Medical Physics Coursework

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Medical Physics PHC801

Contents

1 Plain-language summary on the potential dangers of ionizing radiation in fluoroscopy surgery and the role of a medical physicist in ensuring safe working practices

Fluoroscopy is an imaging procedure that uses several pulses of an X-ray beam to take real-time footage of tissues inside your body. Healthcare providers use fluoroscopy to help monitor and diagnose certain conditions and as imaging guidance

for specific procedures[1]. However, with such use comes the hazardous risk of exposure to radiation and its subsequent potentially detrimental biologic effects towards patients and caregivers alike, most significantly carcinogenesis. Hence, the need for radiation safety awareness and implementation among caregivers is paramount to decrease the risk of radiation exposure and the potential adverse biologic effects[2].

Ionizing radiation is a form of electromagnetic radiation that has enough energy to remove tightly bound electrons from atoms, producing charged particles known as ions. Examples of ionizing radiation include X-rays and gamma rays, commonly used in medical imaging procedures such as fluoroscopy. When ionizing radiation interacts with living tissues, it can cause the ionization of atoms and molecules within the cells, potentially damaging cellular structures and DNA. This damage can lead to adverse biological effects, such as increased cancer risk and other potential long-term health risks. Radiation effects are both deterministic as well as stochastic in nature. Stochastic effects of exposure include carcinogenesis, cataractogenesis, and hereditary impact, which are dose-independent and typically have a more extended latency period than deterministic effects. These effects are secondary to free radical DNA damage. Deterministic effects, also known as tissue effects, are dose-dependent and occur after a specific threshold of radiation exposure, including radiation dermatitis, skin necrosis, and hair loss[3]. Radiation exposure comes from 3 major sources in the fluoroscopic suite, including the primary X-ray beam and leakage and scattered X-ray beams[4]. X-ray particles that traverse through the patient unaffected reach the image intensifier and are utilized directly in image acquisition. Those that lead to incoherent scattering are most concerning healthcare providers as they contribute most to occupational radiation exposure[5].

Regarding decreasing radiation exposure, three guiding principles are time, distance, and shielding[6].

Radiation exposure is cumulative in nature. The exposure time must be limited and monitored to track progression over time. Several tactics to decrease time exposure include utilizing pulsed and low dose image generating modes over continuous or cine modes, using ultrasound over fluoroscopy whenever appropriate, and monitoring annual maximum permissible radiation dose usually via dosimetry[6].

Distance is also an important variable to control as it may be the most effective means to decrease exposure since radiation intensity rapidly falls with increasing distance[6]. According to the inverse square law, as the distance from the radiation source is doubled, radiation exposure is inherently decreased by a factor of $1/4$. This principle also helps guide personnel positioning within the radiology suite alongside appropriate planning, communication, and team dynamics. Patient positioning is also optimized to minimize radiation exposure to the patient, which also decreases the amount of scattering to healthcare workers by maximizing the distance between the table and the radiation source and placing the patient as close to the detector

as possible[7].

Protective lead shielding is an effective means of protection against radiation exposure, especially to sensitive tissues such as the thyroid gland, gonads, bone marrow, and lens of the eye. Hence, protective garments such as lead aprons, thyroid shields, caps, and lead glasses are needed during fluoroscopic procedures. Furthermore, mounted or mobile lead shielding devices can be utilized to decrease further radiation exposure in addition to wearable lead protective devices like table-side drapes, ceiling-mounted shields, and mobile barriers made of lead oxide. As the lens of the eye is one of the most sensitive tissues to radiation damage, protective eyewear is of the utmost importance.

In addition, routine quality control and maintenance of fluoroscopy apparatus are required to ensure accurate dose delivery and reduce potential sources of radiation dose variation. This includes regular performance tests, calibration, and equipment monitoring to ensure compliance with regulatory standards and optimal operation. To further optimize radiation dose management in fluoroscopy, international organizations such as the International Atomic Energy Agency (IAEA) and the International Commission on Radiological Protection (ICRP) have developed guidelines and recommendations for establishing diagnostic reference levels and radiation protection programmes. The Sievert (Sv) serves as the SI unit of measurement for radiation exposure. As recommended by the ICRP, total body dose should not exceed 20 mSv annually; extremities are limited to 500 mSv per year and the lens of the eye to 150 mSv per year, while the European Atomic Energy Community limits exposure to the lens to 20 mSv annually[8].
A Medical Physicist can contribute to safe working practices in several ways. These include-

1. Radiation Safety Training: Medical physicists educate the surgical team, including surgeons, nurses, and technicians, about radiation safety. They educate the team on the dangers of ionizing radiation, the safe management of fluoroscopy equipment, the proper positioning of the patient, and the use of shielding devices to reduce radiation exposure (AAPM, 2019)[9]. This training ensures that the surgical team is well-versed in radiation safety principles and practises, thereby reducing the risk of unnecessary radiation exposure to patients and healthcare personnel.

2. Dose Monitoring and Optimization: Medical physicists monitor and optimize radiation doses during fluoroscopy procedures. They use specialized tools and techniques to measure and analyze radiation doses delivered to patients and provide feedback to the surgical team on keeping doses as low as reasonably achievable (ALARA) while maintaining image quality (IAEA, 2018)[10]. This helps minimize radiation risks to patients and healthcare personnel, as excessive radiation doses can increase the likelihood of radiation-induced injuries.

