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A number of feasibility measurements were performed to assess the x-ray imaging properties of two capillary optics for digital mammography. Optic 1, used in year one, had input and output diameters of 4.15 mm and 7.5 mm, respectively,. Optic 2, used in year two had input and output diameters of 3.62 mm and 6.83 mm, respectively. A mammographic scanning system was constructed to allow imaging of a larger field for some of the measurements. Optic 1 showed good primary transmission, 46%. Optic 2 had better linearity at mammographic energies. Images of a Lucite contrast detail phantom, using a lead blocker, showed that both optics provide an increase in image contrast with a contrast improvement of approximately 1.7, and a reduction of scatter fraction to 0.02. The limiting resolution for the CR phosphor plate system was increased to about 8.5 lp/mm, with an improvement of the MTF at all spatial frequencies. Clinical training was received by the postdoctoral fellow.

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Carolyn McDonald 1/2/98
PI - Signature Date

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Introduction

Nature of the Problem

Digital mammography is a promising technology that can further improve the early detection of breast cancer, offering the potential advantages of improved image quality, digital image processing for improved lesion contrast and computer diagnosis for enhanced interpretation.[1] Digital mammograms have been limited in 1) contrast by the large fraction of scattered photons and the low inherent contrast of the breast tissue, and 2) in spatial resolution caused by focal spot blurring and by the detector itself. In many digital imaging applications detector resolution is a significant limitation. Computed radiography (CR) photostimulable phosphor plates have lower spatial resolution than film and have been limited in their application in mammography[2] where the detection and evaluation of microcalcifications requires very high spatial resolution. Attempts to increase the effective resolution of the CR plates using conventional magnification techniques would be limited to modest magnifications due to the increase in blurring associated with the focal spot.

Background

X-ray capillary optics,[3,4,5] small bundles of hollow capillary tubes with inner diameters as small as a few microns, make use of the nearly total external reflection of x rays in a manner analogous to the way conventional fiber optics guide light. Arrays of curved tapered capillaries can be used to focus, collimate, and filter x-ray radiation.[6,7,8] The critical angle for total external reflection of x rays by glass polycapillaries is given by

$$\theta_c = \frac{\omega_p}{\omega} \approx \frac{3.2x10^{-2}}{E(keV)}$$

where ω_p is the plasma frequency of the glass, and ω is the photon frequency. X-ray capillary optics can be useful in addressing the problems above due to their small angle of acceptance (critical angle = 1.6 milliradians for 20 keV photons). Scattered photons at the entrance of the optic which are at an angle greater than the critical angle would be rejected. Focused arrays of these optics would be used between the breast and detector system to reduce scatter and enhance spatial resolution through magnification techniques.

At the onset of this postdoctoral fellowship, extensive measurements at mammographic energies had been taken by Abreu et al.[9] to determine the performance of individual capillaries and non focused optics. The postdoctoral fellowship made it possible for Abreu to join the Medical Physics group at the University of Wisconsin at Madison where the imaging characteristics of capillary optics had begun to be investigated.

Purpose

The overall objective of this postdoctoral study was to investigate the feasibility of using diverging glass capillary optics for digital mammography. The aim of the study was divided into two stages. Stage 1, which was carried out in year one, consisted of: 1) modifying the scanning gantry to permit measurements of the partial optics; 2) performing measurements on the partial optic prototype (optic 1) in both static and scanned configurations; and 3) designing the final optics. Stage 2, which was carried out in year two, consisted of: 1) more scanner modifications; 2) repeating transmission and scatter measurements on the new optic (optic 2); 3) measuring the contrast improvement with optic 2 using a scatter phantom; 4) investigating the extent of artifacts due to the capillary structure in fixed and scanning modes; and 5) attempting to measure the noise power spectra of the magnified scatter reduced phosphor plate detector. The postdoc also made it possible for Abreu to gain clinical hands-on training relevant to breast cancer research. The project was extended to include one month of effort in the third year, which allowed for preparation of a major review article (Abreu, et al., Physica Medica).

Body: Methods and Results

The system used to take measurements during both years was a Philips Computed Radiography (CR) system with 8"x10" high resolution (HR-III) imaging plates.

