, there may be a critical loss of object contrast resulting from excessive beam hardening. Present and future investigations on the efficient use of molybdenum and tungsten target tubes with various filtration schemes (13, 14), measurements of x-ray spectra through breast material (15), determination of absorbed radiation dose from spectral data (16), and determination of the effect of scatter in mammography (17) will be important for establishing the conditions under which acceptable image contrast can be obtained at minimal radiation exposure levels.

GEOMETRIC AND RECORDING SYSTEM UNSHARPNESS

Image unsharpness in mammography is caused by geometric, recording system, and motion unsharpness. Geometric unsharpness is determined by the size and shape of intensity distribution of the x-ray tube focal spot, in combination with the object-to-recording system distance and the focal spot-to-object distance (cone length). The geometric setup to evaluate the effect of geometric unsharpness for the Senographe molybdenum-anode unit is illustrated in Figure 5 (18). On the left is the geometrical configuration when a conventional cone is used. On the right is the configuration when improved geometry with a long cone is used. The conventional compression cone supplied by the manufacturer provides a focal spot-to-skin distance of 28 cm. For the 5-cm-thick breast, the conventional cone introduces geometric magnifications of 1.18 and 1.03 at object-to-recording system distances of 5 cm and 1 cm, respectively.

The modulation transfer functions (MTFs) of geometric unsharpness in the image plane at these object-to-recording system distances, with the conventional cone, are shown in Figure 6. These MTFs were calculated from those of the focal spot and from the geometric magnification factors corresponding to each object-to-recording system distance (19). They are determined perpendicular to the x-ray tube cathode-to-anode axis. Recording system MTFs of RP/M direct x-ray film, of the DuPont Lo-dose single-screen single-emulsion system for mammography, and of a conventional medium-speed screen film system, Par RP, are included in Figure 6. All of these MTFs were calculated from digital Fourier transformations of line spread functions from slit images. The Par RP system requires 1/150, and the Lo-dose system 1/15, of the exposure for RP/M film to provide radiographs of comparable photographic density at the same kVp setting.

Several important results can be noted from these MTFs. (a) Geometric unsharpness contributes more significantly to image unsharpness than does RP/M film at all object-to-recording system distances shown; (b) at the 5 cm object-to-recording system distance, geometric unsharpness contributes more significantly to image unsharpness than even the Lo-dose system; and (c) the Par RP system is more limiting in resolution than geometric unsharpness at either object-to-recording system distance considered. Certain rare-earth screen-film systems, such as Trimax Alpha 8-XM, have even poorer MTFs and significantly higher noise than the Par RP system.

Typical exposing conditions for mammograms of a 5-cm thick compressed breast, using the Senographe unit with a conventional cone, are 35 kVp, 35 mA (the maximum tube current for this unit at 35 kVp), and an exposure time of 5 seconds when Kodak RP/M direct x-ray film is used. Due to limitations of tube output for this unit, the effect of geometric unsharpness cannot be reduced by increased focal spot-to-recording system distance when RP/M film is used.

Since the Lo-dose system requires approximately 1/15th the exposure of RP/M direct x-ray film, some of this exposure speed can, therefore, be used for an increase in the focal spot-to-recording system distance, and thus for reduction of geometric unsharpness. With the Lo-dose system, even at an increased distance, the patient exposure is reduced by a factor of 15 at the same kVp dial setting. Figure 7 shows the MTFs obtained at the 5 cm object-to-recording system distance when a long cone is used which provides a focal spot-to-recording system distance twice that for the conventional cone. The geometric configuration is that shown on the right in Figure 5. The MTFs of geometric unsharpness are improved considerably with the result that the spatial frequency range is expanded to approximately twice that for the conventional cone. This MTF is even better than the MTF of the Lo-dose system, except at some higher spatial frequencies.

For a visual demonstration of the results obtained from the MTF curves, radiographs have been made of a special test object (Figure 8). The object consists of five stacked Lucite blocks, each 1 cm thick, with microwire mesh patterns located at object-to-recording system distances of 5 cm, 3 cm, and 1 cm (shown at the top, middle, and bottom of the figure, respectively). The five meshes in each pattern contain cyclic fine structures, the fundamental frequencies of which are 4, 8, 13, 16, and 20 cycles per mm (top row to bottom row). The images on RP/M film with the conventional cone on the left are significantly less sharp in the first patch, which corresponds to the 5 cm object-to-recording system distance, than those obtained with the Lo-dose system and the lone-cone technique, shown on the right, due to the effect of geometric unsharpness. The horizontal wires in the first patch are barely imaged on the left, but are sharply imaged on the right with the improved geometry and the Lo-dose system. The sharpness of the mesh patterns at the 3 cm level appears more nearly alike, although the Lo-dose system with the long cone is better. At the 1 cm level, the images made with RP/M film and a conventional cone are better due to the better MTF of RP/M film and the small geometric unsharpness at this object-to-recording system distance.

Recording systems such as RP/M direct x-ray film provide high resolution; at certain object-to-recording system distances and for certain x-ray units, however, the total resolution is limited even more by geometric unsharpness than by the Lo-dose screen-film recording system. In such cases, the Lo-dose system can be used to advantage for three reasons: (a) The effect of geometric unsharpness can be reduced since one can use larger focal spot-to-skin distances (long cone); (b) motion unsharpness can be reduced by use of shorter exposure times; and (c) the exposure to the patient can be reduced significantly. Clinical comparisons have shown that the effect of geometric unsharpness can be crucial in the detection of microcalcifications at certain object-to-recording system distances, and that the Lo-dose system can be used advantageously as indicated above (2, 18).

The effect of geometric unsharpness varies for different x-ray units. If the effect of geometric unsharpness for a given unit is less than that demonstrated here, images on direct x-ray film such as RP/M will be sharper than Lo-dose system images made at increased object-to-recording system distances. Furthermore, although the use of x-ray tubes for mammography with significantly smaller focal spot sizes may result in reduced geometric unsharpness at all planes within the breast when a conventional focal spot-to-skin distance is used, the output of these units may be limited and thus may still require a relatively fast recording system.

