Final Technical Report

Project Title: A Critical Evaluation of Patient Doses in Screening Mammography
DE-FG07-02ID14333

Executive Summary

This project was designed to develop tools that would permit an accurate assessment of the patient doses that are received in screening mammography, and to subsequently demonstrate those tools to perform an objective evaluation of patient doses. The project also provides an educational component through the integration of multiple aspects of applied radiological engineering to provide students with realistic applications of many of the theoretical principles that are studied as part of their graduate curriculum.

The project has contributed to a quantitative evaluation of realistic patient doses that are received through screening mammography examinations. Several tools have been developed that provide the characterization of patient specific doses from these radiographic exams. The tools developed include two series of tissue equivalent phantoms that mimic the radiographic properties of a variety of breast tissues. The phantoms mimic the varying amount of glandular and adipose tissues that are typically observed to vary as a function of compressed breast thickness, permitting a much more accurate determination of radiation dose for the distributions observed in the screening population. The dosimetry phantoms have also been integrated with tools that permit the simultaneous evaluation of image quality for varying compressed breast thickness.

The utilization of these tools has demonstrated that existing dosimetry estimates may differ by up to a factor of 3, either greater or smaller, for some patients when compared to conventional estimates of the mean glandular dose delivered in mammography examinations. The dosimetry study has been applied to several clinical facilities to provide a realistic characterization of other variables that may affect patient doses. These include facility specific radiographic techniques and individual equipment characteristics. The project has also demonstrated the need for some more advanced tools to fully characterize both population and individual patient doses in screening mammography. These needs occur as a result of the observed variation in the content and distribution of glandular tissue in the compressed breast. In response to this issue, we have developed a glandularity step phantom and initiated a detailed survey of the elements of a mammography screening population in order to document and demonstrate the capability to provide these detailed assessments.

The tools and protocols developed through this project are being used to provide a much needed improvement in the evaluation of clinically delivered breast dose. As more substantial data is collected from a variety of facilities, the results can be combined with risk models and the recent ICRP recommendations that increase the breast tissue weighting factor by a factor of 4 (from 0.05 to 0.20) to provide quantitative justification for mammography screening program protocols in the U.S.

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Project Title: A Critical Evaluation of Patient Doses in Screening Mammography

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Project Objective:

The overall objective of this project is to develop tools that will permit an accurate assessment of the patient doses that are received in screening mammography, and subsequently to utilize those tools to perform an objective evaluation of those doses. The project will integrate multiple aspects of applied radiological engineering and provide a student with realistic applications of many of the theoretical principles that are studied as part of the graduate curriculum.

Background:

The project entitled "A critical evaluation of patient doses in screening mammography" was initiated in July 2002. The project built upon preliminary results that were developed as an exploratory effort of an ongoing project that is developing tissue equivalent phantoms appropriate for dose evaluation in pediatric patients undergoing a variety of diagnostic x-ray procedures. In order to successfully apply our previous experience to the important problem of patient doses in screening mammography, we have developed tools and subsequently demonstrated their application, making a significant contribution to the current knowledge of patient doses in screening mammography.

The development of meaningful characterizations of patient doses is important to provide representative dose information in the continuing evaluation of the risk vs. benefit of screening mammography. These evaluations will be particularly important for a complete

characterization and understanding of mammography hardware performance as mammography facilities begin to transition from traditional screen-film imaging to digital imaging systems.

Objectives:

The project has the objective of providing more definitive dosimetry information for clinical screening mammography examinations, an area that has not been very well characterized and produces potential risks to the screening population. The specific objectives of the project have been to:

1. Design and construct a family of dosimetry phantoms that realistically represent the variations in both breast tissue composition and compressed breast thickness for the screening population.
2. Develop a MCNP based computer simulation that permits the "calibration" of mean glandular dose with exposure measurements performed using the dosimetry phantoms.
3. Design and construct a family of imaging phantoms that permits an objective evaluation of image quality as technique factors are changed to accommodate different breast tissue compositions and compressed breast thicknesses.
4. Survey screening mammography facilities and collect an initial series of data for the accurate evaluation of patient doses in screening mammography.