In **year one** (as described in the first annual report), the mammographic scanning gantry was fabricated to allow the measurement of a partial capillary optic prototype (optic 1) built by X-Ray Optical Systems, Inc. (The scanning gantry allowed the optic to be scanned in the horizontal plane while the phantom and detector shift in unison as shown in figure 1. The details of the scanner can be found in reference 10 which is a paper that our group has published in Medical Physics.) Optic 1 was 16.7 cm long, and it tapered from an output diameter of 7.5 mm to an input diameter of 4.15 mm resulting in a magnification of 1.81. The individual capillaries had an output diameter of 24 μm and an input diameter of 14 μm. Though the prototype was not an optimal optic, it still was very useful in the performance of relevant imaging experiments.

First, the <u>primary transmission of the partial optics prototype</u> was measured in the static configuration. The primary transmission was approximately 46%. <u>Scatter fractions</u> with and without the optic were measured using a 5 cm thick Lucite phantom, a field size of 16 cm and a lead beam blocker with a width of 3.1 mm as shown in figure 2. A rectilinear scan was done to obtain an image for the scatter fraction measurement with the optic. Measurements were also done with and without a 5:1 scatter reducing grid. The results for these measurements are summarized in Table 1.

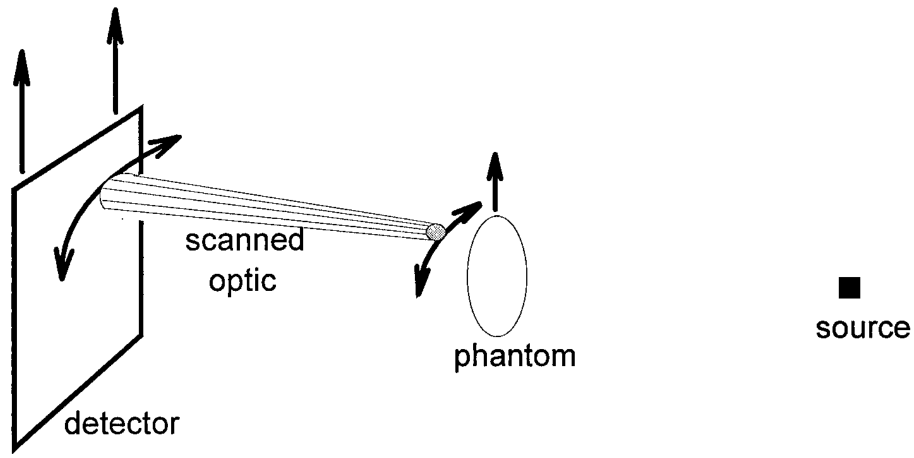


Figure 1. Scanning gantry geometry for year one. The optic is scanned in the horizontal plane while the detector and phantom are moved in parallel vertical planes to allow imaging of the wide area object.

