Final Report
NEER Grant DE-FG07-98ID13648
IMAGE AND DOSE SIMULATION IN SUPPORT OF NEW IMAGING
MODALITIES
Department of Energy
05-18-98 to 7-21-2000

PI: Kuruvilla Verghese
Professor
Department of Nuclear Engineering
Box 7909
North Carolina State University
Raleigh, NC 27695-7909

ABSTRACT

This report summarizes the highlights of the research performed under the 2-year NEER grant from the Department of Energy. The primary outcome of the work was a new Monte Carlo code, MCMIS-DS, for Monte Carlo for Mammography Image Simulation including Differential Sampling. The code was written to generate simulated images and dose distributions from two different new digital x-ray imaging modalities, namely, synchrotron imaging (SI) and a slot geometry digital mammography system called Fisher SenoscanTM. A differential sampling scheme was added to the code to generate multiple images that included variations in the parameters of the measurement system and the object in a single execution of the code. The code is to serve multiple purposes: (1) to answer questions regarding the contribution of scattered photons to images, (2) for use in design optimization studies, and (3) to do up to second-order perturbation studies to assess the effects of design parameter variations and/or physical parameters of the object (the breast) without having to re-run the code for each set of varied parameters. The accuracy and fidelity of the code were validated by a large variety of benchmark studies using published data and also using experimental results from mammography phantoms on both imaging modalities.

All of the results have been published in open literature resulting in four referred publications in archival journals, one conference proceedings and two extended summaries in conference transactions. The work resulted in one PhD dissertation, partial work on a Master's thesis and an undergraduate research project. The PhD dissertation resulted in a Mark Mills Award of the American Nuclear Society (ANS) for the student for the best nuclear engineering publication in the year 2000 by a doctoral student. One of the conference presentations received a Best Paper Award from the Reactor Physics Division of the ANS.

The following is a summary of the various sub-projects and the major publications that resulted from them. Copies of reprints of the major papers are attached.

Sub-Project #1: Measurement of Molecular Coherent Scattering Form Factors of Various Types of Tissues:

Monte Carlo simulations of x-ray radiographic images require accurate compilations of x-ray interaction data. For mammography using 15 keV-25 keV x rays, the major scattering interaction is coherent scattering. Atomic coherent scattering form factors for this energy range is widely available but they do not correctly predict the angular distributions of scattered photons in molecular materials such as biological tissues. Therefore, we proceeded to measure the form factors for various types of biological tissues using monoenergetic x-ray beams from the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory.

Photon scattering angular distributions from various animal tissues were measured at two photon energies of a monochromatic x-ray beam at NSLS. Two plastics and a sample of human breast tissue also were used as samples. The breast sample was provided by the Department of Radiology at the University of North Carolina (UNC) Medical School from a mastectomy specimen preserved in formaline. The other tissues were obtained fresh from a local abattoir. The plastics were Lexan and Lucite. From these measurements, the molecular coherent scattering form factors of each material as a function of the momentum transfer parameter, x , was extracted. A new data analysis technique that uses Monte Carlo based corrections for air scattering, incoherent scattering and multiple scattering was used to extract the form factors. The values are published in tabular form, suitable for use as a data library in computer calculations.

Publication: Douglas E. Peplow and Kuruvilla Verghese, "Measured Molecular Coherent Scattering Form Factors of Animal Tissues, Plastics and Human Breast Tissue", *Physics of Medicine and Biology*, **43**, 2431-2452 (1998).

Sub-Project #2: Simulation of Digital Mammography Images and Radiation Dose for Two New Imaging Modalities Using Monte Carlo Methods:

Design optimization of new imaging modalities requires development of accurate mathematical models. Monte Carlo simulation as a modeling tool offers the advantage that one can separate the effects of absorption and scattering interactions of the photons to assess their individual contributions to the outcomes (images and/or dose). Since existing codes such as MCNP or ITS do not have the appropriate molecular coherent scattering data libraries, we decided to write our own specific-purpose code that can accommodate the two imaging modalities of interest to us: the synchrotron-base system at NSLS and the Senoscan which was undergoing clinical testing at UNC, Chapel Hill. Three significant variance reduction methods were used to keep the run times to a few hours (single digit). The code was executed partly on a 2 CPU Ultra 60 computer from Sun Microsystems donated as an educational grant for this project. Also, another similar machine bought using the NEER grant.