Over the course of the project each of these objectives has been met and a number of additional areas of research have been investigated. These areas have been identified as areas requiring more thorough investigation while pursuing the primary objectives in order to provide definitive dosimetry evaluations for mammography. Several of these areas are areas where little or no previous work has been performed, but is a critical link in the chain to successfully developing dosimetry models for mammography. Work to more thoroughly characterize mammography doses continues through these projects in order to advance current knowledge of clinically delivered doses in mammography.

The results of the project as related to each of the project objectives and additional work that was performed are described in the following sections of this report.

Project Accomplishments and Contributions

Objective 1: Design & Construction of Dosimetry Phantoms

Over the course of the project, *two* complete series of breast tissue equivalent phantoms have been developed and the need for a third, more anatomically correct series of phantoms has been identified. These phantoms provide the fundamental tool for the empirical evaluation of mammography doses that are delivered by clinical facilities. An epoxy resin matrix was selected as the basis for constructing each series of phantoms. The first generation phantoms are homogenous phantoms representative of clinically observed

glandularity and compressed thickness with lateral dimensions matching those of the standard phantom used in mammography quality assurance evaluations, the American College of Radiology (ACR) mammography QA phantom[1]. This geometry provided ready comparison with current dosimetry results, and demonstrates how the glandularity and compressed breast thickness affect phototimed exposures, and mean glandular doses in mammography.

A primary effort of the early phase of the project involved developing breast tissue equivalent materials to accurately mimic the radiological properties and densities of breast tissues of various glandularity. Various chemical constituents were selected and incorporated into the epoxy resin matrix to ultimately produce a series of tissue equivalent materials with the desired properties. The desired phantom materials closely matched the mass attenuation, mass-energy absorption coefficients and density of the known breast tissue over the mammography energy range. Material selection was additionally constrained by the need to produce a cost effective, user-friendly, and low maintenance product from commercially available materials. The phantoms described were fabricated from a mixture of readily available epoxy resins and chemical compounds. A software package, XCOM Version 3.1, written and developed by Hubbell[2] at the Center for Radiation Research, National Bureau of Standards was used to match the total mass attenuation coefficients between the proposed breast tissue substitutes and the adipose and glandular tissue properties reported in ICRU 44[3].

The composite of materials that simulate glandular and adipose tissues were developed individually. By varying the ratios of these constituents the desired physical properties and mass attenuation coefficients for the simulated glandular and adipose tissue material were matched to those predicted based on the tissue compositions reported in ICRU 44. The Breast Tissue Equivalent Series (BRTES) of phantoms was created to reproduce observed correlations of compressed breast thickness and glandularity Once phantoms representing the attenuation properties and density of 0% and 100% glandularity were obtained, they were combined in linear combinations of fractional weight percentage in order to provide BRTES materials of the desired glandularity.

The density of the completed phantom sections were verified by geometrical and mass measurements and the homogeneity was evaluated by mammography imaging. Mass attenuation and mass absorption coefficients for the final compositions were evaluated across the BRTES series using XCOM, as previously described. The resulting coefficients are compared with glandular and adipose tissue compositions provided by ICRU 44 and those of another widely used phantom material, BR12[4].

The methods that were developed permitted the BRTES phantoms to be fabricated in a straightforward manner using readily available materials and simple laboratory techniques. By modifying some of the constituents originally proposed by White we eliminated the need to mix the constituent materials under vacuum, while still obtaining a series of homogeneous phantoms. The modified recipes also provide improved matching of the mass attenuation coefficients and mass absorption coefficients at typical mammography energies. The predicted mass attenuation coefficients of the glandular and adipose tissue

substitutes developed agree with the ICRU 44 values for 100% adipose and 100% glandular tissues within ± 1.3% across the range of mammography energies, from 15 keV to 40 keV.

The density of each completed phantom was measured and compared to those reported by ICRU 46[5] for average breast data across the full range of compositional mixtures. This comparison is detailed in Table 1.

Phantom Composition % Glandular	*Measured Bulk Density (g/cm3)*	*ICRU 46 Average Adult Density (g/cm3)*	*% Difference*
70.0%	1.029	0.999	3.00
60.0%	1.025	0.992	3.33
50.0%	0.993	0.985	0.81
40.0%	0.986	0.978	0.78
30.0%	0.984	0.971	1.34
20.0%	0.981	0.964	1.76

Table 1. Comparison of densities of ICRU 46 and BRTES phantoms as a function of percent glandular composition.