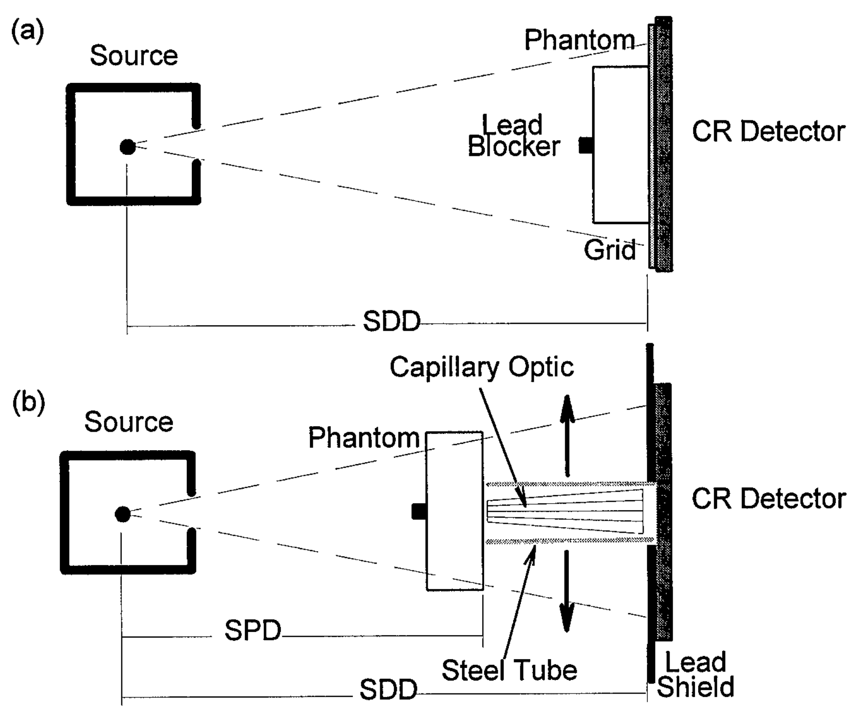


Figure 2. (a) Scatter fraction measurement geometry for normal acquisition with and without the grid. (b) The optic is scanned along with the lead shield. The shield is needed to keep the scatter from bypassing the optic and being detected. The source to detector distance (SDD) = 42 cm and the source to phantom distance (SPD) = 24 cm for the prototype optic.

Method	T_p	T_s	Scatter Fraction
Normal	~1	~1	0.450
5:1 Grid	0.660	0.200	0.170
Capillary Optic	0.460	0.003	0.018

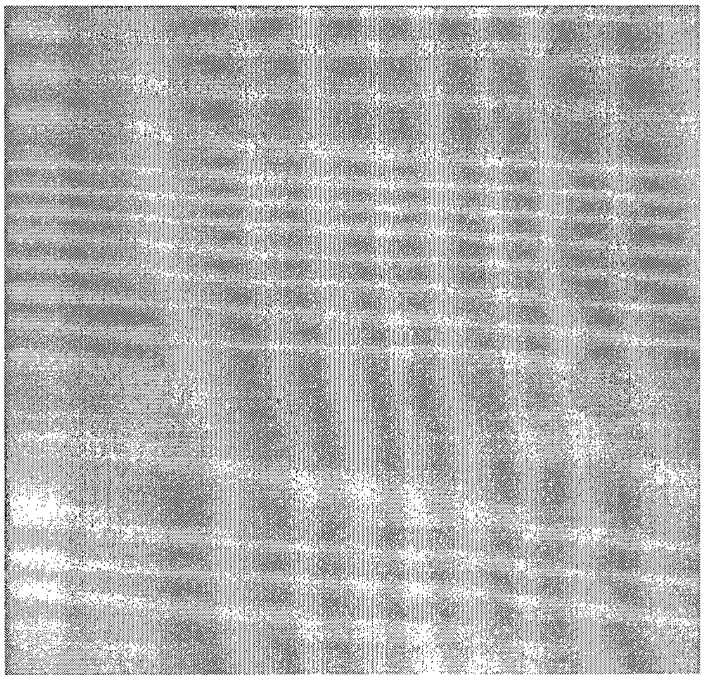
Table 1. Scatter fractions and primary and scatter transmission factors of three methods of image acquisition.

From the scatter fractions in Table 1, a comparison was made of the capillary method to the method using no anti-scatter device to calculate the optic transmission necessary for equal SNR. That point was ≈ 50%. A comparison to the actual transmission of 46% shows that the optic gives the same SNR/dose as a 5:1 anti-scatter grid. Even though this optic is at the break even point compared to a grid, new manufacturing processes and greater linearity are expected to give higher primary x-ray transmissions. Any higher optic transmission will permit additional gains in SNR or a possible decrease in dose with its use.

The contrast improvement was also measured. This is important because it is directly related to reduced scatter. For these measurements a 5cm thick Lucite contrast phantom containing holes of decreasing size in one direction and decreasing depth in another was used. To measure the contrast, the phantom was imaged, with grid and without grid, using CR plates on a GE Senographe mammography unit set at 27 keV and 35 mAs. The phantom was then scanned using optic 1 at 27 keV. These images are shown in figure 3 and a quantitative contrast comparison of the cases with and without grid are shown in figure 4.[10] Capillary optic 1 showed better performance compared to the cases with and without the grid for all hole sizes. The 5:1 grid yielded an average contrast improvement factor of 1.2 compared to no grid. For optic 1 the factor was 1.7, showing that the optic does an excellent job of reducing scattered radiation.