The code, MCMIS (Monte Carlo for Mammography Image Simulation), was benchmarked against a very extensive set of results presented in literature for radiography systems. The accuracy and fidelity of the code was found to be remarkably good. Until this time, image simulations in radiography had not been possible. The simulated images were

benchmarked against experimentally measured images of mammography phantoms on both systems and the contrasts of the different objects in the phantoms were quantitatively compared. The agreement between the measured and simulated image contrasts were found to be excellent.

Publication: D.E. Peplow and K. Verghese, "Digital Mammography Image Simulation Using Monte Carlo", *Medical Physics*, **27(3)**, 568-579 (2000).

Sub-Project #3: Differential Sampling for Perturbation Calculations Within Monte Carlo Simulation:

One of the drawbacks of Monte Carlo simulations is the long computing times required. If one has to compute results with the same tallies for a large set of changes in the values of the input parameters, the run times become prohibitive even with the speed up on modern computers. One way to deal with this problem is to use effectively a perturbation technique to compute the tallies for a wide range of parameter variations. One such technique is the method of differential sampling where one essentially replaces the new tally for a variation in the parameter values as a truncated Taylor Series expansion around a reference set of parameter values and tallies the derivatives of the Taylor series terms as the code is run. Any number of terms in the series expansion can be used in principle although beyond the second order terms, the book keeping becomes tedious for the marginal gain that might be obtained. We used up to second order terms in the expansion and incorporated this methodology within MCMIS (now MCMIS-DS with Differential Sampling). Its usefulness was demonstrated by a set of calculations of images for tumor lesions in the breast with varying densities of the tumor and examining the visibility. In MCMIS-DS, the parameters that are varied cannot be the geometric dimensions, so typically they are physical parameters such as the photon cross sections, source energy spectrum, composition and density of the breast or the tumor, etc.

This addition of DS, greatly enhances the utility of the code in helping answer the "what-if" questions for the designer or the medical physicist.

Publications: D.E. Peplow and K. Verghese, "Differential Sampling Applied to Mammography Image Simulation", *Nuclear Science and Engineering*, **135**, 103-122 (2000). **This paper was awarded the Mark Mills Award to the first author (D.E.P.)**

D.E. Peplow and K. Verghese, "Differential Sampling for Monte Carlo Mammographic Image Simulation", *Proc. Society of Photo-Optical Instrumentation Engineers (SPIE)*, **3771**, 98-111 (1999).

Sub-Project #5: A Lucid Explanation of Differential Sampling for the Users of Monte Carlo Simulation:

In applying differential sampling to image simulation, we had encountered a fairly steep learning curve for the implementation of the theory of differential sampling in practice. The fundamental papers on differential sampling are generally written for the mathematician and so we decided to undertake a project to write a paper elucidating how to practice differential sampling. We were invited by a review journal to do this. The resulting paper contained the methodologies for the Monte Carlo practitioner as well as examples to demonstrate the power of DS.

Publication: D.E. Peplow and K. Verghese, “Differential Sampling for the Monte Carlo Practitioner”, *Progress in Nuclear Energy*, **36(1)**, 39-75 (2000).

Other Publications:

D.E. Peplow and K. Verghese, “Monte Carlo Image Simulation in Support of Improvements in Mammography”, *Trans. Amer. Nucl. Soc.*, **77**, 358 (1997). Best Paper Award for the use of reactor physics methods in biology and medicine.

D.E. Peplow and K. Verghese, “Differential Sampling Applied to Mammography Image Simulation”, *Trans. Amer. Nucl. Soc.*, **81**, 145-146 (1999). **Delivered at the Mark Mills Award Presentation.**

Research Students:

Douglas E. Peplow, Ph.D. awarded by NC State University, May, 1999.

Dissertation Title: “Monte Carlo Mammography Image Simulation with Measured Coherent Scattering Form Factors and Differential Sampling”, Under the direction of Kuruvilla Verghese

Gary B. Zeigler, M.S. degree in progress. Expected graduation date: May 2002.

Thesis Title: “An Investigation of the Discernability of Microcalcification Cluster Patterns in Breast Tissue”

Christopher McElroy, Undergraduate research student.

Project: “A Measurement System for the X-ray spectra from Mammography Tube Sources”, and “Simulation of Spiculations in Breast Tumors”. Expected graduation date: December, 2002