Low Radiological Exposure CT Scanning on a Human Body Phantom in GEANT4

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Introduction

Computerized Tomography (CT) scans utilize X-ray radiation that must be used sparingly. The typical CT scan averages 10mSv in absorbed dose and represents, roughly, a 0.1% increased probability of death per patient, per scan. But what if this percentage could be lower? Our goal is to investigate high-efficiency low-dose CT scanning, to assist in bringing the percentage of additional deaths down from current rates.

CT reconstruction is the process of taking a slice of a specific 3-dimensional system and making a 2-dimensional reconstruction out of the results. CT scans are acquired by taking one-dimensional projections of a specific 3-dimensional system via the detection of x-ray photons . An x-ray image is acquired at differing angles from 0 to 180 degrees. The x-ray images are then manipulated via a computer program and back projected to give a two-dimensional cross section of the original object. But what about dosage?

Through a process of radiation dosimetry, the absorbed dose is calculated from the absorbed energy divided by the exposed mass, measured in units of Gy. When multiplying the Dose by the Relative Biological Effect (RBE) we obtain the dose equivalent, measured in units of Sv.

Bremsstrahlung and Contrast

The photons for the particle gun are generated through a process called bremsstrahlung or "breaking radiation". Accelerated electrons collide with a metal anode and lose kinetic energy. As the accelerated electrons collide with the metal anode at the atomic level, the electron slows as it passes close to the nucleus and release a photon that conserves energy for the process. The photon energy is equal to the difference between the final and initial kinetic energy of the electron. Finally, the photons are emitted from the beam gun, into the human body phantom.

The visual clarity of the image is determined via the differing attenuation coefficients, or the contrast. High contrast imaging is desired. For the imaging of the heart, a contrasting agent of iodine is introduced. Since iodine/blood mixture and general soft tissue have a great difference in attenuation coefficients, the introduction of contrast "lights up" the heart and makes it easily seen on the sonograph and tomograph.

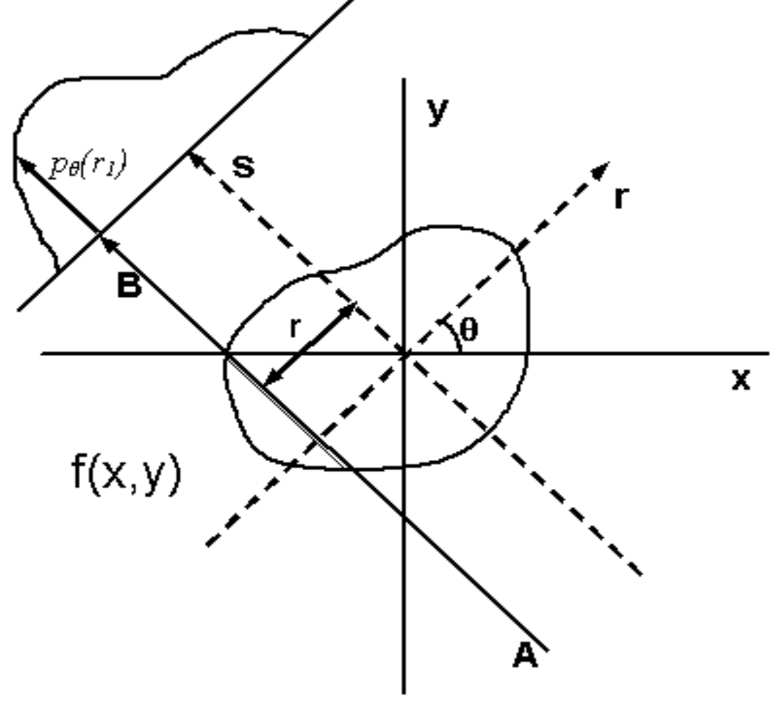

Figure 1: Parallel beam geometry used in tomographic reconstruction [1].