3. Equipment Quality Assurance: Medical physicists conduct routine quality assurance tests on fluoroscopy equipment to ensure that it delivers accurate and safe radiation doses and functions correctly. They utilize established protocols and guidelines to evaluate the performance of the apparatus, including image quality, radiation output, and safety features (AAPM, 2021)[11]. This ensures that the apparatus is safe for fluoroscopy surgeries and reduces the likelihood of radiation-related incidents by identifying and resolving potential problems.

4. Protocol Development and Implementation: Medical physicists are involved in developing and implementing standardized protocols for fluoroscopy procedures. Based on best practices and radiation safety principles, they work closely with the surgical team to establish guidelines for equipment settings, imaging techniques, and patient positioning (AAPM, 2019)[9]. These protocols help ensure consistent and safe practices across the surgical team, reducing the risk of errors or variations that could result in increased radiation exposure.

Word count: 1081

2 Comparative analysis of different dosimetry studies

Determining which dosimetry study works better for a particular dosimetry problem depends on various factors. This includes the level of accuracy required, the availability of data and resources, and the characteristics of the radiation field and the system being studied. It also highly depends on the specific research question in mind.

Observational field studies allow researchers to study dosimetry in real-world clinical settings. This can in turn, provide valuable insights into how radiation is used and administered in clinical practice. These can be conducted without exposing participants to additional radiation, making them ethically favourable in certain situations. They can leverage existing clinical practice or population-based data and provide valuable information on dose accumulations, dose-response relationships, and long-term outcomes. There are well-established standardised methods for quantifying animal or human image data to provide numeric radiation dose estimates, for instance, from radiopharmaceuticals [12]. One can get sufficiently stable and reproducible results by strategically placing calibrated dosimeters.

Experimental measurements can also provide direct quantitative data on the radiation doses received by individuals or objects, which is vital in radiation protection and safety applications.

However, there are several shortcomings to the use of dosemeters in practice. Physical dosemeters exhibit significant uncertainties in the radiation energy and

radiation dose rate ranges relevant in IR [13]. Other dosemeter properties, e.g. angular dependence, also further influence the uncertainties and can be a challenge for making accurate assessments of whole-body dose, equivalent dose to the skin and equivalent dose to the lens of the eye. Background fluctuations can profoundly impact the measurements, especially when doses are close to the detection limit[14].

They vary in their ability to detect differing radiation types (photon, beta, electron or neutron). Their signal can fade over time, affected by environmental factors such as temperature, light and humidity[15].

Furthermore, due to the inhomogeneous radiation field, proper placement of the dosemeter on the body is crucial, and several dosemeters may be required. There is even a possibility of shielding the dosemeter placed on the body during a treatment. The staff must often fully comply with rather complicated procedures for wearing dosemeters. Additionally, optimising radiological protection requires radiation doses to be evaluated in detail after a limited number of procedures have been performed. The relatively low radiation doses from the procedures may challenge such measurements even more[16].

Even in the paper presented [14], we see that the Mean Hp(3)/KAP for the eye lens depended on the surgeon's height. Hp(3) measured close to the eye lens presented in this study did not give an overall picture of the dose normalised to single procedure variability on a large scale. These limitations were associated with the small number of procedures enrolled in the study, so more measurement runs would have helped assess Intra centre variability.

In the case of patient-individualised dosimetry, particularly in the case of radiopharmaceutical therapy administration, performing calculations is difficult and expensive, requiring too much effort. There are no standardised methods for performing individualised dose calculations, and the methods vary significantly among institutions; dose calculations performed to date have had poor success in predicting tissue response. There needs to be some objective evidence that using radiation dose calculations provides a positive benefit that justifies extra effort and cost[12].

On the other hand, the computational approach is instrumental, particularly in dose reconstruction for large-scale epidemiological studies, where dose measurements are not feasible. One can incorporate dosimetric uncertainties into radiation dose estimates using Monte Carlo simulation methods. Monte Carlo simulations are highly accurate and precise probabilistic methods for providing dose estimates. They can improve the accuracy of dose calculations - especially under complex circumstances such as inhomogeneity, complex radiation fields acting, irregular system geometry, and the radiation interacting with multiple materials or tissues. They can provide highly detailed information on the dose distribution within a system and can be used to optimise radiation therapy plans or assess radiation protection measures. They can even provide insights into the spatial and temporal distribution of radiation exposures, allowing for detailed dose mapping and visualisation.

For instance, in IR, image acquisitions and fluoroscopy are used extensively throughout a procedure. X-ray machine protocols and irradiation geometries vary significantly, resulting in a complex radiation exposure situation. The radiation exposure situation changes between different treatments and during treatment[17]. This requires a model of the irradiation situation that includes detailed information about the irradiation events coupled with the movement and body postures of the person of interest in a proper geometrical model. Monte Carlo simulations are thus extensively used and can facilitate the same[16].

Although it is possible to estimate organ-absorbed doses, e.g. equivalent dose using computational methods, which can prove to be an excellent alternative to physical dosemeters, However, to perform such simulations, data about the radiation source, the position of the c-arm, the use and position of radiation shielding and the position of the staff is required. Keeping track of staff to determine positions and postures is understudied. Moreover, the complexity of the clinical exposure situation and its impact on prerequisites for the computational methods needs to be investigated.

