“Monte Carlo study of the gamma yield of various scintillating crystals in a simple Positron Emission Tomography (PET) system”

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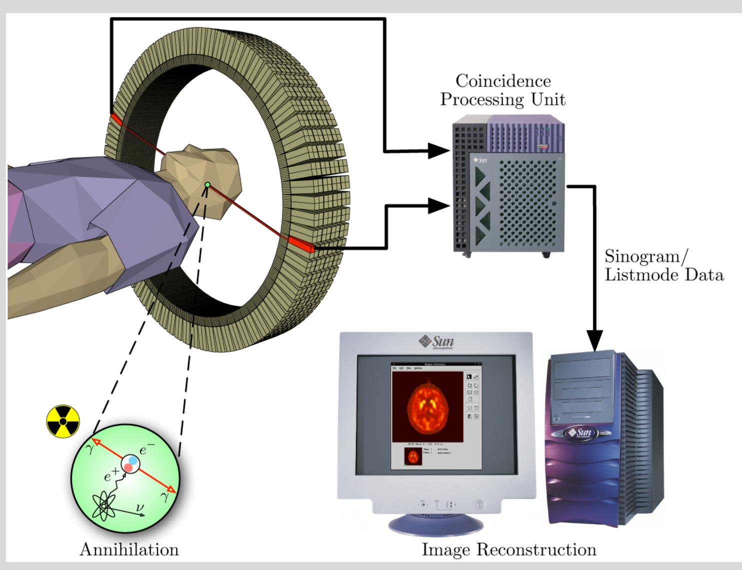
Introduction

Positron Emission Tomography (PET) is a nuclear medicine functional imaging technique that is used to observe the metabolic processes in the body as an aid to the diagnosis of disease. It is based on a radiopharmaceutical idea, which involves attaching a positron-emitter to a molecule.

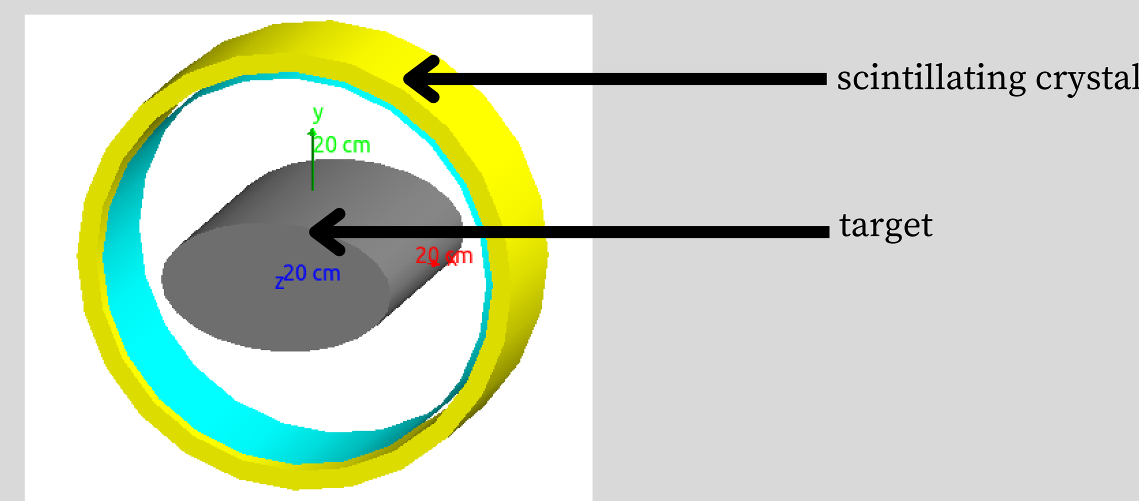


Motivation

This study aims to investigate the number of secondary exit gamma particles, annihilation gamma particles, and photons with an energy equivalent to 511 keV, which are essential data for imaging, and the delivered dose when the radioactive source’s emitted gamma particles are increased.