Following the construction of the first generation phantoms, a second generation of phantoms were constructed to more accurately reflect the lateral shape and extent of the compressed breast anatomy. The first generation phantoms present a 8 cm x 8 cm projection from the x-ray source in order to provide direct comparisons to the ACR phantom geometry. These were constructed based on previously published data that demonstrated correlation of compressed breast thickness and glandularity. This, however, neglects the lateral dimensions of the compressed breast, variations of which can significantly affect the scatter radiation field.

Detailed information regarding the lateral dimensions of compressed breasts could not be found in the literature, so a survey of clinical mammograms was performed in an effort to develop these correlations. The resulting survey developed relationships that permit the characterization of lateral extent of the breast with compressed thickness, but also is permitting us to perform a more detailed delineation of the distribution of glandular tissue in the compressed breast. From these data a second generation of phantoms were constructed. Using the same tissue equivalent materials, a set of homogeneous phantoms were constructed to simulate the mean dimensions extracted from the survey data. These second generation phantoms are being used as the primary tool for clinical dosimetry surveys, and are illustrated in Fig. 1.

Figure 1. The BRTES phantom series of varying glandularity and compressed breast thickness.

The survey data have also demonstrated the importance of accurately determining the glandularity, and the distribution of glandular tissue and the examination view (cranio caudal views vs. medio-lateral oblique views) throughout the breast when trying to determine patient specific doses. These parameters have never been fully characterized for mammography dosimetry, yet significantly affect the dose through the absorption properties, and the tissue attenuation in front of the automatic exposure control phototimer. This has led to the development of a third test phantom that will ultimately be utilized to evaluate the glandular fraction for individual patients with the resultant ability to perform accurate dosimetry calculations. The dosimetry differences between homogeneous and heterogenous phantoms will be evaluated using computational models in the MCNP 5 environment. The Monte Carlo model environment allows a direct comparison of the MGD under these two physical construction methods. The heterogeneous model will be compared against the homogeneous model to determine whether the dose conversion factors being utilized are adequate. A phantom correction factor will be developed for various compressed thicknesses and glandularity based on these calculations if the MGD of the two models exceeds 10%.

Objective 2. Develop a MCNP simulation for the relating exposure measurements to mean glandular dose in the BRTES phantoms

The Monte Carlo Neutral Particle Code version 5 (MCNP 5) developed by the U.S. DOE was utilized as the platform for determining dose conversion factors that permit the conversion of air kerma, or exposure measurements, to MGD for each of the different glandularity phantoms. This is required to model not only the energy absorption effects of the BRTES phantoms, but also the x-ray and filtration effects of the mammography system. Traditionally, one of the weakest links in performing Monte Carlo simulation for mammography applications is obtaining an appropriate mammography x-ray spectrum. For our studies we have employed a sophisticated x-ray spectrum simulation for mammography spectra that has been created at the FDA's Center for Devices and Radiological Health (CDRH). The software simulator permits the inclusion of a variety of filter materials and thicknesses to permit the beam to be closely tailored to the spectra

realistically produced by clinical x-ray systems. Mammography spectra differ significantly from generic x-ray spectra because they utilize target/filter combinations that result in strong contributions from the characteristic x-rays, with the bremstrahlung portions heavily filtered above the K-edges of selected target/filter material (typically Mo or Rh). The software model provides realistic spectra, but these may still vary for individual mammography systems due to differences in generator characteristics, filtration, tube age, collimator assembly, etc. It is therefore necessary to characterize the spectrum of individual x-ray tubes by measuring the half-value layer and matching the filtration to match this half-value layer as verified by MCNP.