Computational simulations, obviously, require significant computational resources and, thus, can be time-consuming to set up and run. The simulations' accuracy depends on the input data's accuracy. The computational complexity and the accuracy also depend on the assumptions made in the model, the complexity of the simulated problem, and the simplifications implemented. Thus, uncertainties in the physical input parameters and deviations in the particle simulation from the actual exposure also limit the accuracy of the dose conversion coefficients[18].

Analytical calculations can also provide quick and relatively accurate estimates of radiation doses. They are particularly useful for simple radiation fields with well-defined geometries and are helpful for initial assessments or screening studies. Analytical calculations can be performed without sophisticated equipment or extensive computational resources, making them cost-effective.

However, they may not be suitable for complex radiation fields with irregular geometries or multiple scattering media or in research questions that involve intricate or dynamic radiation interactions, where the accuracy of the calculations may be compromised. Moreover, assume certain simplifications and may not account for all factors that affect radiation dose, leading to potential inaccuracies.

Furthermore, these methods are often used in conjunction with each other. Combining multiple methods or using a multi-disciplinary approach can help overcome limitations and provide more robust findings in dosimetry research. For instance, Analytic approaches can be used to simplify the calculations and aid computational models, which can reduce computational complexity, thus, increasing efficiency and boosting dose calculation accuracy. In [18], they proposed an analytic method to improvise existing computational methods further and accurately calculate organ

equivalent dose from external photon irradiation without considering numerous and complex photon transport computations used in existing photon transport computer codes.

Similarly, experimental measurements can be benchmarks for verifying and validating dose calculations through computational and analytical methods. Controlled experiments can also be designed to meet specific research objectives and allow for replication and even establish cause-and-effect relationships between radiation exposures and outcomes. Thus, these experimental measurements are essential for a proof-of-concept as well. The interplay of different dosimetry evaluation techniques can thus, benefit by providing complementary information and improving the accuracy and reliability of the overall dosimetry evaluation. By carefully selecting and combining different dosimetry techniques, one can overcome the limitations of each technique and obtain a more complete picture of the radiation exposure.

Evaluating the accuracy and precision of the various approaches to predicting radiation doses is one of the criteria that can be used to determine which dosimetry research performs better for a particular dosimetry situation. This can be done by comparing the various approaches. This can be accomplished by comparing the results acquired from analytical calculations, computational simulations, and experimental observations with one another and with reference data or standards that have already been established. One also needs to consider the research problem's complexity, the simplifications and the assumptions required. When deciding which dosimetry research to use, it is important to take into account the difficulty of the issue at hand along with the degree of uncertainty already present. The required degree of accuracy and precision is what essentially governs what method to use at the end. Available time and resources and other physical constraints are also important factors to keep in mind.

Word count: 1368

3 Monte Carlo simulation to analyse the dose received by a surgeon performing a fluoroscopy procedure using GATE

3.A Aim

To Conduct a Monte Carlo experiment investigating the dose that might be received by a surgeon in a typical fluoroscopy procedure.

3.B Background and Context

Fluoroscopy examinations have become more common in diagnostic radiology since the 20th century due to the wide application of interventional and contrast studies to functionally study the human anatomy and assist the treatment of pathologies.

In fluoroscopy and interventional radiology examinations, relatively high level of occupational dose is delivered to healthcare workers due to prolonged radiation exposure in imaging procedures. The radiation dose delivered to the staff mainly originates from the scatter radiation. The knowledge on the nature and geometric patterns of scattered radiation has long been inadequate and researchers have proposed different methods to identify the scattering properties based on different radiation sources. As the spatial difference in dose is never negligible, the scatter radiation distribution under fluoroscopic exposures is thus worth investigating.

Monte Carlo simulation is a sophisticated statistical method, which is widely applied for modeling scatter radiation in general X-ray examination room.

For our study we'll be using GATE which is a simulation toolkit developed by the CERN (European Organization for Nuclear Research) for modeling the interaction of particles with matter in the context of medical imaging and radiotherapy.

3.C Method

3.C.1 Geometry and Materials Used

Looking at the literature, the figure 1 and is representative of the positioning of the personnel in the operating theatre of a fluoroscopy procedure. Figure 2 shows the side view of the experimental setup. Figure 3 shows a schematic diagram of C-arm, patient and radiation scattering effect.

These give us a rough idea of the relative positioning of the equipment and the staff. We however, simplify the operating theatre even further by only putting the patient, the surgeon and the operating table into the scene. We note that the table is to be kept at a distance of 100cm as per the recommendations for the source to table distance given by AAPM. Also, the surgeon phantom is kept at a distance of 50 cm to ensure that the surgeon safety standards are imposed[21].

As for the materials used, we employ water phantom boxes to represent the patient and the surgeon, since the human body is almost 65-70% water. The boxes have dimensions of an average human body (170 cm height, 50 cm broad and 30 cm thick). The operating table is made up of aluminum frame which is a material generally used in an actual table to keep things as realistic and accurate as possible. The table is 200 cm long, 50 cm broad and 5 cm thick[22].

Figure 4 shows the diagrammatic representation of our simplified operating theatre. The dimensions of the world are set to 5m in each of X,Y and Z directions, so that they can easily incorporate these dimensions without any bounding errors.