To determine the limiting resolution for the phosphor plate system with and without the optics, modulation transfer function (MTF) measurements were performed. The MTF was measured using the edge response function of the phosphor plate imaging system (CR) with and without optic 1. (For details of this experiment see reference 10.) The MTF curves are shown in figure 5. The MTF limiting resolution point for this comparison was defined to be the spatial frequency at which the MTF curve drops to 5%. When optimal geometric magnification (and large focal spot = 0.3mm) is used the limiting resolution increases to 5.4 lp/mm. Using the capillary optic in a stationary mode (with large focal spot = 0.3mm), the 5% MTF level is increased to 9 lp/mm. With the scanned optic mode the limiting resolution is 8.4 lp/mm. The scanned MTF is reduced relative to the stationary case because the scanning produces the possibility of blurring due to a non-linear taper of the optic or mere vibration of the scanning system. The performance of the scanned optic could be improved by having an optic with a more linear taper or by eliminating the vibration of the scanning system with the use of a more elaborate system.

(a)



(b)

Figure 3. Images of a contrast-detail phantom (a) with a 5:1 grid and (b) with capillary optic 1.

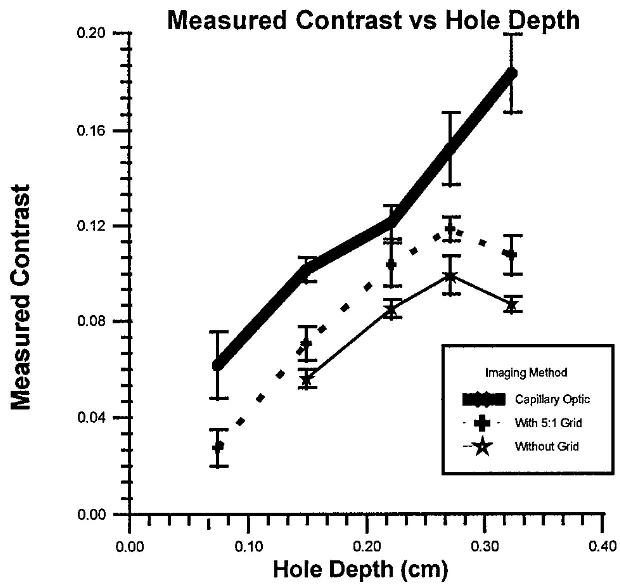


Figure 4. The average measured contrast of the contrast-detail phantom is plotted versus depth for the methods with optic 1 (thick line), with a 5:1 grid (dashed line) and without a grid (thin line).

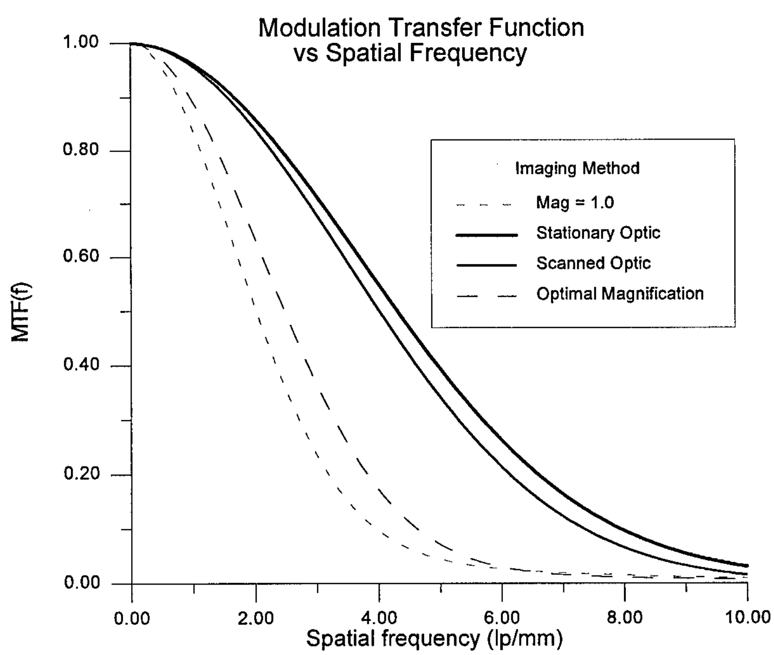


Figure 5. MTF's of four CR imaging methods, optic 1 is used in two of the imaging methods.