The MCNP model was developed to physically represent the clinical environment and the elemental composition of each BRTES phantom in the series. Features include the unique x-ray spectra used in mammography and the physical geometry. The geometry was measured from clinical mammography systems and replicated in the model. The spectra that was utilized has been characterized by the FDA, Center for Devices and Radiological Health. The model was clinically calibrated by taking free-in-air exposure measurements of geometries previously characterized by the ACR, using the ACR phantom. At the low energies used for mammography all of these features become important necessitating the empirical bench marking of the Monte Carlo simulations. MCNP studies in mammography have traditionally utilized only very simple geometries to represent the compressed breast. We have duplicated several of these geometries successfully and are proceeding to develop more anatomically realistic models within MCNP. To provide the ability to account for the scatter contributions that affect dose for various compressed breast thicknesses the lateral extent of the breast must also be accounted for. This feature has not been included in any of the previous Monte Carlo models used for breast dosimetry and permits free-in-air exposure measurements to be related to the Mean Glandular Dose through a series of dose conversion factors.

Objective 3. Design and construct a family of imaging phantoms to evaluate image quality

Image quality comprises an important component of the mammography screening process. Currently mammography image quality is reviewed on a weekly basis by the technologist, at least annually by the physicist and periodically by the ACR and MQSA inspectors for certification and facility accreditation. These evaluations heavily emphasize images of the ACR accreditation phantom. While this permits a consistent evaluation of image quality, it does so only for the particular parameters associated with attenuation and scattering produced by a 4.2 cm thickness of Lucite. We have developed a set of tissue equivalent materials that permits the integration of the test objects from the ACR accreditation phantom to be used in conjunction with the BRTEST family of dosimetry phantoms. The ACR image quality test objects are accurately constructed and incorporated into a thin layer of paraffin that can be removed from the Lucite test phantom. We had initially considered incorporating these standard test object into the first generation of BRTES phantoms that were constructed, but found that inhomogeneities within in tissue equivalent materials made the consistent evaluation of image quality using these test objects difficult. The inhomogeneities occur on a small spatial scale on the order of 100 microns, which does not

affect phototimer response, or the dosimetry results, but makes it difficult to characterize the thin fiber and small speck patterns in the test object. By refining the fabrication process during construction of the second generation of BRTES phantoms an improved homogeneity of the TE materials was achieved that permitted the ready incorporation of the ACR image quality test objects. This permits us to evaluate image quality as a function of tissue glandularity and compressed breast thickness which can subsequently be compared with the daily image quality evaluations performed at each facility using the ACR phantom assembly. A representative image used for image quality evaluations is illustrated in Figure 2.

The need to evaluate image quality as a function of compressed breast glandularity is an important issue, since not only does the mean glandular dose depend strongly on the glandularity and compressed breast thickness, but increasing levels of glandularity have an overall degrading effect on image quality and the radiologist's ability to extract diagnostic information. The competing effects of breast glandularity and dose are evaluated on their impact on the available clinical diagnostic information available to the radiologist. The technique for evaluating image quality as a function of glandularity has been developed and data has been collected from several facilities. Three sets of images representing 67.8%, 42.6% and 16.2% glandularity have been collected from each of these facilities. In order to objectively characterize the image quality a set of independent radiologists have been recruited to evaluate the image quality of randomly assembled image sets. This will provide the basis for a detailed Receiver Observer Characteristic (ROC) test, which is a continuing effort of the project.

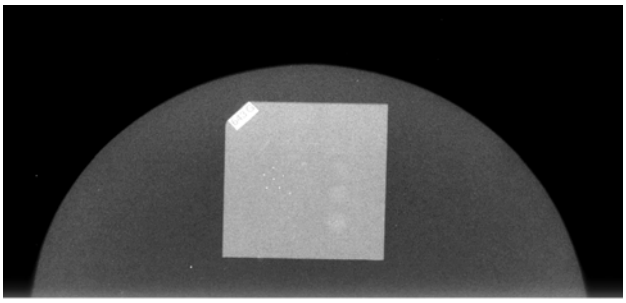

Fig. 2. Radiograhic image of the ACR image quality indicators superimposed on the 2 cm BRTES phantoms. Contrast levels have been modified to better permit the visualization of the test objects in this image presentation format.

Each of the image sets contains five negative films and five positive films. Each positive image within a set contains an image-quality test object. Each negative image within a set will contain no image-quality test object. The radiographs will be provided to ten radiology professionals (radiologists, physicists and technologists) to score the incorporated objects. The subjects will evaluate each radiograph for detectability of each object and their confidence in the detection as delineated in the score sheet. The data provided by the test subjects will be used to develop a receiver-operating characteristic curve (ROC). At the completion of the ROC evaluation, each radiograph will be repeated to maximize visualization of test objects and MGD will be evaluated for the new conditions.