At present, it is difficult to make a quantitative comparison of resolution differences between Xeroradiography and the conventional image-recording systems such as direct x-ray films and screen-film systems commonly used in diagnostic radiology. Xeroradiography, however, is still considered to be a rather high-resolution recording system. In Xeroradiography, therefore, geometric unsharpness may also be a significant factor when the same x-ray unit is used in combination with the short compression cone, and a significant reduction in total unsharpness could be obtained by use of a long compression cone with an increased focal spot-to-skin distance (20).

If the Senographe x-ray unit is used, the combination of a higher kVp setting with a 0.5 mm aluminum filter rather than a molybdenum filter facilitates the increased exposure output required for breast Xeroradiography. The exposure conditions commonly used are 42-48 kVp, 30 mA, and 1-second exposure time when the short cone supplied by the manufacturer is employed. The kVp setting is adjusted for proper exposure conditions according to breast thickness and anatomical composition. Most examinations are done at 43 kVp. For the comparisons between the short cone and the long cone discussed here, the kVp setting remained constant, and the exposure time was increased when the long cone was used.

The test object, shown in Figure 8, was used also to evaluate the effect of geometric unsharpness in Xeroradiography by comparison of the conventional short-cone technique with the long-cone technique. The configuration employed for Xeroradiography of a 5-cm-thick breast was that shown in Figure 5. Images of the test object, obtained with Xeroradiography, are shown in Figure 9. The images with the conventional cone on the left are significantly less sharp in the first patch, which corresponds to the 5 cm object-to-recording system distance, due to the effect of geometric unsharpness. The horizontal wires in the first patch are barely imaged on the left, but are sharply imaged on the right with improved geometry.

In Xeroradiography, geometric unsharpness can be a significant factor in image degradation. When the Senographe unit is used at the same kVp dial setting, it is necessary to increase the exposure time from approximately 1 second for the short cone to 3-4 seconds for the long cone which provides an increased focal spot-to-skin distance. For our clinical comparisons, motion unsharpness due to the increased exposure time has not been a problem compared to the marked improvement in the sharpness of microcalcification images. However, the effect of motion unsharpness as well as the effects of kVp (beam quality) and beam filtration must be studied in more detail in the future.

RECORDING SYSTEM CHARACTERISTIC CURVE AND NOISE

Other important imaging properties in mammography are the shape of the characteristic curve and the noise properties of the recording system. The characteristic and gradient curves of RP/M film and of the Lo-dose system (Fig. 10) were measured with an x-ray inverse-square sensitomer (21). They show that RP/M film has a steep characteristic curve and that the Lo-dose system has wide latitude. The gradient of RP/M film increases monotonically up to approximately 4.6 as the density increases to 2.6. The Lo-dose gradient varies gradually with density and has a maximum at a density of approximately 1.5.

At densities below 1.5, the Lo-dose gradient is higher than that of RP/M. With RP/M film the high contrast provided by direct x-ray film is utilized only if the average density of the mammogram is high, because of the low gradient at low density and the narrow latitude of the film. The range of photographic densities corresponding to films categorized as properly exposed, underexposed, or over exposed, based on a method used in a recent study (22), is also noted in Figure 10. In this study, photographic density measurements were made in three areas on each mammogram: (1) the area of lowest photographic density, (2) the area of highest density, and (3) the area which represented the average density of the film. The films were evaluated by three observers and divided into the three categories: (1) properly exposed, (2) underexposed, and (3) overexposed. Underexposure or overexposure can result in films which make proper diagnosis extremely difficult and which cause unnecessary radiation exposure to the patient because of the necessity for repeated radiography. Poor-quality films can also result in loss of detection of microcalcifications or of subtle mass lesions.

The noise properties of film and screen-film systems are evaluated by means of Wiener spectrum measurements. The Wiener spectra of RP/M film and of the Lo-dose system are shown in Figure 11. These Wiener spectra were measured by electronic Fourier analysis of transmission fluctuations through the film (23, 24). The noise in the Lo-dose system is apparently greater than that in RP/M film. The Wiener spectrum of the Lo-dose system contains a low spatial frequency component due to quantum mottle, which is not present in the noise Wiener spectrum of direct x-ray films. The noise in higher-speed recording systems such as the rare-earth Trimax Alpha 8-XM system can be expected to be significantly greater than in the Lo-dose system (23).

In order to demonstrate the effects of some of the imaging properties discussed above on radiographs of microcalcifications in the breast, a section of resected breast containing a carcinoma was used. The size of the specimen was approximately 3 cm by 5 cm by 1.5 cm thick. Radiographs of this specimen spaced in air at an object-to-recording system distance of 5 cm are shown in Figure 12. The radiograph on the left was made with RP/M film with the conventional cone and that on the right, with Lo-dose and the long cone. The effect of geometric unsharpness is apparent in this comparison: the detection of microcalcifications is confusing and difficult in the images with RP/M film and the conventional cone (left). Many of these microcalcifications appear more sharply imaged and are clearly distinguishable on the right, with the Lo-dose system and the long cone which yield improved geometry. Figure 13 shows images of the breast tissue in contact with the recording system, made with RP/M and the conventional cone (left) and with the Lo-dose system and long cone (right). In this comparison, the effect of geometric unsharpness is small. A difference in sharpness between the RP/M and Lo-dose systems is apparent, but most microcalcifications appear to be imaged and distinguishable with both systems. The background noise of the Lo-dose system is slightly greater than that of the RP/M, in agreement with the results of the Wiener spectrum measurements. The slightly increased noise does not seem to affect the visibility of microcalcifications significantly, however, either in this comparison or in the comparisons shown in Figure 11, where the visibility of microcalcifications is improved with the long-cone geometry and Lo-dose system. It is not known at present to what extent, if at all, background noise influences the detection of smaller and lower-contrast microcalcifications.