[1] Wikimedia Foundation. (2022, May 2), Parallel beam geometry graphic https://en.wikipedia.org/wiki/Tomographic_reconstruction#/media/File:Tomographic_fig1.png

Methodology

I utilized the following software for our research:

- GEANT4, the simulation of particles through matter.
- ROOT, data analysis assistant for high-energy physics.
- TomoPy, python toolbox used for tomographic reconstruction.

The following methodical process was used:

1. Utilize GEANT4 to create a C++ program that involves the creation of human phantom geometry filled with desired materials, along with an ideal rotatable detector plane for parallel beam geometry with a particle gun for "shooting" photons through the geometry.
2. Organs, bones and other soft tissues, filled with appropriate biological materials. Other materials: heart with iodine/blood contrasting agent, and lungs with air. See figures 2a through 2c for visual representation of the geometries.
3. Program loops, generating 1,000,000 desired events from 0 to 180 degrees at mid chest level into a sinograph that TomoPy uses for reconstruction.
4. ROOT is used for data analysis of histograms, and sinograph visuals of the cross-sectional area generated.
5. Calculate number of photons absorbed by the body, and energy deposition.
6. Calculate mass in kg of absorbed phantom body.
7. Calculate absorbed dose and compare it to average CT scan dose.

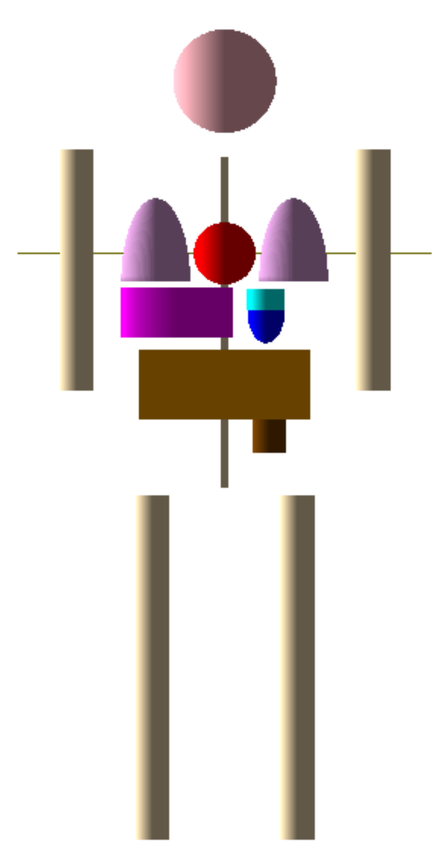

Figure 2a: Front view of human phantom.

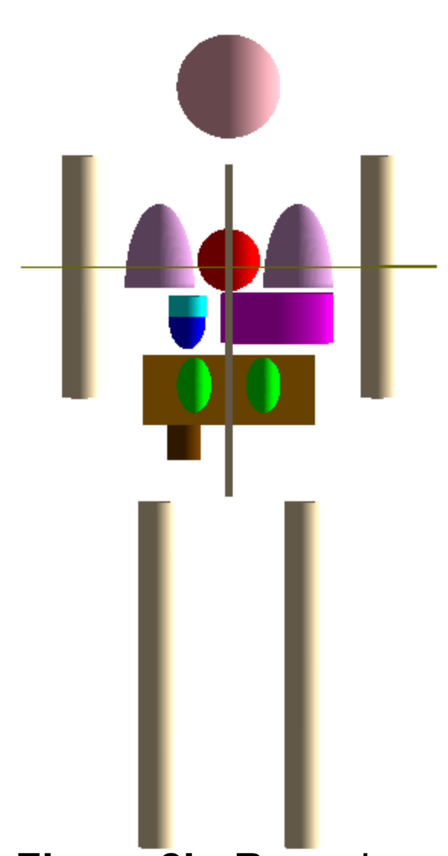

Figure 2b: Rear view of human phantom.