Methodology

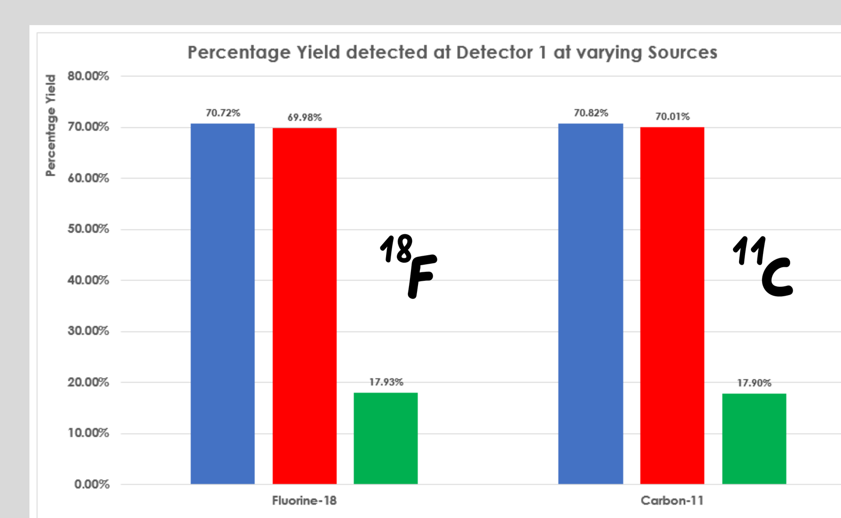
In this study, Monte Carlo simulations were performed using the GEANT4 v.10.3.2 via GATE v.8.0 software. The simulation is composed of a radioactive source, an elliptical tube water phantom that acts as the torso of the patient, a PET detector that is composed of a cylindrical inorganic scintillating crystal, namely: Thallium-Doped Sodium Iodide (NaI[Tl]), Bismuth Germanium Oxide ($Bi_4Ge_3O_{12}$) Cerium-Doped Lutetium Oxyorthosilicate (Lu_2SiO_5[Ce]), and a detector.

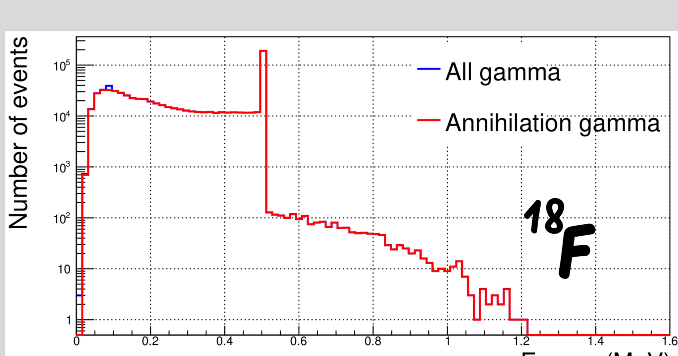


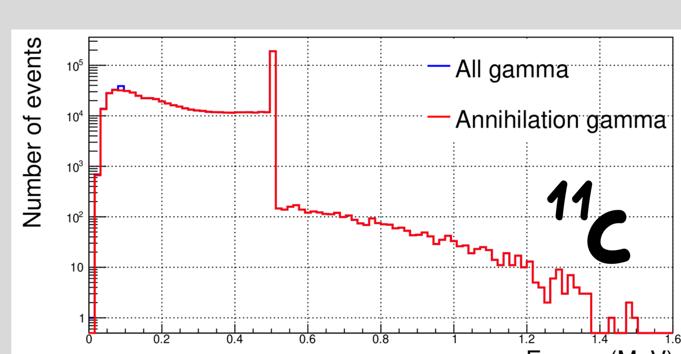
The physics lists "emstandard_opt3" are utilized in this simulation. This list contains electromagnetic interactions of charged particles and photons with matter, which are suitable for simulations of ionization, bremsstrahlung, photoelectric interaction, Compton scattering, pair production, annihilation, and other processes.

Results and Discussion

The figure on the right shows that for the case of fluorine-18 the number of secondary exit gamma particles that passed through the phantom and were detected by the detector are 70.72%, 68.98% of it are from annihilation and 17.93% are the photons that have energy equal to 511 keV. For this, 52.79% of the total annihilation photons detected are considered as random and scattered coincidences or noise in the PET image acquisition. We can also observe that the same trend also applies to the carbon-11 source but about a fraction higher that fluorine-18, this is because of their maximum positron energies.