Studies with the Kodak Min R system have shown empirically that its resolution and noise are comparable to those of Lo-dose, with exposure reduced by a factor of 2 to 3 (25, 26). It should be noted with caution, however, that increased recording system speed can, in some cases, result in increased noise and loss of resolution. In the comparison of geometric unsharpness and recording systems, for example, the higher-speed recording system limited image resolution even more than did the worst case of geometrical unsharpness. At present, it is also not clear how the speed, curve shape, resolution, and noise characteristics of Xeroradiography (27) and electron radiography compare with film and screen-film systems. Such measurements for these and for new screen-film systems applicable to mammography should be forthcoming. Recent studies on magnification techniques for mammography may also offer advantages for improved image sharness and noise (28).

IMAGE EVALUATION

Given the discussion above, the question remains: "Which imaging technique should be used in mammography?" In order to decide which of several alternative imaging factors or diagnostic procedures is best, one must first formulate a very specific answer to the question: "Best for what?" After some thought, it should be apparent that the best imaging technique is not necessarily the one that provides the highest detectability of disease, since ever higher detectability can usually be "purchased" at ever higher "cost" in terms of risk and patient radiation exposure. Clearly, some compromise must be made between the benefit expected from correct diagnosis of breast cancer and the radiation risk incurred in the performance of the diagnostic procedure. Perhaps less obviously, one must consider the trade-off expected between the benefits of correct diagnoses made with a given procedure or imaging technique and the costs of the consequences of incorrect diagnoses. Each of the benefits and costs considered must be weighted by the probability that the benefit or cost in question is incurred in a particular diagnostic situation.

In essense, then, any meaningful comparison of the usefulness of alternative diagnostic procedures or imaging techniques should take into account the costs and risks incurred when the procedure is performed, the costs or benefits of the consequences of the various possible types of correct and incorrect diagnostic decisions resulting from the use of the procedure, the relative frequencies of correct and incorrect decisions, and the medical context in which the diagnostic procedure is employed. Concerning the latter consideration, one should note that a highly definitive mammographic technique involving high radiation exposure may be very beneficial when it is applied to a carefully screened population if the consequence of a correct positive diagnosis is a probable cure of breast cancer, whereas use of the same technique may not be justified for mass screening of an unselected population.

The concept of "average net benefit" has been proposed as an approach to the evaluation of diagnostic studies which takes these factors into account (29, 30). This approach combines disease detection performance, as measured by Receiver Operating Characteristic (ROC) curves (31), with benefit and cost considerations. The "average net benefit" can be generalized to the evaluation of alternative sequences of diagnostic tests as well as alternative procedures, and hence can be used to explore optimal diagnostic strategies.

CONCLUSION

The factors and complex interrelationship among factors that affect image quality in mammography make the choice of optimum imaging techniques difficult. Knowledge and understanding of these factors and, in particular, the resulting trade-off between image quality and patient radiation exposure are of the utmost importance to the selection of the best imaging method for each patient. The concept of "average net benefit," which combines disease detection performance as measured by Receiver Operating Characteristic curves with benefit and risk considerations, offers a quantitative approach to the evaluation of diagnostic studies which takes these factors into account.

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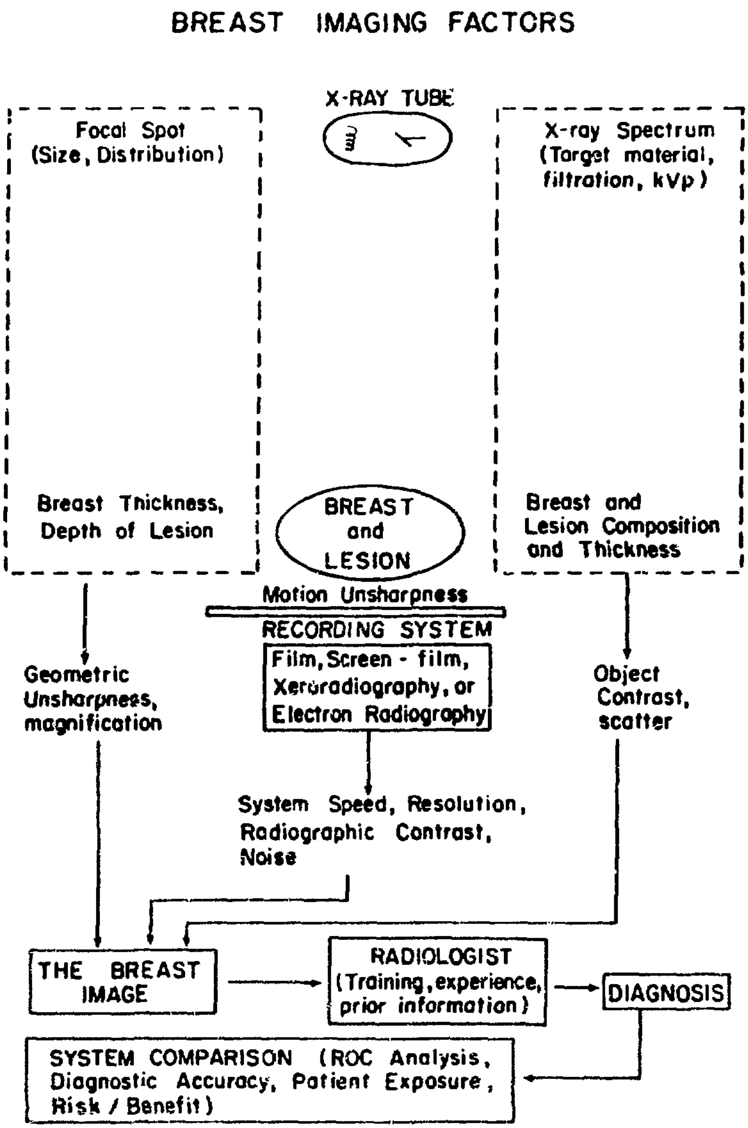


Fig. 1. Diagram of the various factors and of their complex interrelationship, as they affect image quality.