In **year two**, attempts were made to image a Radiation Measurements, Inc. (RMI) Mammography Accreditation Phantom, Model 156, with the original scanning gantry and optic 1. The RMI phantom contains objects which simulate micro-calcifications, fibrous structures in ducts, and tumor-like masses.[11] (A schematic of the RMI phantom is included in the appendix.) This phantom is used by mammography quality assurance groups as an integral test in determining the ability of a mammographic unit to image structures similar to those found clinically. Since the optic had a small output diameter and the RMI phantom contained objects in a 8cm x 8cm region, the mammography unit had to be modified to allow it to run continuously so that the optic had enough time to scan the phantom. Due to the scanner's limited ability in both the horizontal and vertical planes, the mammography unit's heating load and the optics small useful output diameter (2mm), the scans had to be taken in 9 thin slices on each half of the phantom. This created problems in getting a full image of the phantom since a full image would have to be constructed from a total of 18 image strips. Nonetheless, the scans of the RMI phantom with the optic showed improved resolution and contrast as compared with a conventional mammogram image of the phantom. This was especially true when comparing the region materials 5, 10, and 14 of the RMI phantom (refer to the appendix).

To avoid some of the problems above, the scanning apparatus was upgraded. The scanner used in year one was designed only to scan in one direction. It performed two dimensional scans quite awkwardly. The new scanner consists of a gimbel mount for the x-ray tube, a rigid arm between the x-ray tube and the mounting hardware for the optics, and stepper motors for both directions. The optic and source which now move in unison are scanned while the detector and object remain motionless. Figure 6 shows a simplified schematic of the new scanning geometry.

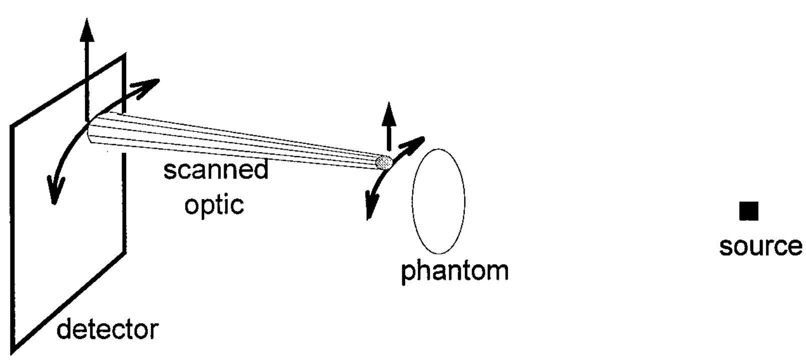


Figure 6. Scanner geometry for year two. The optic and source move in unison while the detector and object remain motionless. The optic is scanned in a two dimensional plane.

A new linear optic was received from X-Ray Optical Systems in Feb. '96. This optic was also a linear focused bundle of borosilicate glass capillary fibers. This optic had been fabricated with our requirements, and the results of the measurements from optic 1, in mind. The new optic (optic 2) was 27.3 cm long, with input and output diameters of 3.62 mm and 6.83 mm respectively, a magnification ratio of 1.89, and individual capillary channel diameters of 8μm and 15μm. Although the output diameter is slightly less than optic 1, the useful diameter (as described below) was significantly greater; the full 6.83 mm as opposed to ≈ 2 mm for the previous optic.

The acceptance focal length of the optic is defined as the distance, from the focal spot to the optic, at which all input fibers accept x-rays from the focal spot. The geometric focal length is the distance from the optic at which a point of rotation will produce a one-to-one mapping of all points on the input end of the optic to a point on the exit end of the optic. For a scanning geometry the x-ray focal spot and point of rotation must be placed at the geometric focal point. However, when the optic is positioned nearer to the source than its acceptance focal length, the transmitted spot size (and effective diameter of the optic) is reduced because all but the central capillaries point to some position behind the source and x-rays impinging on these outer capillaries strike at greater than the critical angle. At the acceptance focal length, the individual capillaries are pointed at the source and the total optic transmits. An ideal optic is expected to have equal geometric and acceptance focal lengths. The experimentally determined acceptance focal length for *optic 1* was 45.3 cm. The geometric focal length was calculated from the magnification and length and was 20.6 cm for this optic. When the focal spot was placed at the geometric focal distance the optic transmits only in the central 2 mm section of the optic. *For optic 2, the acceptance focal length (30.7 cm) was close enough to the geometrical focal length (30.9 cm) that the entire output diameter (6.83 mm) of the optic was useful.*