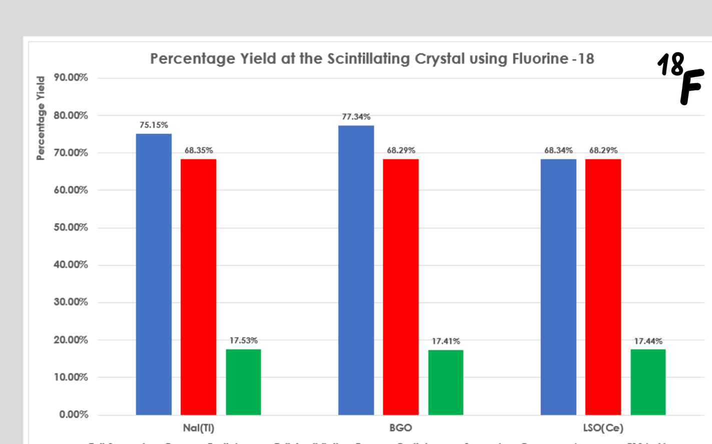


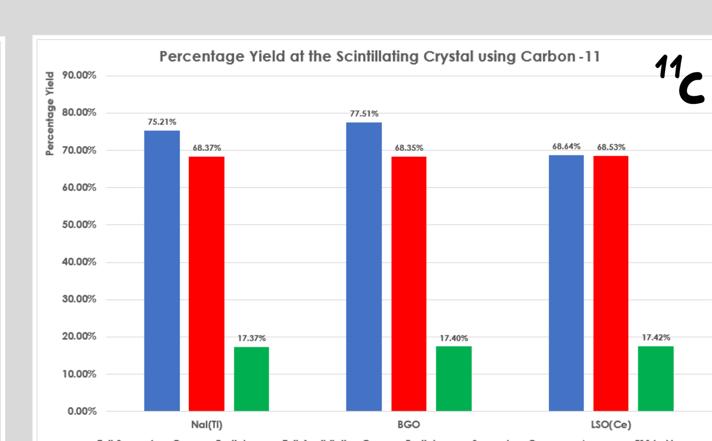


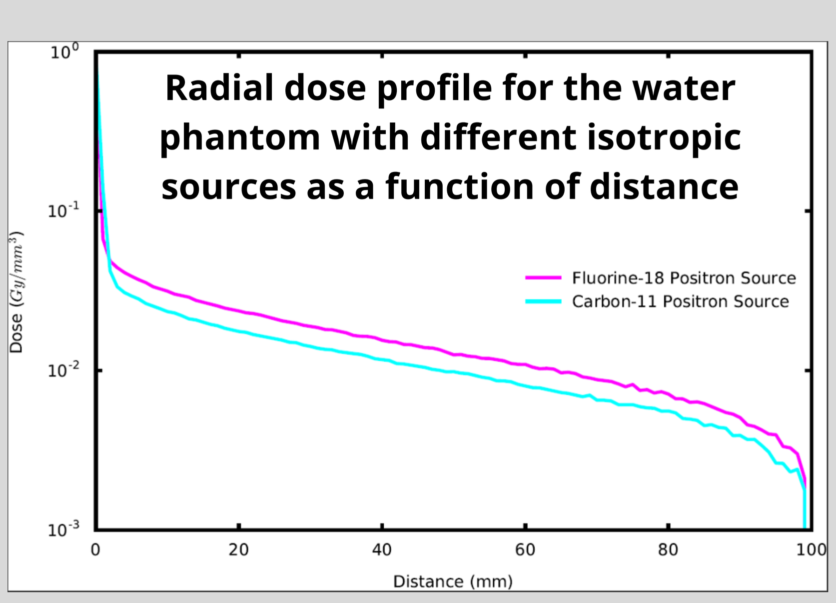


In the figures on the left, we can observe that there are events where the gamma has energies greater than 511 keV, this is due to the fact that during beta-plus decay, positrons from the nuclei of a particular isotope are released within a range of energies up to its maximum endpoint. Positrons lose their energy by Coulomb interactions with atomic electrons, following a tortuous path until they are brought to rest (dependent on their energy and the effective atomic number of the medium).

Figure on the right shows that for all sources (a) fluorine-18 and (b) carbon-11, up to 5% - 7% increase in all the secondary gamma particles has been detected in NaI and BGO which means that the random and scattered coincidence increases, which also increase the noise or unwanted data in image acquisition. We can also observe that the yield at the LSO crystal was decreased by about 2%, which means the noise was also decreased.







In the figure on the left, for all sources, the dose delivered to the phantom decreases exponentially as the distance from the point source increases. This is supported by Beer-Lambert's law:

$$I = I_o e^{\mu x}$$

The intensity in Beer-Lambert's law is related to the dose by the number of gamma particles that imparted its energy or fully stopped at a specific voxel. The greater the number of gamma particles at the specific voxel, the greater the dose it acquired. Furthermore, we can notice that the dose of both sources are highly localized which is a good indicator that these sources when placed at the target volume, only the tissue that has cancer receive the maximum dose while the nearby healthy organs receive a small amount. Also, when zoomed we can clearly see that fluorine-18 is a bit higher than carbon-11, this is because the carbon-11 has a greater maximum energy emission than fluorine-18 which results in a bit less gamma particle deposited or left during its travel from the phantom to outside of it. That is why, carbon-11 deposits less dose that \ch{^{18}F}.

Conclusion

- An average of 30% of the incident gamma particles are absorbed, or converted to secondary particles, during their journey to the phantom and left only with 70%, then decrease farther after passing through varying scintillating crystals.
- The dose delivered to the phantom decreases as the distance from the point source increases which agrees with Beer-Lambert’s law. Due to this dependence, a significant amount of gamma particles are absorbed by the phantom and is responsible for the dose absorbed by the phantom.
- The dose of both sources are highly localized which is a good indicator that these sources, when placed at the target volume, only the tissue that has cancer receive the maximum dose while the nearby healthy organs receives a small amount.

Acknowledgement

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