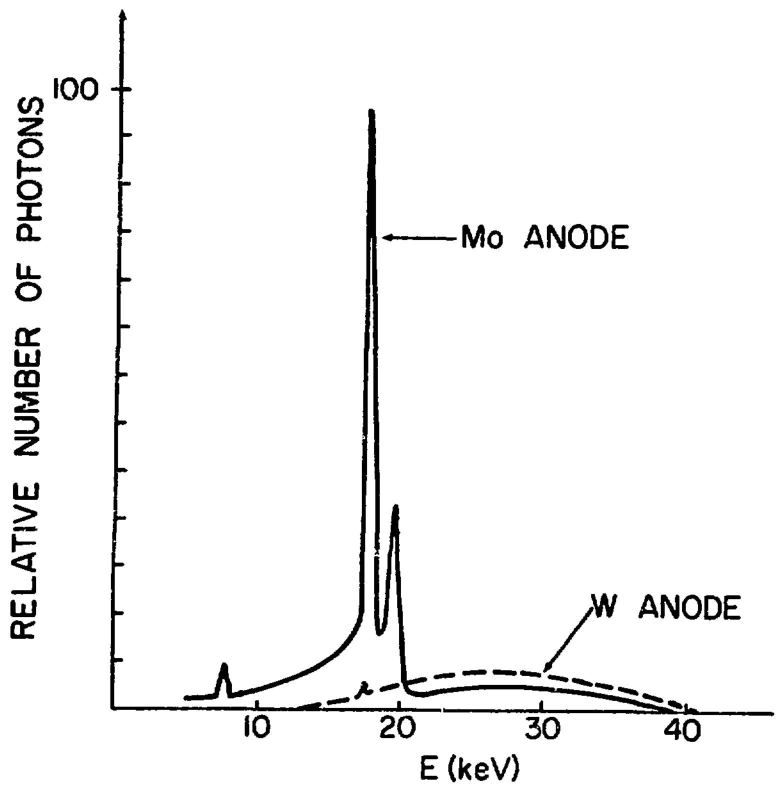


Fig. 2. X-ray spectra emitted by a molybdenum and a tungsten anode tube.

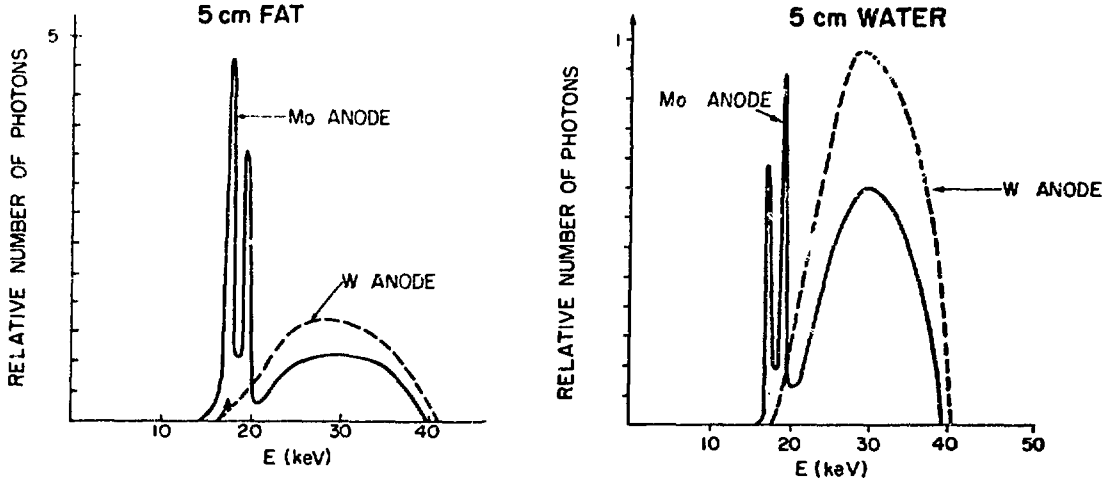


Fig. 3. X-ray spectra from the molybdenum and the tungsten anode tube, transmitted through 5 cm of fat (left) and through 5 cm of water (right).

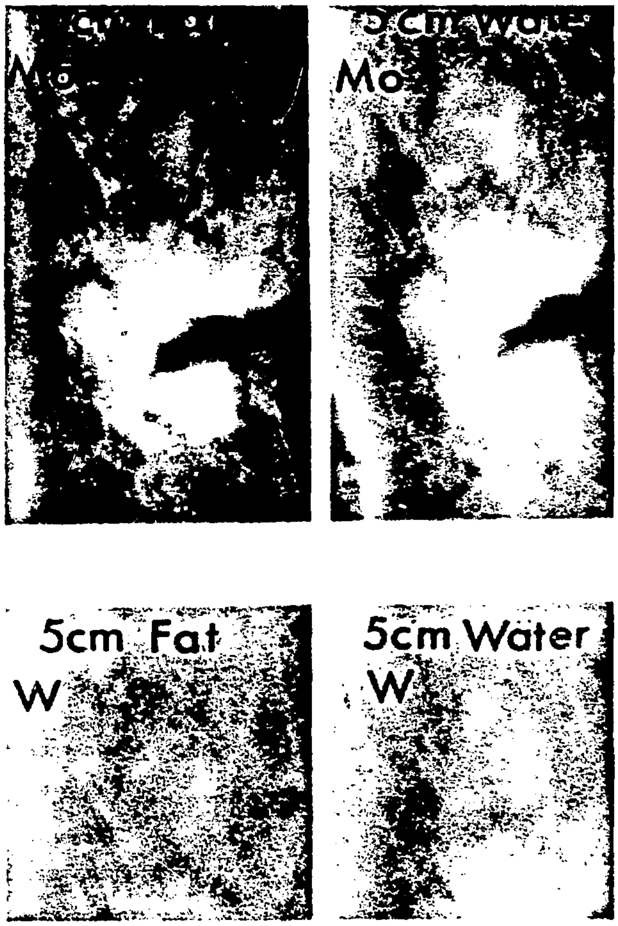


Fig. 4. Radiographs of a 1.5 cm thick section of resected breast tissue with 3.5 cm of lard (left) and 3.5 cm of water (right) superimposed to simulate 5 cm thick fat- and water-equivalent breast. The images made with the molybdenum tube are on top and those with the tungsten tube, on the bottom.