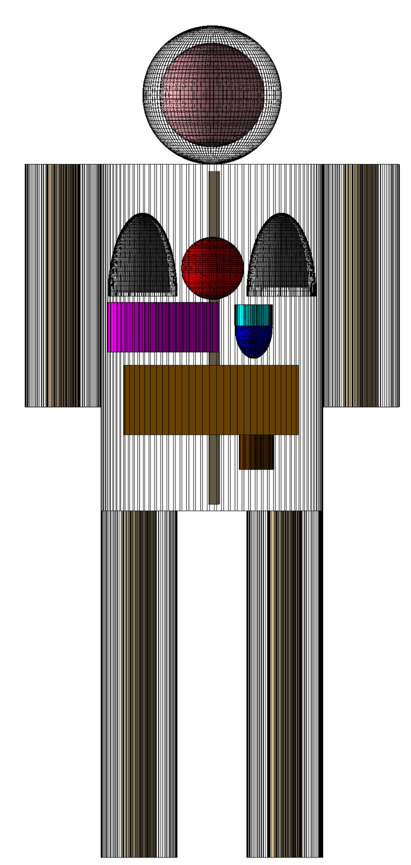

Figure 2c: Front view of full human phantom.

Data

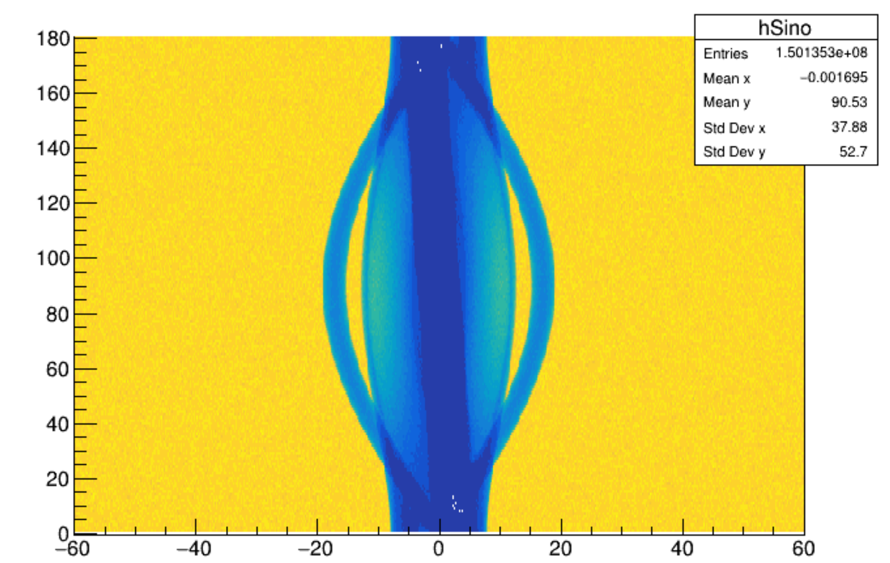

Figure 3: Sinograph: Angle versus detector hit position with color representing number of hits (yellow greater than blue).

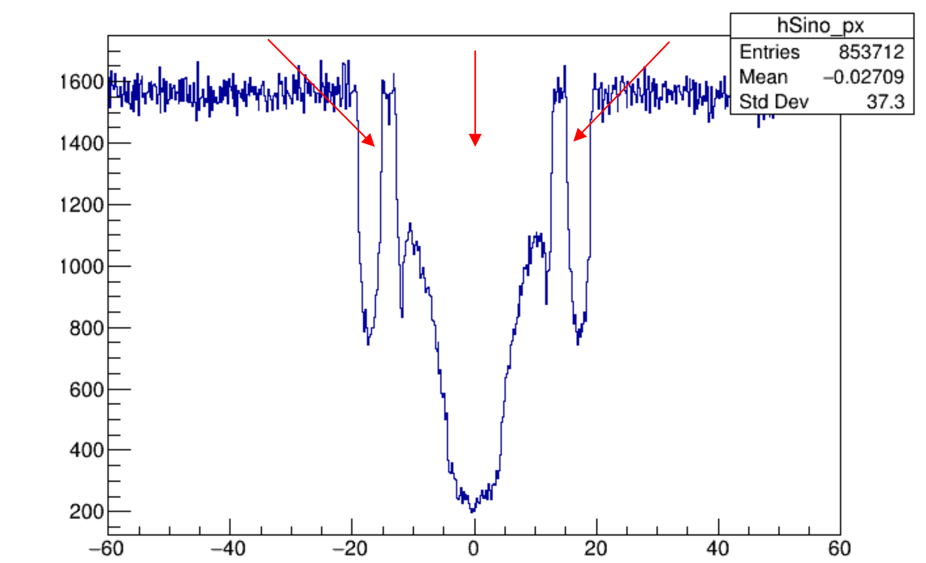

Figure 4: Occupancy of detector hit position for an angle of 90°.