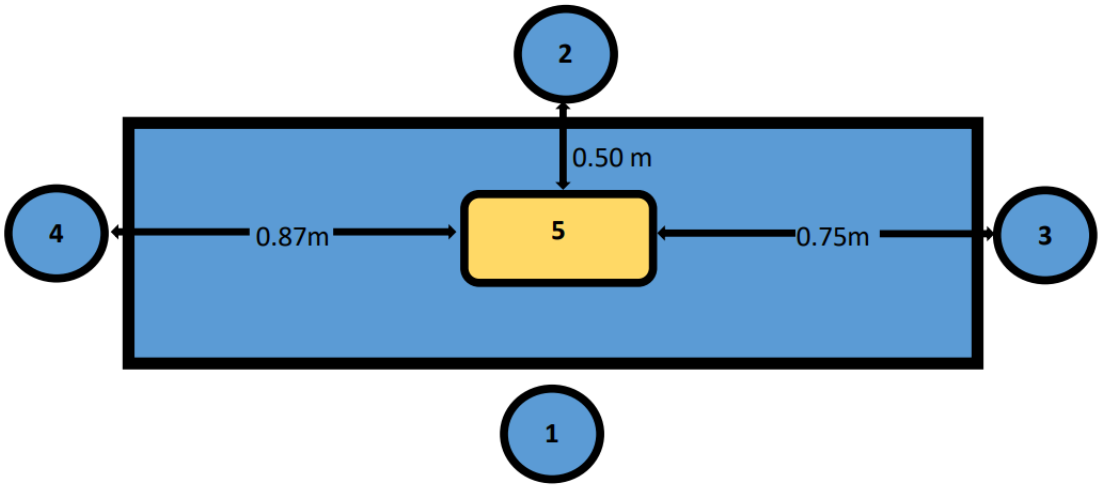

Figure 1: Top view showing positions of personnel in the orthopedic suit[19]

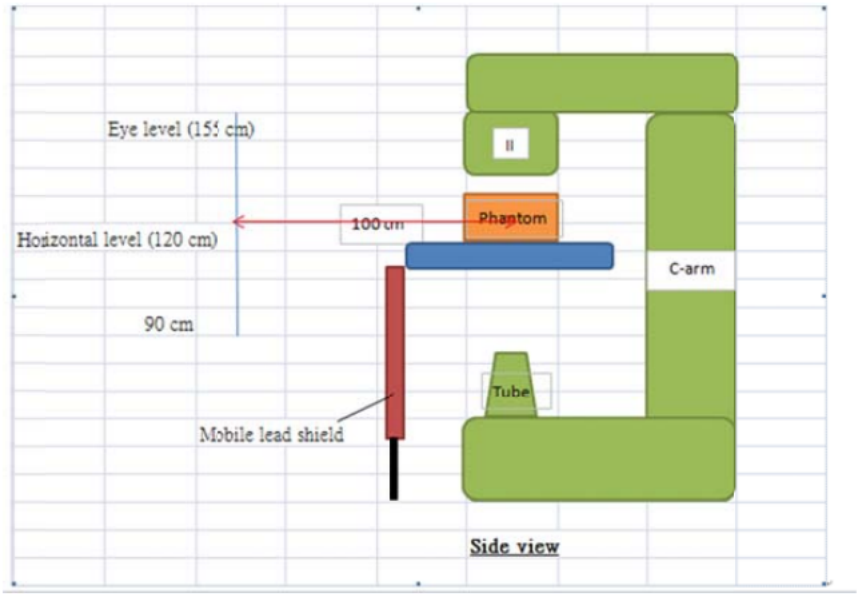

Figure 2: Side view of the setup[20]

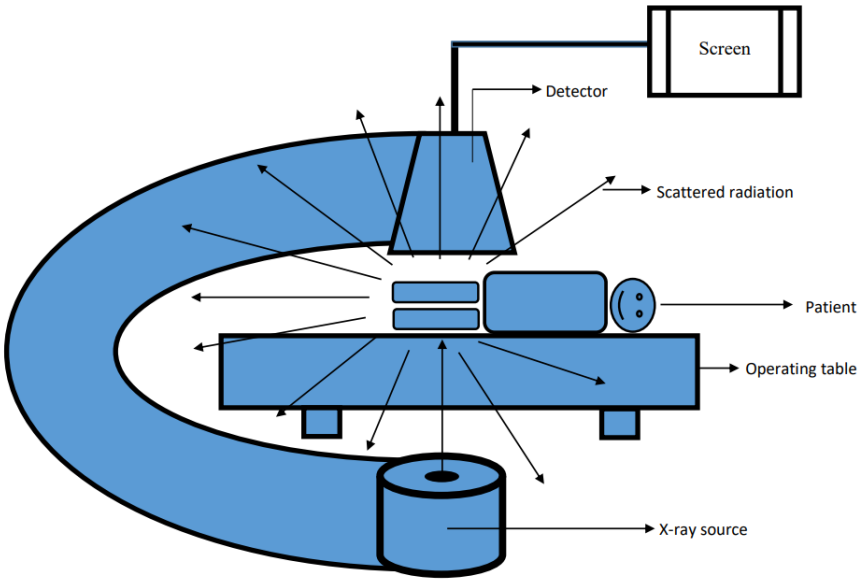

Figure 3: Schematic diagram of C-arm, patient and radiation scattering effect[19]

3.C.2 Physics

We use the standard physics list emstandard_opt3 as it works well for our simulation needs. We set the gamma cut in regions for the world at 10mm while we use 0.01mm for the table, surgeon and the patient.