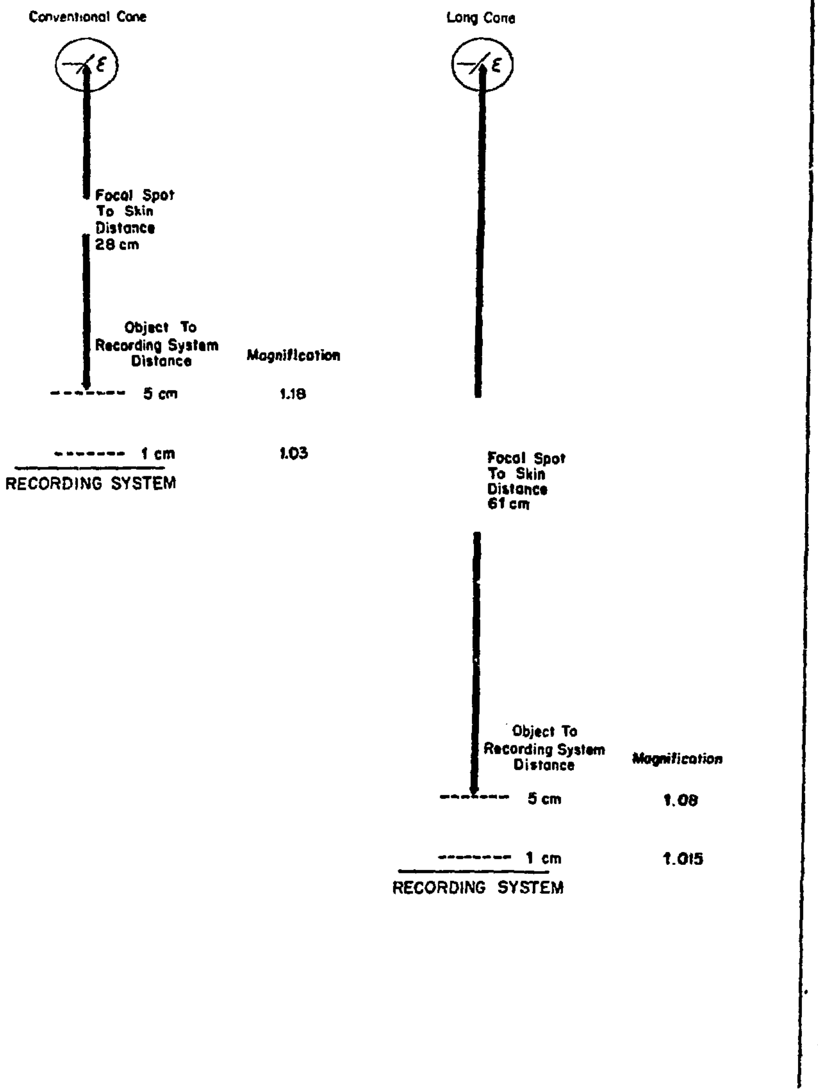


Fig. 5. Geometric setup for mammography (left) with conventional cone; (right) when improved geometry with a long cone is used.

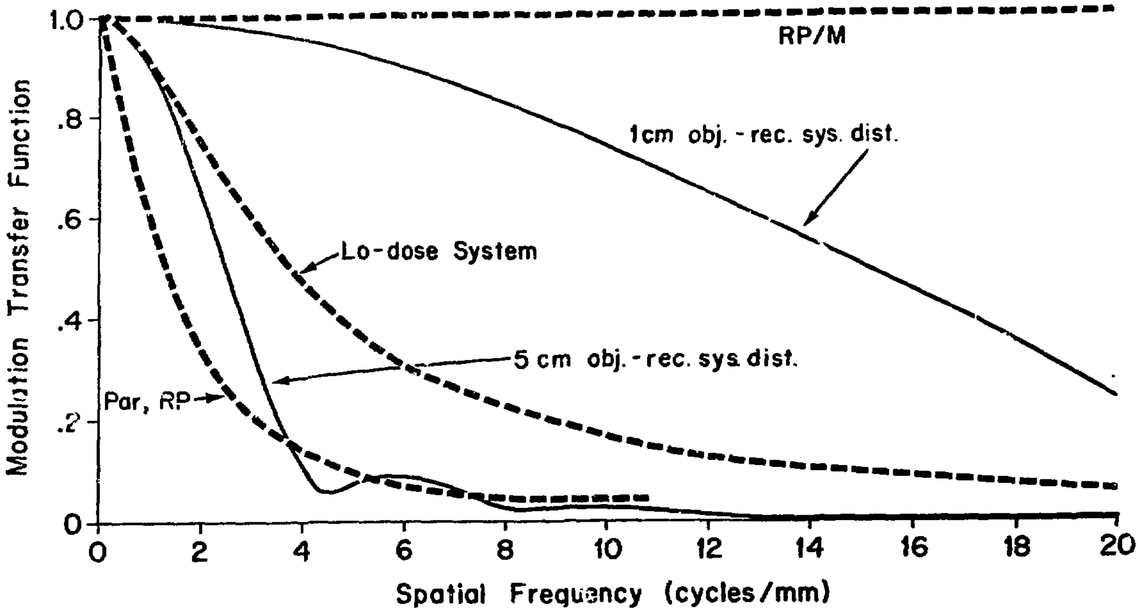


Fig. 6. MTFs of geometric unsharpness (in the image plane) when the conventional cone is used (focal spot-to-skin distance 28 cm), at object-to-recording system distances of 5 cm and 1 cm; recording system MTFs of RP/M film, Lo-dose system, and Par, RP system.