Objective 4. Survey screening mammography facilities and collect an initial series of data for the accurate evaluation of patient doses in screening mammography.

Dosimetry measurements were made for the complete line of BRTES phantoms and compared to a parallel set of measurements performed on commercially available BR12 and ACR accreditation phantoms (available from Nuclear Associates). Measurements were performed on a General Electric Senographe DMR using a Keithley 35050A Dosimeter and 15cc ion chamber to quantify exposure. Mean glandular dose (MGD) for each of the phantoms were evaluated across a range of energies using the standard measurement technique described by the American College of Radiology (ACR). In each case the phantom being evaluated was used in the same physical location occupied by the ACR phantom when performing standard dose measurements.

The MGD was evaluated across the energy range most likely to be encountered for the particular combination of glandularity and compressed thickness being tested. Radiographic techniques were generated by selecting the desired kV and permitting the automatic exposure control system to select the mAs. In order to convert the measured entrance air kerma to MGD for phantoms of varying glandularity it is necessary to develop a more expansive set of dose conversion factors than are provided by the ACR. These factors were developed as a function of glandularity, thickness, kVp, and HVL based on the Monte Carlo calculations of Wu[6]. The dose conversion factors were interpolated using a linearly weighted combinations of the dose conversion factors for 100% glandular, 50% glandular, and 100% adipose tissues. Equation (1) can then be used to convert the air kerma to MGD,

$$Dg = D_{gN} * X \quad (1)$$

where Dg is the average glandular dose, DgN is the average glandular dose per entrance air kerma, and X is the breast entrance air kerma.

The BRTES phantom series that has been constructed permits the measurement of MGD's that can more realistically reflect the patient dose received in mammography. MGD was measured for breast tissue across a full spectrum of glandularity and compressed thickness. Figure 3 illustrates the observed variation in phototimed mAs at 27 kVp for a series of 4.2 cm thick phantoms of differing glandular content. As expected, greater glandularity, representing denser tissue, results in increased phototimed mAs. However, it is clinically observed that increasing compressed breast thickness is correlated with a decrease in glandularity. This decreasing glandularity may be expected to offset the predicted increase in MGD with increasing compressed thickness to some degree.

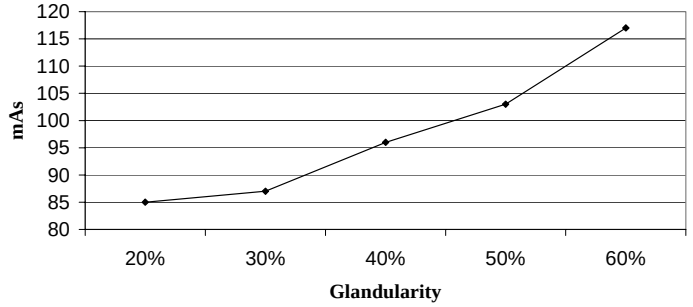

Fig. 3. Phototimed mAs required for the varying glandularity of the BRTES phantoms at a constant thickness of 4.2 cm.

Dosimetry measurements show that MGD decreases for each phantom in the series with increasing kVp . The results are quantitatively very similar to the changes in average dose as a function of kVp reported by Lavoy etal.[7] for the ACR phantom. For this particular phantom, the dose is observed to decrease from 25 kVp to 28 kVp, with the 28 kVp dose being 77% of the 25 kVp dose. While similar reductions are observed for phantoms throughout the BTRES series, the magnitude of the dose changes dramatically with compressed thickness and composition, as illustrated in Figure 4.

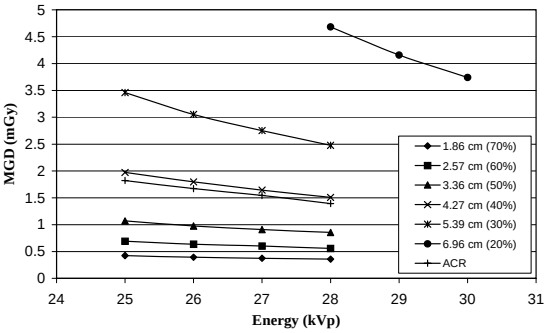

Fig.4 MGD vs kVp for BRTES phantoms representing compressed breast thicknesses of 1.86 cm, 2.57 cm, 3.36 cm, 4.27 cm, 5.39 cm, and 6.96 cm (corresponding to glandularity of 70%, 60%, 50%, 40%, 30%, 20%, respectively) to that predicted by the 4.2 cm thick ACR phantom.