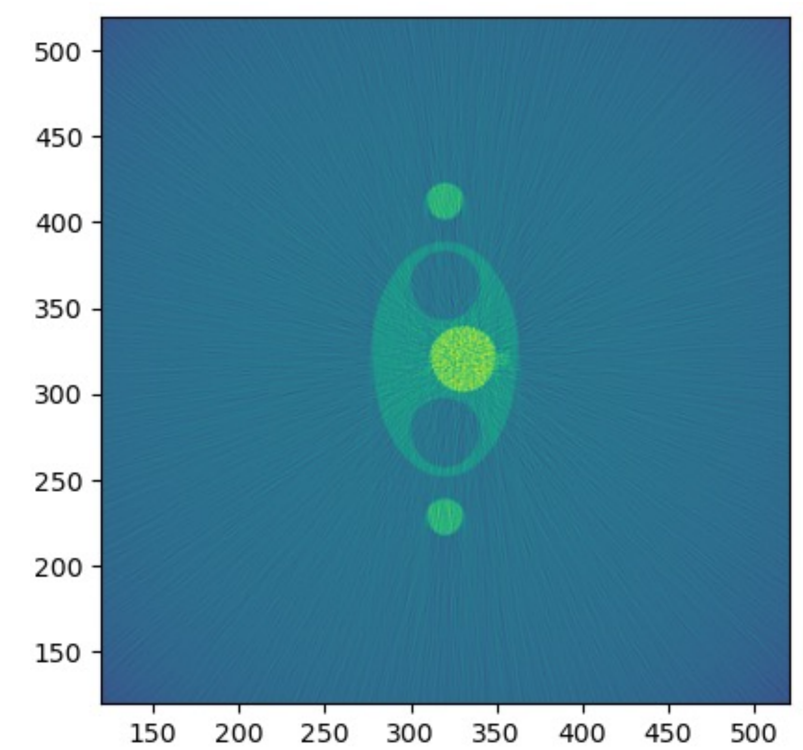

Figure 5: Computerized tomographic reconstruction of cross-sectional chest area in arbitrary units.

Analysis

Figure 3 shows the sinograph for 1,000,000 events, ran from 0 to 180 degrees at beam energy of 0.1MeV, through a cross-sectional chest area, where the heart, lungs, spine, and arm bone can be seen in the tomograph (Fig. 5). The sinograph is a 2D histogram that shows the intensity of the detected photons with dark blue being least absorbed and yellow being most absorbed. The horizonal projection histogram in Fig. 4 shows the intensity measured along the detector plane for a fixed angle of 90°. From left to right in Fig. 4, the red arrows align with the right arm, chest, and left arm, respectively.

The energy deposition was calculated to be 1 μJ for the CT scan. The mass of the exposed portion of the body is 0.32kg. Using the formula for calculating absorbed dose, we find that 1 μJ/0.32 kg = 3 μGy. Multiplying this by the relative biological effect of photons we find that 3 uGy*1 RBE = .003 mSv or 0.03% of the average dose for a CT scan.

Future

This study represents a simplified case where the detector plane is assumed ideal, the human phantom is a basic resemblance of a human body and the photon beam was monoenergetic. Therefore, one could hypothesis that lowering the radiological exposure is *possible*. However, the detector plane must be constructed for realistic standards along with the energy profile of the X-ray beam. For the future, we plan to make the beam profile more realistic and to instrument our detector plane with realistic detector elements (e.g. cesium iodide crystals) to create a more realistic simulation.