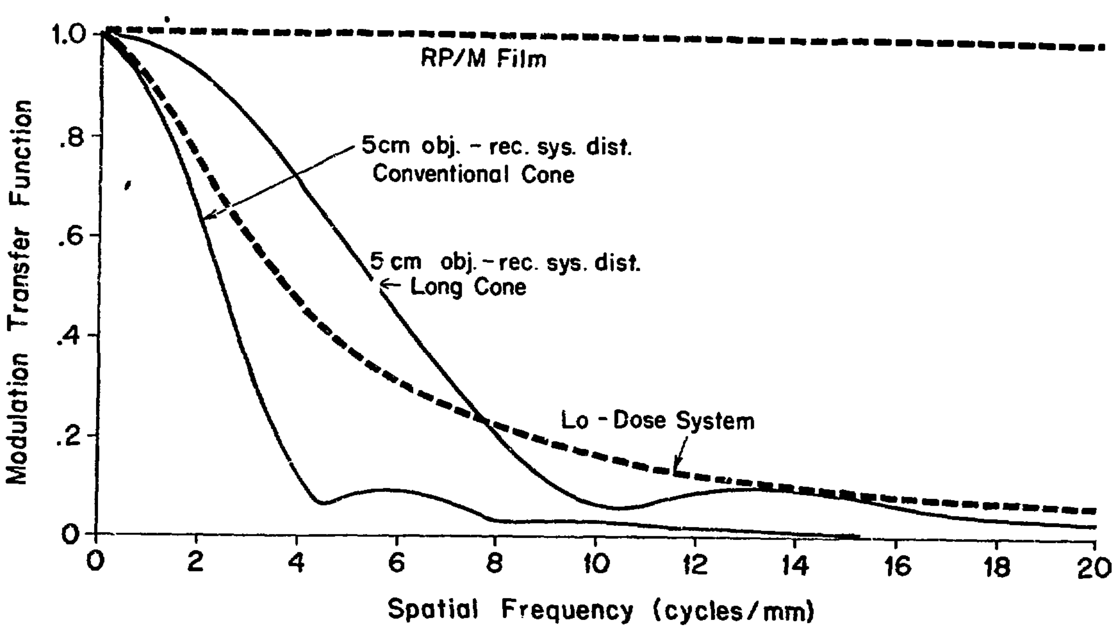
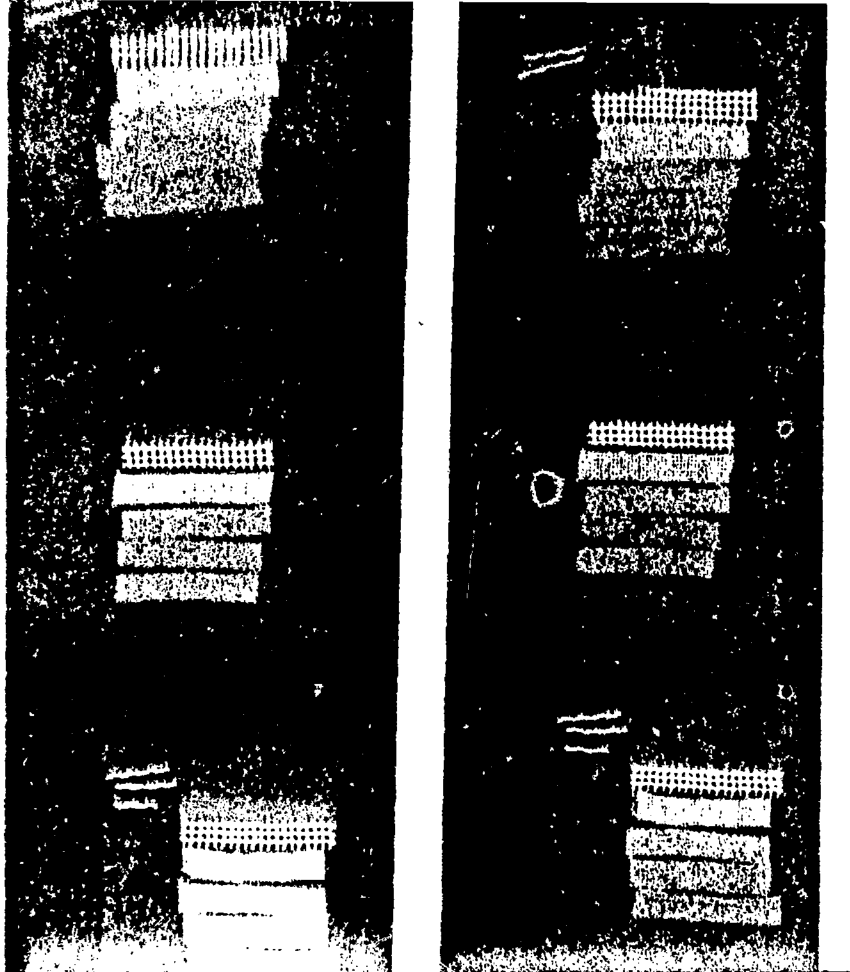


Fig. 7. MTFs of geometric unsharpness when the conventional cone and the long cone with improved geometry are used at an object-to-recording system distance of 5 cm; MTFs of RP/M film and Lo-dose system.