<u>Transmission and scatter measurements were obtained for optic 2.</u> The transmission of the new optic was was consistent throughout the entire output area. The optic was produced using preforms with low transmission to avoid sacrificing higher quality material while developing the profile control technology. The optic transmission was only slightly less than that of the preform indicating that the pulling process did not degrade transmission. For the scatter measurements, the source to detector distance (SDD) = 59 cm and the source to phantom distance (SPD) = 30.9 cm for optic 2 (refer to figure 2). The scatter fraction results for the new optic (≈ 0.023) were consistent with the older optic.

<u>Contrast measurements were also obtained for optic 2</u>. A CR image of the Lucite contrast phantom is shown in figure 7. When compared with the CR image of optic 1 (figure 3b), notice that *there is little scanning artifact with optic 2* and

that the image was obtained in one continuous scan. The scan with the new optic was obtained at a lower exposure than the old one so the quantum noise is somewhat higher. The measured contrast values were similar to the values obtained with the previous optic.

Resolution measurements were taken using the new optic. The MTF was measured using the edge response function of the phosphor plate imaging system (CR) with and without optic 2. The MTF curves are shown in figure 8. The limiting resolution of the CR system is 5 lp/mm. Using the capillary optic in a scanning mode, the 5% MTF level is increased to 8.6 lp/mm. A resolution pattern was also scanned. The image is shown in figure 9. The image has no observable artifacts. The modulation depth of the 8.5 lp/mm group was measured at 5%. The 10 lp/mm group was not resolved. These results are consistent with the MTF measured with the older optic. Imaging of the RMI phantom was performed with the revised scanning gantry and optic 2. The problem of having to scan in thin slices was resolved with the design of the new scanner.

The mammography imaging lab in Madison was moved from one end of campus to another towards the later part of this grant. We then ran into some problems getting our CR system up and running after the move to complete further measurements under this grant. These measurements will be performed at a later date by the ongoing collaboration of the University of Albany with the University of Wisconsin medical physics group. The postdoctoral fellow supported by this grant has moved on to another position in Connecticut.

Throughout the two years, Abreu was also able to gain a wide variety of clinical experience relevant to breast cancer research and medical physics by sitting-in classes and labs and by working with the quality assurance group at the UW Hospital. The classes and labs sat in included Dosimetry, Diagnostic Radiology, Ultrasound and Radiological labs in Digital Angiography, Ultrasound, Magnetic Resonance Imaging (MRI) and Computed Tomography (CT). All aspects of quality assurance (including report writing) were performed on a number of diagnostic radiology machines which included Mammography units, CT scanners, MRI units, overhead radiation equipment, ultrasound units and transducers, and C-arm radiation equipment.

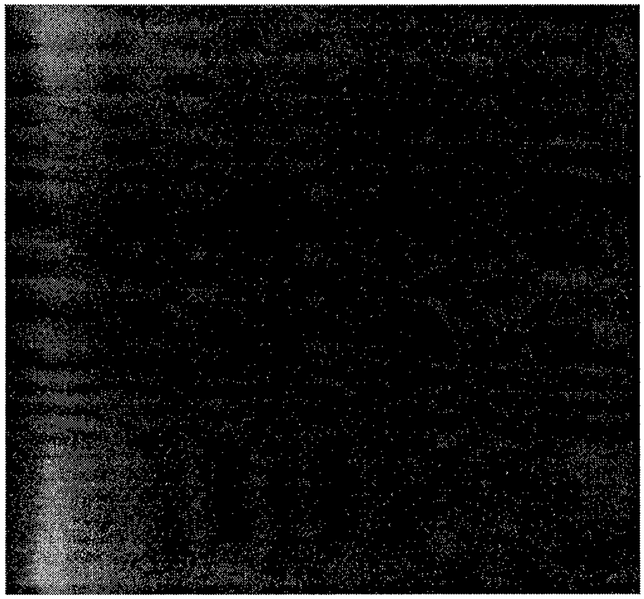


Figure 7. Computed radiography image of a contrast phantom obtained with the new optic.

