Influence of Patient Size on Dose to Female Breast Tissue During Routine Computed Tomography Scans

Peter C. Scully

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Department of Physics and Astronomy
Vanderbilt University
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Research Advisor: Dr. Michael Stabin

I. Introduction

Radiation dose is defined as the quantity of energy deposited by ionizing radiation per unit mass of tissue. The SI unit of absorbed dose is the gray (Gy), which is equal to one joule per kilogram; the sievert (Sv) is the SI unit for equivalent dose, and is the dose in gray multiplied by a dimensionless "radiation weighting factor", defined for different radiation types (alpha particle, photon, etc.). Radiation dose is an important quantity to monitor because of its link with potentially harmful effects of radiation, including carcinogenesis; following epidemiological studies of the atomic bomb survivors in Japan, the World Health Organization [1], the Centers for Disease Control and Prevention [2], and the National Institute of Environmental Health Sciences [3] have all officially classified x-rays as carcinogenic.

Ionizing radiation has been employed in diagnostic medicine for over a century. The doses associated with diagnostic imaging are generally considered to be low, and are almost always justified by the potential benefits of accurate diagnosis of disease conditions. A traditional x-ray radiograph of the chest delivers only 0.02 mSv [4]; by contrast, the average yearly dose to humans worldwide from natural sources such as cosmic radiation and radionuclides in the environment (e.g. potassium-40 (^{40}K) or radon-222 (^{222}Rn)) is approximately 2.4mSv [5].

Computed Tomography (CT) is one of the fastest growing imaging modalities in hospitals worldwide. The past two decades have seen a dramatic increase in the number of CT scans being performed in US hospitals; approximately 60,000,000 studies were performed in 2005, up from just 3,000,000 in 1980 [6]. The benefits of CT are undeniable; by taking multiple x-ray projections of the subject from different angles, it is possible to reconstruct a three-dimensional image of the internal structures of the body, which offers far more detailed information about the patient than that the two-dimensional representation obtained in traditional radiography. However, the large number of projections necessary to generate the third dimension leads to a significant increase in the number of x-rays passing through the patient's body, and thus the dose received. The dose associated with a CT of the chest is estimated to be 8.0 mSv, roughly a 400-fold increase over traditional planar radiography, and approximately three times the average yearly dose from natural sources [4].

Even in this case, however, the dose is relatively small in terms of cancer risk. The most comprehensive epidemiological study of the Japanese atomic bomb survivors found a statistically significant increase in the incidence of cancer at effective doses in excess of 50mSv [7]. There is no evidence for increased cancer risk at lower doses, and the question of extrapolation of risk to these lower doses remains controversial [8]. However, when multiple or repeated studies are performed, potentially harmful dose levels can accumulate, and it is not uncommon for radiologists to report patients undergoing twenty or more CT scans in the space of a few years [9]. Concerns have been raised about the cumulative risk from exposure to repeated CT scans [10]

Whatever the risks involved in CT, they must be weighed against the potential benefits of proper diagnosis. No patient who requires a CT scan should be denied one for fear of ionizing radiation;

at the same time, no patient should be subjected to one or more CT scans if the same diagnostic information could be obtained in other ways, e.g. the use of non-ionizing diagnostic methods, prior CT scans, etc. Minimization of dose is an important concern in maintaining the balance between risks and benefits for patients undergoing diagnostic CT, and as such it is important for physicians and radiologists to realize how dose delivered by CT varies as a function of different patient-specific parameters.

This study focuses specifically on dose to the female breast during CT scans of the upper body. This has been identified as a particularly interesting area of study for two reasons: First, the female breast is well known to be sensitive to ionizing radiation; breast cancer ranks first among cancers affecting women worldwide, and ionizing radiation, particularly during developmental years, has been recognized as a contributing factor in causing the disease [11]. Second, the location of the breasts results in their receiving significant dose during many types of CT scans, even when they are not the organ of interest in the diagnosis. This study seeks to quantify the dose to female breast tissue during such a routine chest CT, and specifically how the dose to breast tissue varies as a function of patient size. Wide variation in breast size and shape is observed among the female population, and these are certainly important variables in determining the dose to breast tissue during a given scan protocol. A characterization of the relationship between breast size and dose would be of use to physicians and radiologists in assessing the risks involved in CT for female patients.