The resultant data may alternately be visualized by graphing the MGD as a function of compressed thickness for each kVp, Figure 5. The specific values of MGD illustrate the performance of this particular system. Other mammography systems would be expected to have similar trends in dose as a function of kVp and compressed breast thickness although the quantitative values of MGD and the magnitude of differences as a function of compressed breast thickness and kVp are likely to differ due to variations in HVL, AEC adjustments, tube performance, etc.

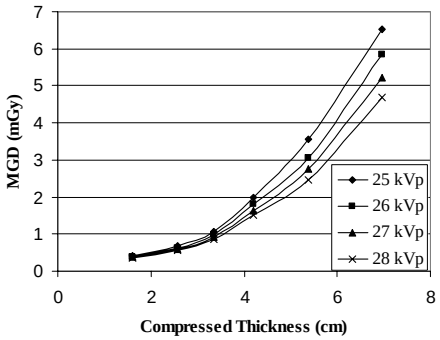

Fig. 5. MGD vs compressed breast thickness for commonly used values of kVp. Note that the mean glandularity is changing with compressed thickness as described above.

The results illustrate the significant differences that may be observed between patient doses and those estimated using the ACR phantom. The survey of Geise and Palchevsky[8] showed the average patient breast in their study population was best simulated by a 34% glandularity, 16% less than the glandular content assumed for the routinely used phantoms. Figure 3 illustrates that the ACR phantom responds similar to an average breast of slightly greater than 40% glandularity. These results have several implications for physicists evaluating the performance of mammography equipment and quantifying patient doses in mammography. It is quite clear that the ACR phantom does not provide a good representation of a breast of 50% glandularity as is commonly assumed, nor does it match the average glandularity observed in demographic studies. Figure 3 shows that the ACR phantom is likely to measure a dose of approximately 60% of the MGD delivered to the average patient.

Physicists frequently utilize BR12 to provide a better tissue substitute for the "average" breast of 50% glandularity. While BR12 does accurately mimic the radiological response of 50% glandular breast tissue, it is not likely to represent the average patient, as previously described. Lucite phantoms are commonly used for evaluating field uniformity but present concerns when used for developing technique charts or dosimetry applications. Lucite has a higher density than the majority of breast tissue and results in more robust radiological techniques for any given compressed thickness. Dosimetry measurements performed using Lucite will consequently produce a greater dose at any given compressed thickness than do the BRTES phantoms. Entrance skin exposures using Lucite phantoms yielded approximately 36% greater exposures than obtained when using a BRTES phantoms.

In order to obtain dosimetry information at higher spatial resolution we will integrate the Monte Carlo models with dosimetry measurements that are made throughout the phantom materials. An important tool in this assessment is a dosimeter that is small in size that can be incorporated throughout the physical phantoms, yet sensitive to the low energy x-rays used in mammography. A good candidate for such a dosimeter is a recently developed MOSFET dosimeter manufactured by Thomson–Nielsen Inc. We have worked with their development staff and obtained several prototype dosimeters that were evaluated for their sensitivity, energy dependence and angular sensitivity across the mammography energy range. Several types of the dosimeter that were evaluated exhibited a significantly greater

angular dependence than is observed at higher energies used in diagnostic radiology. The angular variation can be as great as 50 percent greater

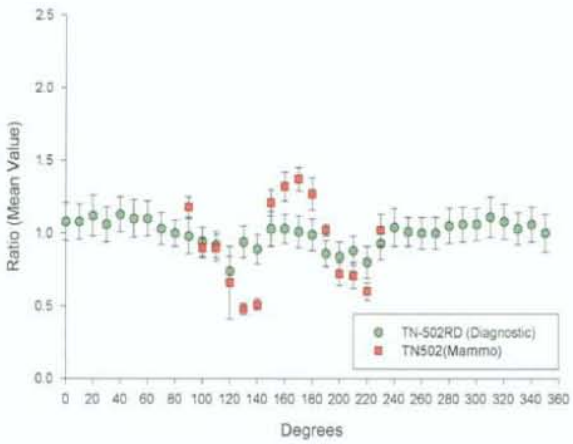

Fig. 6. Angular response of MOSFET dosimeters at 70 kVp (diagnostic) and 26 kVp (Mammo) x-ray energies.