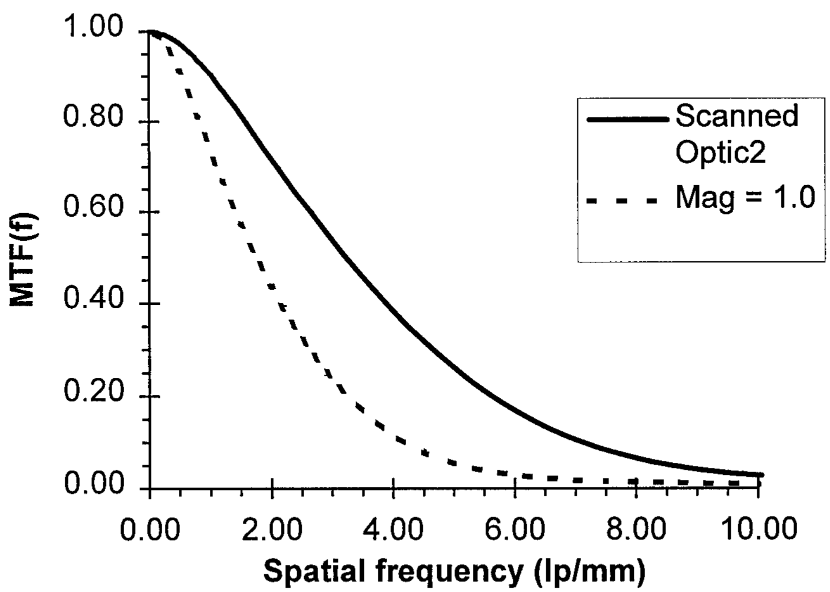


Figure 8. MTF's of two CR imaging methods

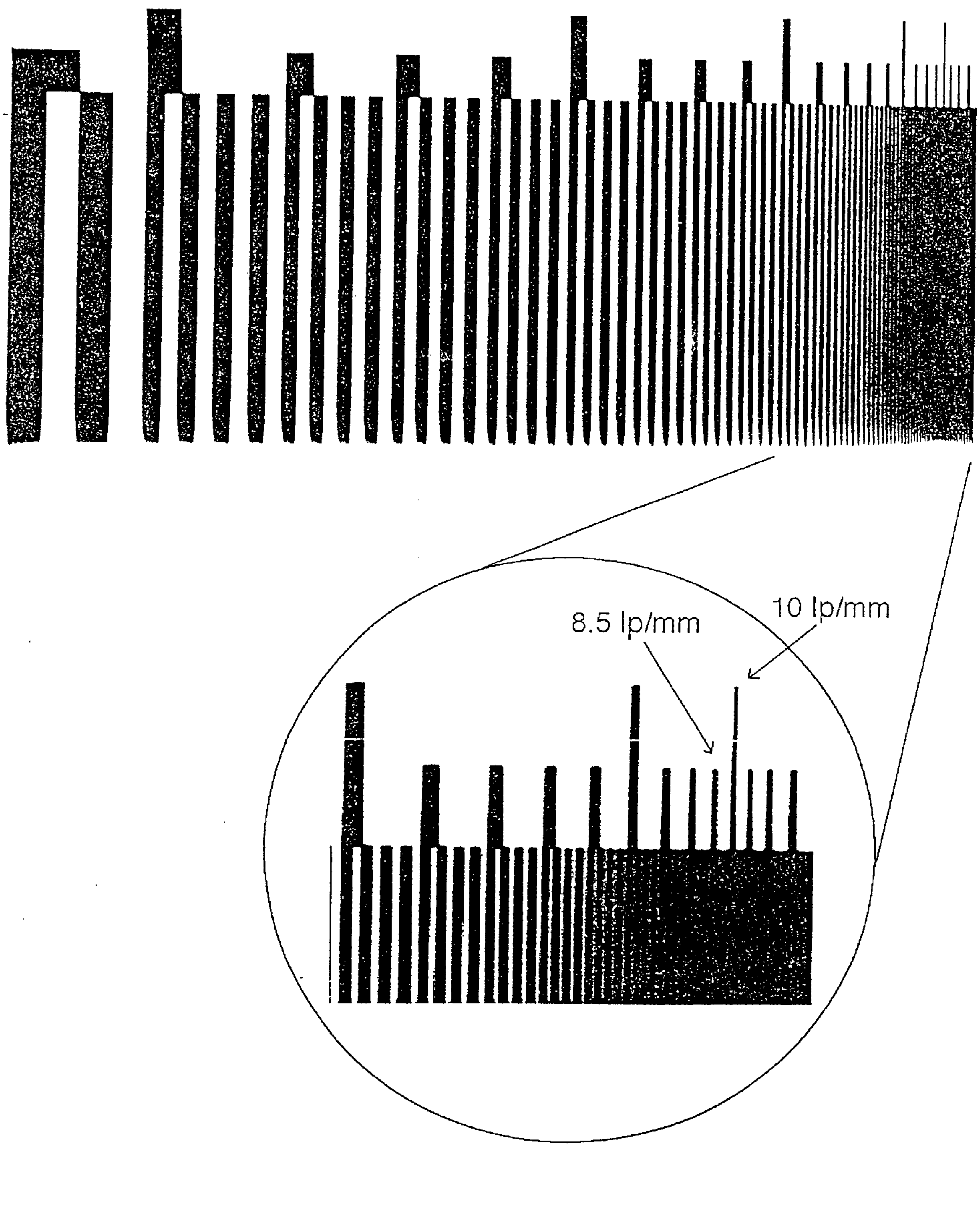


Figure 9. An image of a resolution pattern obtained with optic 2.

Conclusions

The potential of x-ray capillary optics for application in digital mammography has been demonstrated. Capillary optics showed nearly total rejection of scatter in the scanned images. This reduction in scattered radiation causes an improvement in image contrast by an average of 70% over methods with no anti-scatter device and 40% over methods using a 5:1 grid. The transmission of optic 1 was 46%, which was very promising since good total transmission is required to give a reasonable total breast dose. The transmission of optic 2 was 18%, which was not desirable but that transmission was consistent throughout the entire output area unlike optic 1.

MTF comparisons using the optics to other CR methods showed a significant increase in resolution. The resolution increase is linearly dependent on the magnification factor of the optic. If an optic with a magnification of 3 was obtained , then the limiting resolution could be increased to 15 lp/mm. New optics with larger magnifications should facilitate the use of phosphor plates as digital detectors capable of imaging the entire breast. Digital mammography would have all the advantages of digital processing, such as image processing, image transmission and storage, and computer aided diagnosis.

Neither test optic was large enough to be clinically feasible. However, because the measurements of the optics have shown excellent agreement with theoretical predictions, improvements in the manufacturing technology of the optics should produce imaging improvements as well. The optics' ability to achieve a simultaneous increase in contrast and an increase in effective resolution of CR images is a remarkable achievement.

Publications and Personnel Report

Papers resulting from research work done on this grant

D.G. Kruger, C.C. Abreu, C.A. MacDonald, E.G. Hendee, A. Kocharian, W.W. Peppler, and C.A. Mistretta, "Imaging characteristics of x-ray capillary optics in mammography," Medical Physics, **23**(**2**), pg. 187-196, 1996.

C.C. Abreu and C.A. MacDonald, "Beam Collimation, Focusing, Filtering, and Imaging with Polycapillary X-Ray and Neutron Optics, invited article, Physica Medica, in press.

C.A. MacDonald and W.M. Gibson, "Medical Applications of Polycapillary X-Ray Optics," in R.B. Hoover and M.B. Williams, **X-Ray and Ultraviolet Sensors and Applications**, SPIE Proceedings, vol. 2519, 1995.

Personnel receiving pay from the negotiated effort

Carmen Abreu	Ph.D.	Postdoctoral Fellow

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