II. Materials and Methods

A quantitative estimate of dose to breast tissue during a chest CT was evaluated through use of Monte Carlo simulations—a computational technique that models the phenomenon being studied (here radiation transport and deposition), using a probabilistic approach (see Appendix A). In order to properly characterize this problem in a Monte Carlo simulation, two separate geometries had to be defined and modeled, one corresponding to the CT scanner and another corresponding to the patient herself.

The model for the scanner was based on the parameters obtained for the 64-slice spiral CT machine currently in use at the Vanderbilt Clinic. In order to obtain a realistic x-ray energy spectrum and fluence, the x-ray tube of the CT machine was modeled. Input parameters included the tube current (mAs), peak voltage (kVp), and the size and angle of the tungsten anode. The filters and collimators associated with the CT machine were also included to model collimation and beam hardening. Figure 1 provides a rendering of the array of filters and collimators, while Figure 2 gives a visualization of the tracking histories for particles generated within the x-ray tube during a test-run of the simulation. The entire scanner array rotates along a helical path during the simulation, modeling the motion of the spiral CT machine, assuming a pitch of 0.9 and a source to isocenter distance of 104cm.
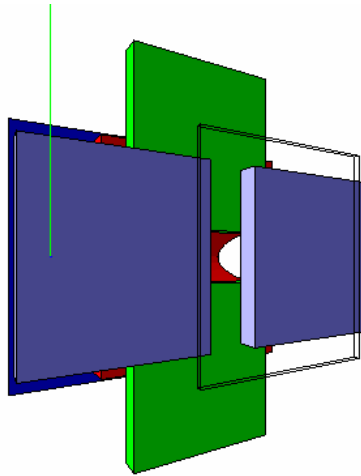
Figure 1: Shows the aluminum filter (in wireframe, black), the first pair of collimators (blue), the second pair of collimators (green), the Teflon bowtie filter (red), and the titanium filter (dk. blue) which comprise the scanner array.
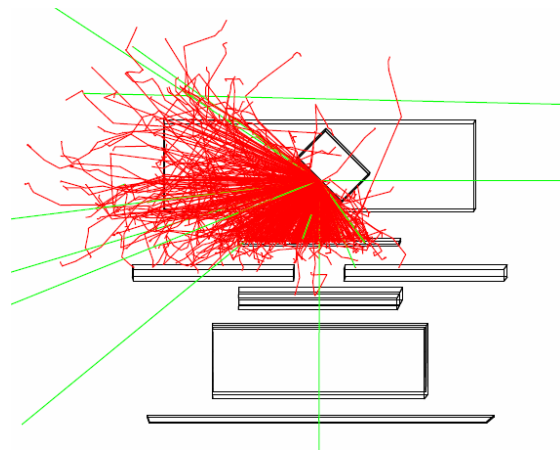

Figure 2: Shows the tracking of 1000 particles generated in the x-ray tube (red). The filters and collimators are also pictured.

The patient geometry was modeled using the non-uniform rational b-spline (NURBS)-based anthropomorphic adult female phantom developed by Dr. Paul Segars of Duke University [12] (Figure 3). Patients of three different sizes were generated by scaling the phantom to 100%, 120%, and 140% of its original size. This was the most reasonable way to systematically model an increase in breast size; while the size increases from one phantom to the next, within each phantom the size of the breasts relative to the other organs remains constant. This allows for direct comparison between the three phantoms. A single layer of tissue-equivalent voxels was added to the phantom to model the attenuation of x-rays by the skin.
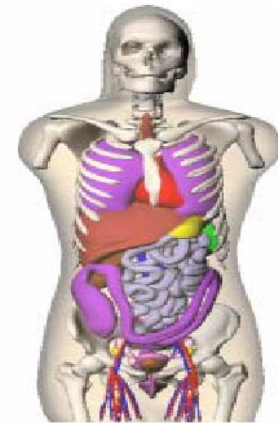

Figure 3: NURBS-based adult female anthropomorphic phantom

The phantom was positioned relative to the CT scanner array such that its central axis (head-toe) coincided with the axis of the helical path taken by the CT scanner. This approximates the standard procedure followed for patients undergoing CT scans in the clinic.