or less than the response observed at higher diagnostic energies (70 kVp) as illustrated in Figure 6. The larger variation in response is primarily when radiation is incident from behind the dosimeter. This would have minimal effect for the proposed use as real-time dosimeter in mammography since all dosimeters can be uniformly exposed in a direction ensuring the most uniform response. Of greater significance is the strong energy dependent response that is observed across the mammography energy range. The MOSFET dosimeters have previously been observed to have a relatively flat energy response across the range of diagnostic x-ray energies. At the low energies used in mammography, however, a more significant energy dependence is observed. The response of the 1002RDI dosimeter is illustrated in Figure 7 as a function of beam energy for several different target/filter combinations. The sensitivity of this particular dosimeter is adequate for mammography, but varies by approximately a factor of two across the energy range where it would likely be used. The current energy dependence would require a careful characterization of x-ray unit kVp to ensure that the output is as indicated, and the use of energy dependent calibration factors. The energy dependence may be minimized through the development of more advanced dosimeters in the future which would make them more feasible for applications in mammography dosimetry. Until better responding MOSFETs are available we will utilize thermoluminescent dosimeters to provide high resolution dose mapping through the anthropomorphic phantoms. We currently have TLD 100 and 700 dosimeters available and can integrate a large number of these sensitive, but labor intensive, dosimeters across the planes of various depths in the physical phantoms.

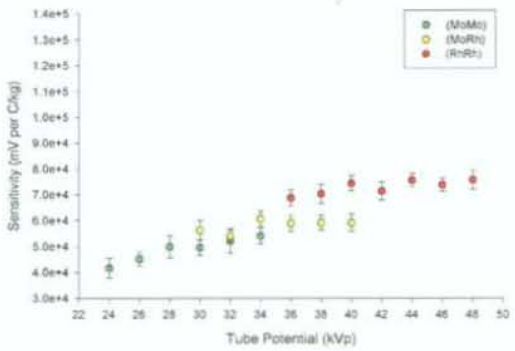

Fig. 7. Sensitivity response of MOSFET dosimeters as a function of kVp for several target/filter combinations.

In the course of evaluating the correlations of compressed breast glandularity and thickness that have previously been presented in the literature, several areas of concern were identified. Several different non-invasive techniques had previously been utilized to evaluate glandurity, but they are based on the area of glandular tissues projected onto the image. A review of mammography films also illustrated that there is a significant variation in the distribution of glandular tissues throughout the compressed breast from patient to patient. In order to better account for the three-dimensional variation of glandular tissue, and it's resulting effect on phototimer operation in mammography equipment we felt that it was important to obtain a more complete characterization of the glandular tissue distribution. This also permits us to construct a third style of phantom, a glandularity step phantom that allows us to unambiguously identify the average glandualarity for individual patients having a variety of compressed breast thicknesses.

In order to obtain the requisite information for this effort a retrospective study of a screening mammography population was initiated to determine the appropriate anatomical geometries of a compressed breast. A study was approved by the Institutional Review Boards of the U.S. Navy and the University of Florida to retrospectively collect mammogram data for three months (January-March 2004) from the United States Naval Hospital Jacksonville, Jacksonville, FL. Currently 253 patient records are considered appropriate to our study out of 415 patient records reviewed (i.e. having a BIRADS diagnosis category 1 (negative) or category 2 (benign). This will provide approximately 500 films for characterization.