3.C.3 Detectors

We use multiple DoseActors to analyse the dose profile of the surgeon in different ways. All the DoseActors used are essentially placed at the center of the body to get an indicative of the dose recieved by the entire body.

Namely dose3d to analyse and plot the dose maps in all the three dimensions and to analyse is graphically as well. We use the data from this for a comparative analysis of the energy deposited and the dose recieved in X,Y and Z as well.

We then use the data from the depthdose DoseActor to store and analyse the trend of the dose received by the surgeon as a function of the penetration depth, along with associated uncertainty.

We use the data from the doseprofile DoseActor to study the side profiles of the received dose in Y and Z direction. For this purpose, we plot the values averaged along the other axis as a representative. We however, also plot an interactive plot to get a better feel of the data, along with the uncertainties.

It is important to note that the uncertainties measured depend on the number of primaries used in the simulation, and that the dose values obtained in the graph

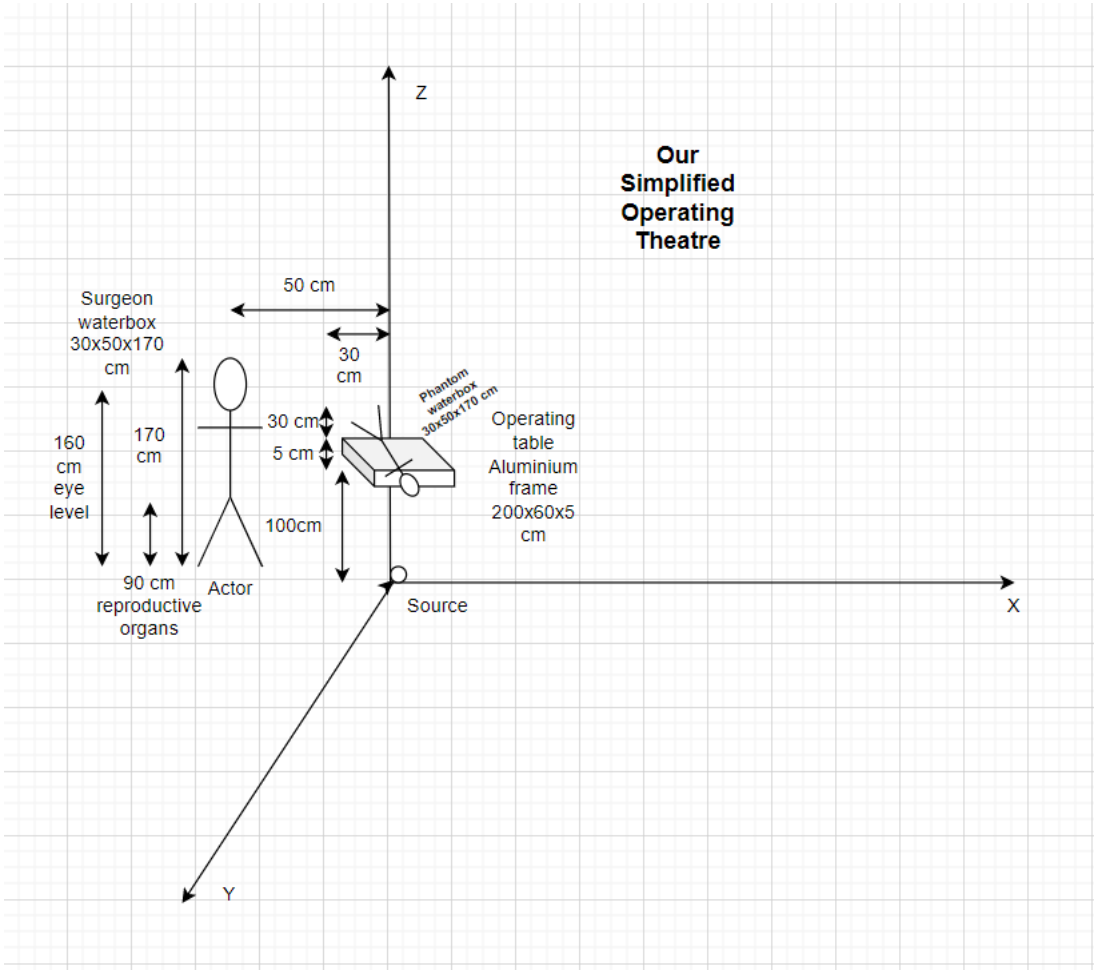

Figure 4: Our simplified operating theatre

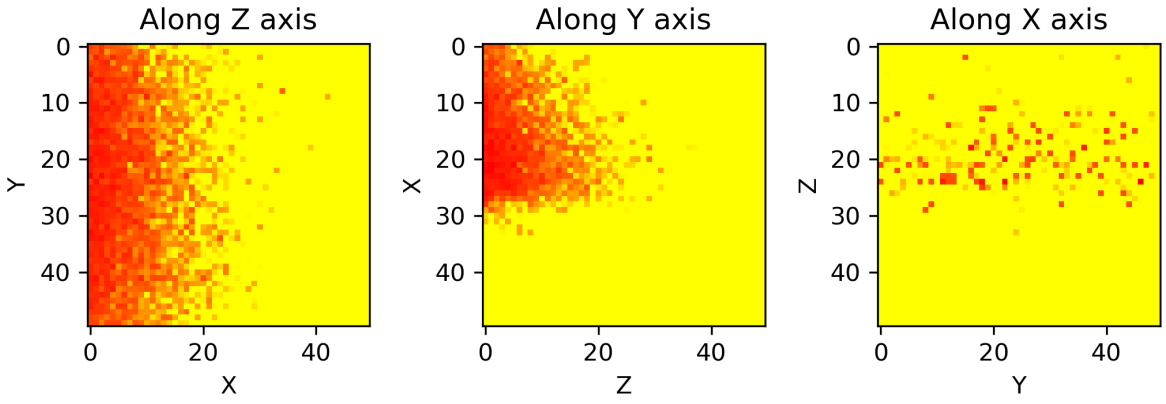

Figure 5: Dose Maps of the surgeon

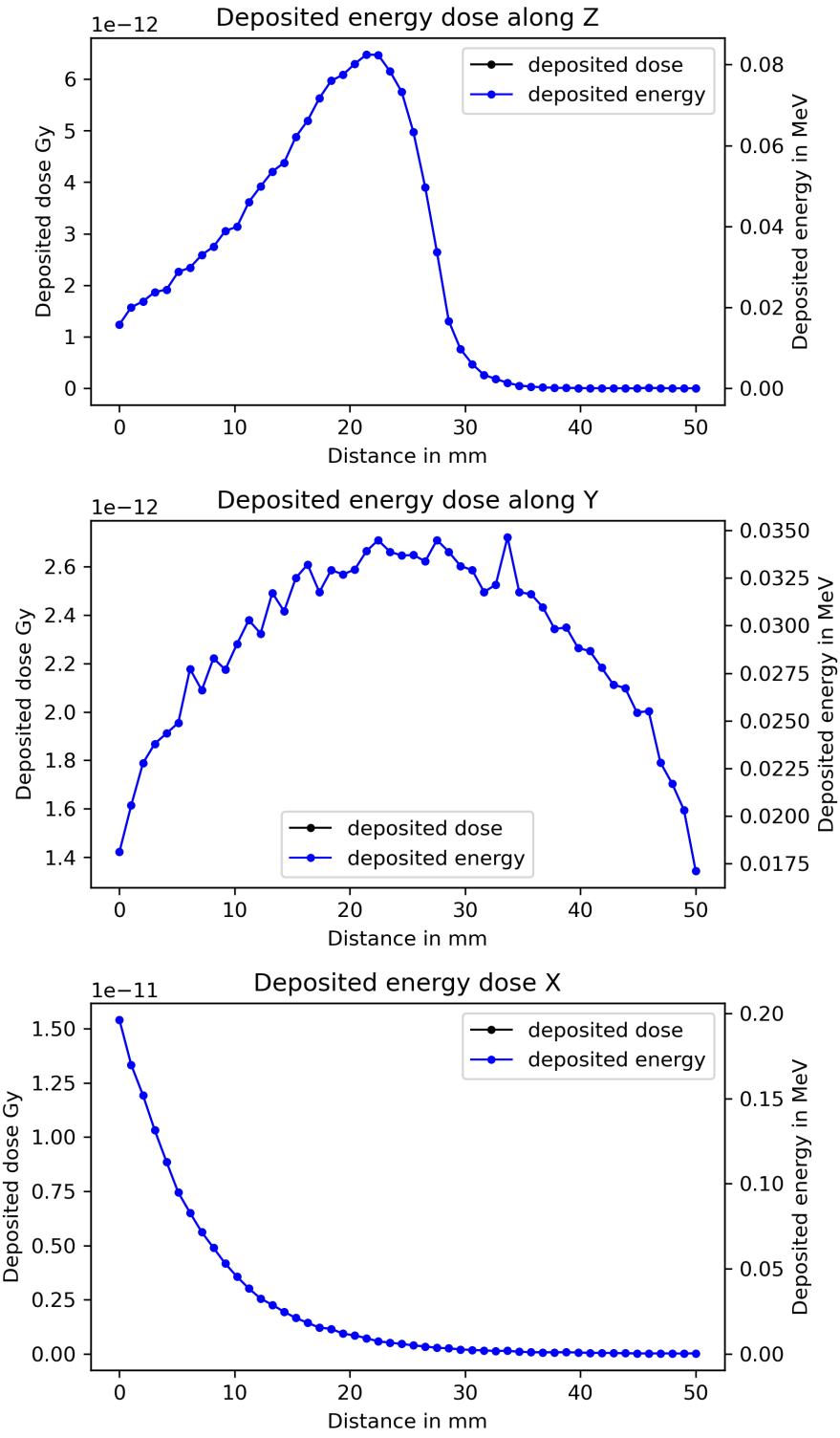

Figure 6: Deposited dose and energy

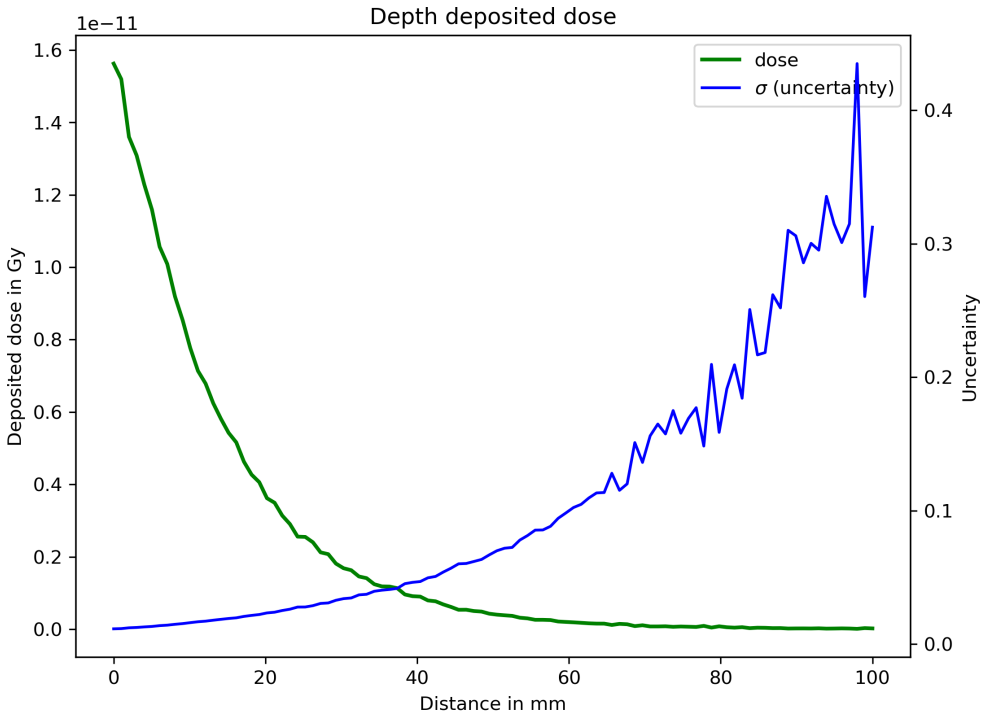

Figure 7: depth vs dose

are only indicative, hence we use the plots only for a qualitative analysis. We choose the resolution to be equal to 100 for the depthdose and doseprofile DoseActors and 50 for dose3d DoseActor. The resolution only tells us about how frequently the data points are sampled.

3.C.4 Beams

We use a gamma circular particle beam source with a gaussian particle distribution and no angular distribution (to keep things simple) to simulate the X-ray source[23].

We keep the standard deviation of the beam profile in both the X and Y directions to be 3mm. The mono-particle energy of the X-rays are set to 43 kV as per a rough estimate of the standard technical factor of the X-ray sources used in a typical fluoroscopy setup (43kV, 4mAs)[19][24], with a spread of 2kV.

3.D Results and Analysis

Figure 5 shows the dose map plots of the surgeon. These are interactive plots so you might want to play around a bit in the .ipynb file. Looking at Figure 6 we plot the deposited dose and energy and do a comparative analysis. We see that both the