The scanner and patient geometries were simulated using the GEANT4 Monte Carlo tool kit, implemented on the Vanderbilt multi-node computing cluster (Advanced Computing Center for Research and Education (ACCRE)), and simulations were run for each of the three phantoms.

Entrance dose and average glandular dose to the breast were recorded for the three geometries, and the results were directly compared. Comparison was also made between the results of this study and others in the literature.

III. Results

Numerical results are expected within the next few weeks. The modeling phase is nearing completion, and it is just a matter of getting the various files into the correct formats and submitted to the ACCRE computer cluster. My initial estimate is that thirty million particle histories per run will provide good statistics for the study, though this number may have to be modified once the results are generated.

As the study continues, we will present results from our simulations for the three model sizes as a function of subject size, study kVp and mAs, and other variables of the simulations. Direct comparisons of the doses, with trend evaluation, will be shown. Comparisons will also be made to the work of others (e.g. DeMarco et al. [13]).

IV. Discussion

Although we have not yet generated results of our own to report, a few other related studies have been published which give us some indication of what to expect.

Our initial expectation was that an increase in the dose to breast tissue would be observed as a function of patient size. If the three patients are positioned at approximately the same location relative to the CT scanner, then the breasts of the largest woman will be closest to the x-ray tube. This implies that more x-rays will pass through the breasts of the larger woman than of the smaller woman, which reasonably suggests that a higher dose should be observed for the larger woman. However, with a larger patient, x-rays that are generated when the scanner is behind the subject will be attenuated to a greater degree. The net effect that we expect is a higher dose for the breast in larger women, however, a recent study by DeMarco et al. actually shows the opposite trend [13]. Although they used a different series of phantoms, a different scaling technique, and a different Monte Carlo code, the basic principle of using computer simulation to evaluate organ dose from a helical CT scan as a function of patient size was very similar to our own study. Their results showed a definite *decrease* in dose to breast tissue as a function of patient size. It was not clear from their article whether the patients were each positioned in the same location relative to the axis of the CT scanner; it may be the case that the larger phantoms were positioned farther from the x-ray tube, so that the breasts of each phantom would be at the isocenter of the CT machine. This seems unlikely, however, especially given the fact that the doses to organs other than breast were investigated as well; the lack of any comment to the contrary suggests that no change in the geometry was made. We will contact these authors to see if we can clarify the positioning of the various models relative to the x-ray source.

Another study by Boone et al. [14] also showed a decrease in dose with increased breast size. A key difference between this study and our own is that Boone was investigating dose from a pendant-geometry dedicated breast CT, as opposed to the full-body helical scanner characterized in our own study. Despite this difference, Boone's study found that the highest doses were delivered to women with the smallest breast diameter. In this case, it is not additional attenuation that is responsible for the decrease in dose to larger breasts, since the geometry is such that the x-ray beam never enters from the back of the patient. On the other hand, because this is a dedicated breast CT, the breasts of each woman are centered as much as possible in the

same location relative to the x-ray source. Similar fluence should therefore be seen by all breasts regardless of size, which means that the larger breasts, with their larger masses, should receive a smaller radiation dose in this geometry.

The physician and CT technologist have significant control over the study parameters chosen (kVp, mAs, etc.) and thus the radiation dose received by each subject. Ultimately the goal of CT is to provide the physician with the necessary information to diagnose the patient, and it is the operator's responsibility to choose parameters that will yield an image of sufficient quality to do so. A physically larger person will certainly provide more attenuation of the x-ray beam than a smaller person, which will result in a decrease of the signal to noise ratio of the image. To compensate for this loss of image quality, the mAs of the x-ray tube may be increased, sending more photons into the patient. This effect has not been modeled in our study, but it may well be a cause of increased dose to breast tissue for larger patients.