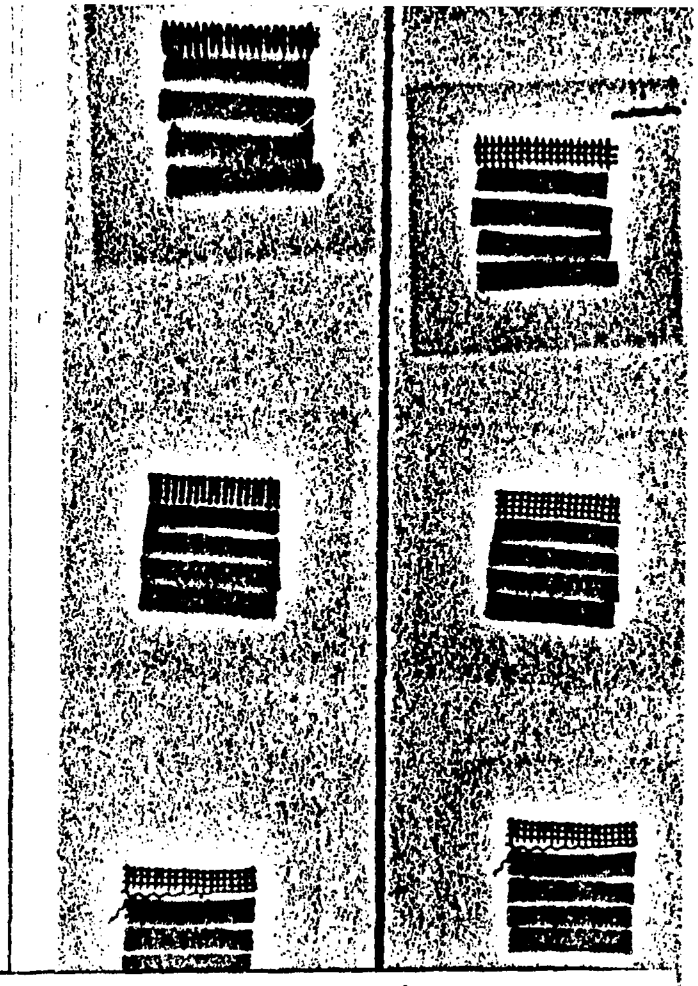


Fig. 8. Radiographs of five stacked Lucite blocks, each 1 cm thick, with microwire mesh patterns interposed at object-to-recording system distances of 5 cm (top), 3 cm (middle), and 1 cm (bottom). Conventional cone, RP/M film (left). Long cone, Lo-dose system (right).

Fig. 9. Xeroradiographs of resolution test object shown in Fig. 8. Conventional cone (left); long cone (right).

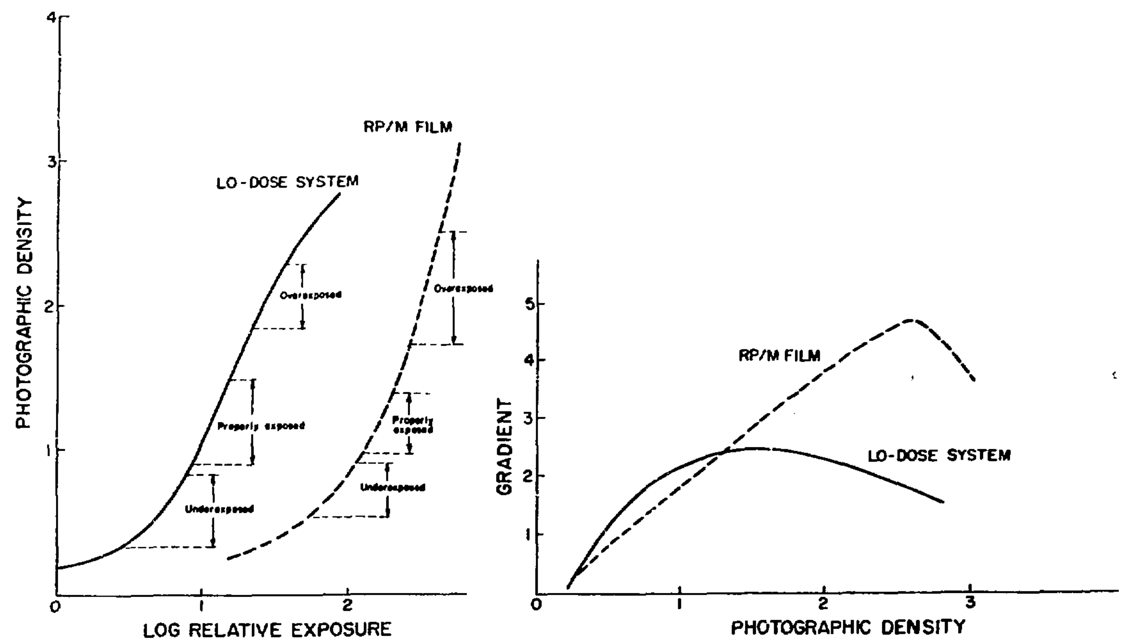


Fig. 10. Characteristic and gradient curves of RP/M film and Lo-dose system.