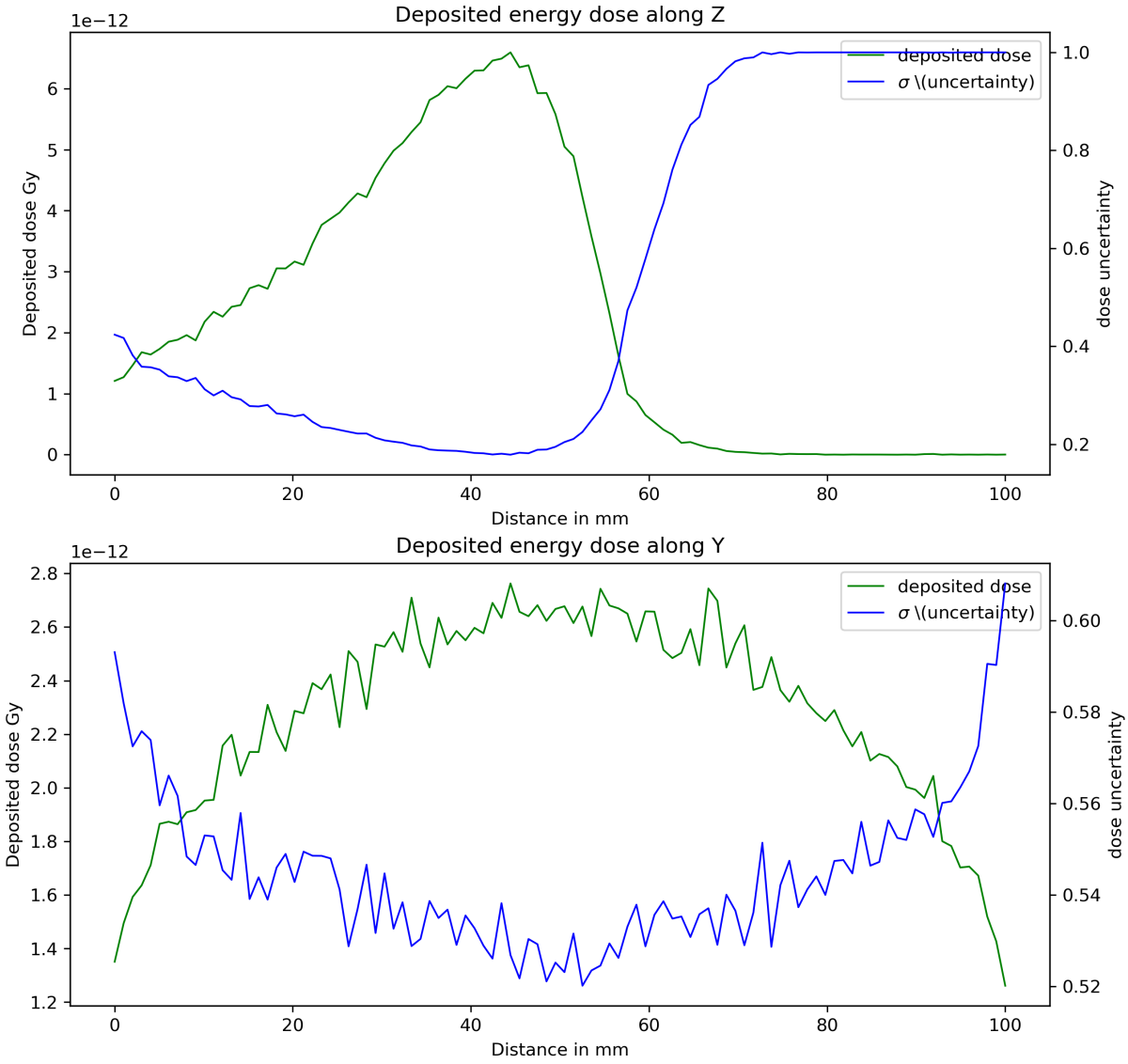

Figure 8: Dose profiles along the Z and Y cross-sections

plots in all the X,Y and Z directions completely overlap. Their shape characteristics are the same and only differ in the scale. A thing to remember is that since we're using X-rays, the quality factor is 1 and hence the units Gy and Sv can be used interchangeably.

Then we have Figures 7 and 8 which show the depth dose and dose side profiles on the surgeon along with the uncertainties. We must remember that the axes values are only indicative since the number of primaries used for simulation are nowhere near the real world figures. We also have an interactive plot for the cross-sections which does not take the averaged value of the plots like we do in the other figures, instead gives us the plot along a particular cross section slice.

As for the shapes of the plots, we see that along the X axis, which is the along the thickness of the phantom, the dose decreases as a function of depth, which is to be expected, since the particles lose their energy, the further they travel in accordance with the beer lambert law.

We expect the distribution along the Y-axis (the breadth of the surgeon) to be-

1. Symmetric about the center since the surgeon is placed right in the middle and there is no bias towards any of the directions.

2. Have maximum intensity in the center, because that higher order deflections are less probable, so most particles should be incident in the middle.

And this is exactly what we get. Along the Z-axis however, We expect the maximum intensity to be in the center for the same reason as above, and as we do observe. But we don't get a symmetric curve. This is because the beam source is not placed symmetrically to the phantom with respect to the z axis. The source is kept at the bottom (or at Z=0) and hence, there will be scatter beam particles coming in directly from the source at the bottom half of the phantom. And so, the graph abruptly goes down to 0 at the right-hand side, while the decline is gradual on the left.

3.E Discussion

It goes without saying that the following Simulation is 'oversimplified' with several loose assumptions. In order to make it more accurate, several things could've been improvised and changed and/or put in place. For instance, We could've used carbon fibre instead of aluminium for the operating table, but unfortunately the material wasn't available in the material database file. We even could've used a voxelized phantom instead of our waterbox phantom, using more humanized materials, but I couldn't find .mhd input files for an entire human body. We could've used incorporated secondary particle emmissions in our simulations, however, I couldn't figure out how to configure them as the documentation wasn't clear on the same. It also goes without saying that incorporating other elements of the operating theatre,

including the personnel and the equipments would've made the simulation more realistic.

I even tried putting different DoseActors in place to analyse the dose distribution near the reproductive regions and the eye lens, as they're most sensitive to radiation. However, I couldn't figure out how to set the voxel sizes using the setRegion command.

As for in the beam source, Ideally we should have opted for a point source with a bremsstrahlung distribution type for a better approximation, but I couldn't find the exact specifications of the point source and the temperature at which the source operated, which was a required parameter for the bremsstrahlung distribution, and so to keep thing simple we chose gaussian beam instead.

For the purpose of our simulation, to keep things simple we use the standard GateMaterials.db file as the material database, we set the Engine seed generator to auto. We also use a SimulationStatisticActor to keep track of the steps, cuts and the simulation runtime and the primary trajectories. Finally we perform the simulation using 10000000 (1e7) primaries to get as accurate and precise results, smooth graphs as possible within a reasonable amount of running time.

However, I tried to make note of the number of photons actually generated during a typical flouroscopy procedure from the given technical factor (43kV, 4mAs), for which I came across the following calculator[25]. However, I was not so sure about the legitimacy of it. Even still, it suggested a photon flux of the order of approx. 1e12 which anyways wouldn't have been possible to simulate for the purpose of our experiment. For us to get better calibration of the axes, the number of primaries is essential.
I have adapted the code examples of the tutorials by david sarrut for my usecase. The tutorial site [26] and the Gate documentation [27] are key references. The code is also available on my GitHub[28].

Word count- 1777

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