V. Conclusion

Monte Carlo methods are well suited to the evaluation of radiation transport phenomena. The scalable phantoms employed in this project permitted rapid creation of three models of similar geometry, but different body habitus. It is difficult at this point to draw any conclusions about the relationship between patient size and radiation dose to breast tissue during CT scans of the chest. However, the results of DeMarco et al. suggest that we may find a more complicated relationship between breast size and breast dose than we anticipated. Whatever the relationship, it is important that physicians and radiologists realize how dose delivered by CT varies with breast size, so that an effective balance of risks and benefits may be obtained for all patients in diagnostic CT imaging.

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Appendix A

The Basics of Monte Carlo Methods

The town of Monte Carlo is a tourist resort on the French Riviera; it is the largest city in Monaco, and it is also the home of one of the world's most famous casinos. It is in honor of this casino that Enrico Fermi and other physicists working at Los Alamos National Laboratory named any computational method that takes advantage of randomness and probability to determine the behavior of physical phenomena.

As any recreational gambler could easily attest: the secret to success at a casino is to quit while one is ahead; if a person plays the game long enough, the house will always win. It is a simple matter of statistics. Consider the case of a coin toss: For any individual toss of the coin, it is impossible to predict whether it will come up heads or tails. If the same coin is tossed multiple times, however, then the equal probability of each outcome leads one to predict that an equal number of heads and tails will be observed. In practice there is usually some deviation from this expected result: if a coin is tossed one hundred times, it may happen that tails occurs 60 times while heads occurs only 40 times. In this case, the experimental data disagree with the theoretical model by 20%. The significance of these random discrepancies can be reduced by performing a large number of iterations; if the coin is tossed 1,000,000 times, a difference of 20 between the number of heads and tails observed accounts for only a 0.002% disagreement with the theoretical model. After an infinite number of iterations are performed, the experimental data will conform to the theoretical model, determined by the probabilities for each outcome, even if the outcome for any individual trial is impossible to determine.

Casino owners worldwide take advantage of this principle by setting the odds slightly in favor of the house. While it remains impossible to predetermine the outcome of any individual wager, as long as enough independent wagers are made, then over time the house will take in more money than it pays out. In the same way, any patron who continues to place bets indiscriminately is sure to lose money in the long run.

This principle can also be exploited in physics to study phenomena that obey the laws of probability. As a classic example, it is impossible to predict the precise moment at which an unstable nucleus will decay, yet physicists are able to determine the half-lives of radionuclides by observing the behavior of macroscopic quantities. A few grams of sample will contain on the order of 10^{23} atoms, which approximates infinite sampling for all intents and purposes. In this case it is reasonable to conclude that the experimental data match the theoretical probability of nuclear decay.

The experiment that is the subject of this paper follows the same principle, but the case is slightly more complicated. The probability that an x-ray will interact with matter depends both on the energy of the photon and on the atomic number and density of the material with which it interacts. Therefore, the location of the ultimate deposition of the photon's energy in the phantom—that is, the radiation dose delivered to the various organs—is a complicated function of the probabilities of interaction with the various structures that make up both the phantom and

the scanner array. The problem becomes more complicated when one considers that multiply scattered photons may deposit portions of their energy in two or more different regions. The direction of scatter is also a matter of probability. This complexity makes hand calculations of dose to the various organs generally unfeasible. It is also impractical to attempt to measure the dose directly by placing physical radiation detectors within a human subject's various organs. The best way to characterize radiation dose, then, is to employ high-performance computers: Once the probabilities associated with each interaction are known—the energy and direction of the photons, the probabilities for interaction with each of the different materials that make up the simulation, etc.—then it is simply a matter of tracking enough photons that the experimental data begin to approach the actual dose theoretically delivered by the CT machine.