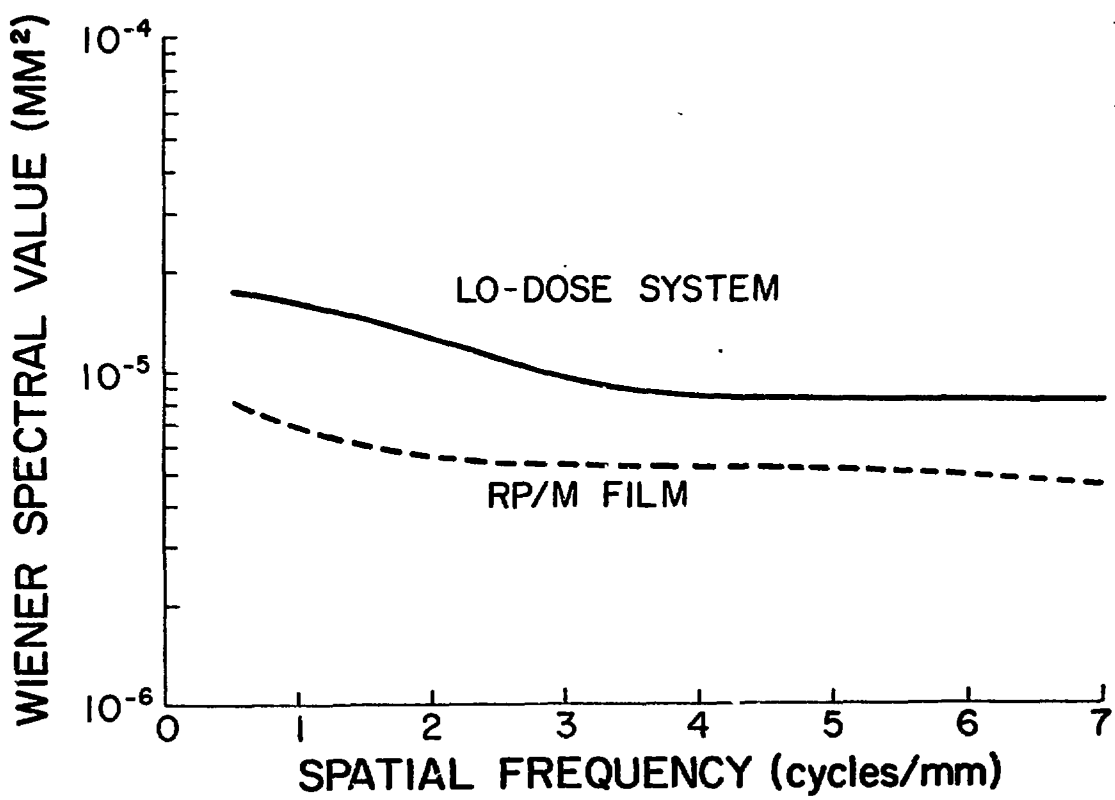


Fig. 11. Wiener spectra of RP/M film and lo-dose system. Average density, 1.0; x-ray tube voltage, 35 kVp.

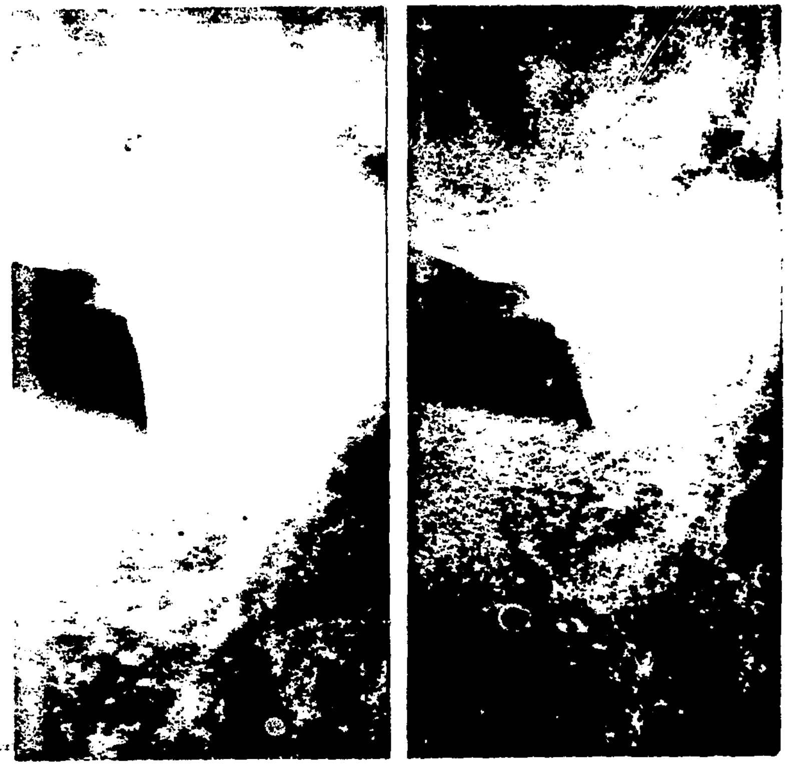


Fig. 12. Radiographs of section of a carcinoma from a resected breast. The speciman was spaced in air at an object-to-recording system distance of 5 cm. Left, RP/M, conventional cone; right, Lo-dose system with long cone.

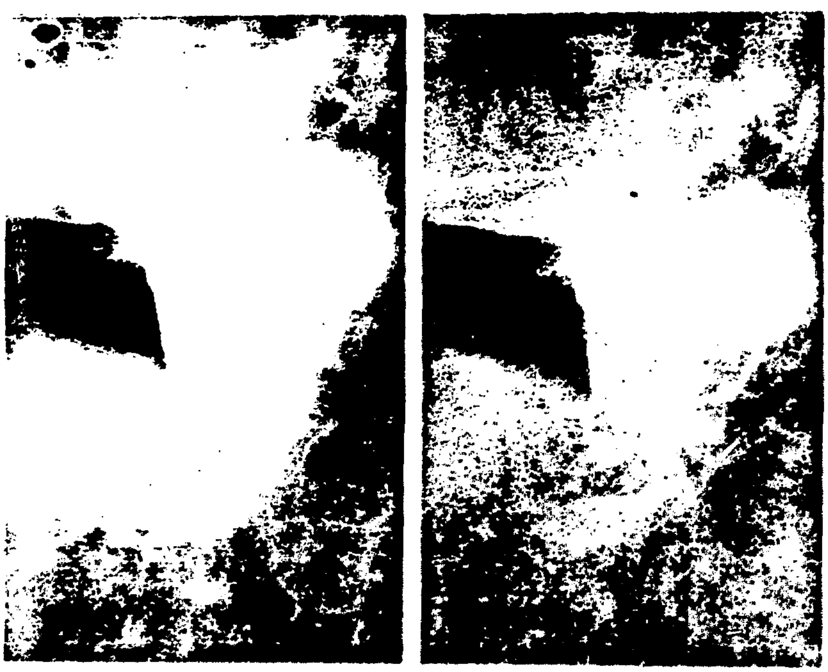


Fig. 13. Radiographs of section of a carcinoma from a resected breast. The specimen was in contact with the recording system. Left, RP/M with conventional cone; right, Lo-dose system with long cone.