The 3-D step phantom was designed and constructed to permit the quantification of glandularity retrospectively and is illustrated in Figure 8. A radiographic image of the phantom imaged on a GE DMR mammography system is illustrated in Figure 9. When imaged at the equivalent radiographic techniques used in mammography screening, the optical density of appropriate thickness steps of the phantom permit

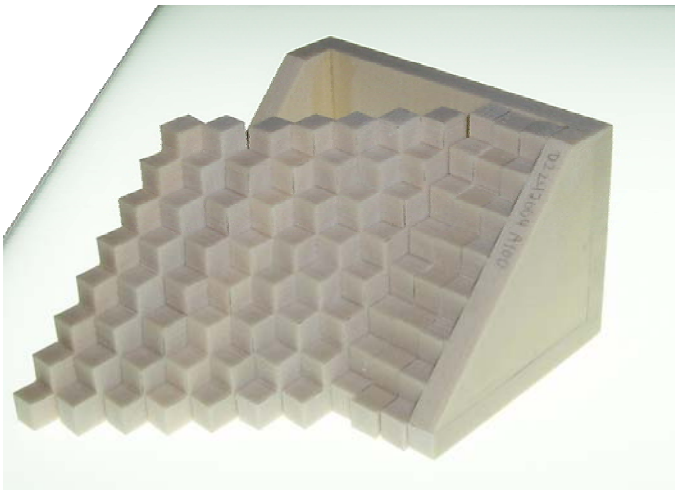

Fig. 8. The 3-D step phantom provides a 2D array of BRTES steps in glandularity and tissue thickness.

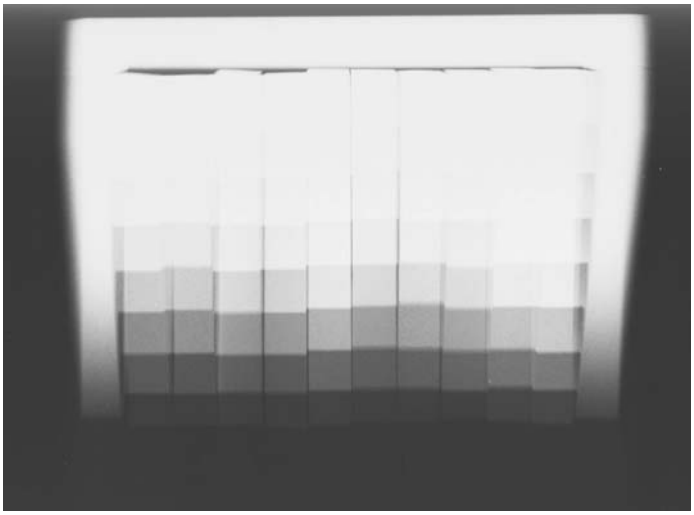

Fig. 9. A radiographic image of the 3-D glandularity step phantom with window and level optimized to best view the mid-range steps in this report image format.

Other Accomplishments & Summary

This project also has a strong educational component through which current engineering and radiological techniques have been presented to assist in the graduate education of students. The project has provided opportunities for several graduate students to apply the fundamental theories of radiological engineering to develop clinically useful tools through the integration of design principles, radiation transport calculations and computer modeling. The project has provided research topics for three graduate students over the past year, two students pursing M.Sc. degrees in Nuclear Engineering Sciences[9,10] and one student pursuing a Ph.D. in Nuclear Engineering Sciences[11].

This work has resulted in publication in the Journal of Clinical Medical Physics (JACMP)[12] and one published abstract and oral presentation at the 2004 meeting the American

Association of Physicists in Medicine (AAPM)[13] and an accepted paper to the Radiological Society of North America (RSNA)[14]. Three additional publications that are in preparation will address 1) the comparisons of the Monte Carlo calculations with empirical measurements, 2) evaluation and characterization of the MOSFET dosimetry system, 3) Results of our screening mammography population survey and 4) the development application of the glandularity step phantom and 5) Facility surveys integration the results of dosimetry and image quality measurements. The work initiated under this grant has also produced proposal submissions to the National Institutes of Health (NIH) and a cooperative project with the U.S. Navy that will continue these initial efforts to a broader set of clinical facilities.

The tools and protocols developed through this project are being used to provide a much needed improvement in the evaluation of clinically meaningful breast dose. As more substantial data is collected from a variety of facilities, the results can be combined with risk models and the recent ICRP recommendations that increase the breast tissue weighting factor by a factor of 4 (from 0.05 to 0.20) to provide quantitative justification for mammography screening program protocols in the U.S.

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