A public collection of reference dosimetry ionization chamber models in EGSnrc

Jigar Lad, Reid Townson*, Frédéric Tessier
corresponding author: Reid.Townson@nrc-cnrc.gc.ca
Ionizing Radiation Standards, Metrology
National Research Council Canada
1200 Montreal Rd, Ottawa ON K1A 0R6

Introduction

Ionization chambers are sensitive radiation detectors useful in applications requiring a high degree of precision, for example calibrating radiation therapy equipment. Under high voltage, the chamber measures the charge accumulated between the central electrode (anode) and the thimble wall (cathode), as incoming radiation such as x-rays, γ-rays or β-rays ionize air molecules in the chamber cavity [1].

International protocols for radiation dosimetry [2, 3] rely on detailed Monte Carlo simulations of individual electrons and photons interacting within the chamber, as shown in Figure 1. EGSnrc has been developed at NRC over the last 35 years to support calibration services and further research in radiation metrology; it is available as free software [4].

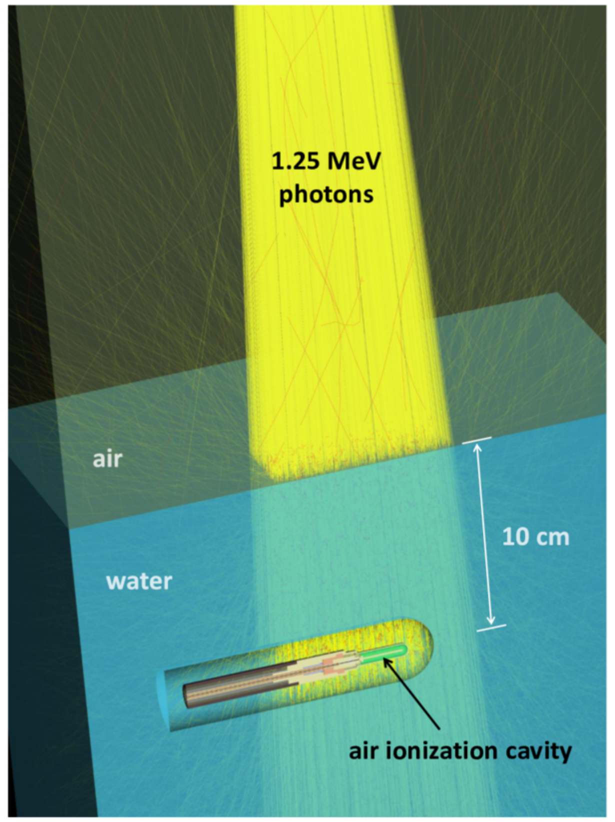

Figure 1. Cross sectional view of an EGSnrc Monte Carlo simulation of the Exradin A12 chamber, immersed in a water phantom, displaying a few of the sampled particle tracks. A collimated point source emitting 1.25 MeV monoenergetic photons is located in air, 100 cm above the water surface. Photon tracks are shown in yellow, and electron tracks in red (water transparency around the chamber is for illustration only).

Problem

Technical chamber specifications are proprietary, and thus **cannot be shared with collaborators nor peer-reviewed.** Consequently, individual researchers obtain this information confidentially from manufacturers in order to build their own simulation models.

The precision of EGSnrc simulations—as well as other Monte Carlo software such as Geant4 [5] and PENELOPE [6]—is now such that even small geometrical differences may lead to noticeable inconsistencies in simulation results. But since the models are confidential, there is no way to assess whether or not any claim about such discrepancies is substantial.

Solution

We aim to **build standard ionization chamber models** and distribute them publicly as part of EGSnrc, with three immediate benefits: 1) users can model detectors quickly, without building geometries from scratch; 2) simulation results can be compared and peer-reviewed; 3) models are continuously validated by a community of users.

Method

1) Seek manufacturer approval

Three out of the five leading companies we contacted decided to participate at this initial stage: **Standard Imaging** (US), **PTW** (Germany) and **Phoenix Dosimetry** (UK). We worked with each company to determine the chamber design elements that could be disclosed publicly, within EGSnrc plain text input files.

2) Build EGSnrc chamber geometries

Starting from exact EGSnrc models (derived from confidential technical specifications), public versions were developed. Negotiations with each manufacturer allowed us to reach an agreeable level of detail deemed **suitable for public release, yet also sufficient for accurate simulation.** One such ionization chamber geometry example is shown in Figure 2.

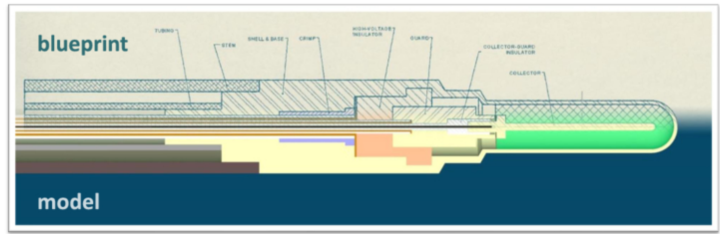

Figure 2. The Exradin A12 ionization chamber by Standard Imaging: the original technical drawing obtained from the manufacturer (top, physical dimensions not shown), and the corresponding EGSnrc simulation geometry (bottom).

3) Verify the chamber models

The Fano theorem [7] states that if atomic interaction cross sections are homogeneous in space, then the energy deposited per unit mass (the *dose*, given in J/kg or *Gray*) is also uniform. Most importantly, it does not depend on *local* mass density variations. Thus, **the dose in every geometrical region must equal the theoretical *Fano value,*** i.e., the total energy injected by source particles, divided by the total mass.

This theorem becomes a powerful verification tool, upon running a simulation with uniform atomic cross sections, as shown in Figure 3. Under this *Fano condition,* the algorithm's accuracy in each geometrical region is quantified directly: it is the difference between the dose and the Fano value. If the dose *matches* the Fano value, then the Monte Carlo simulation is indeed solving the coupled Boltzmann transport equations for electron and photons.

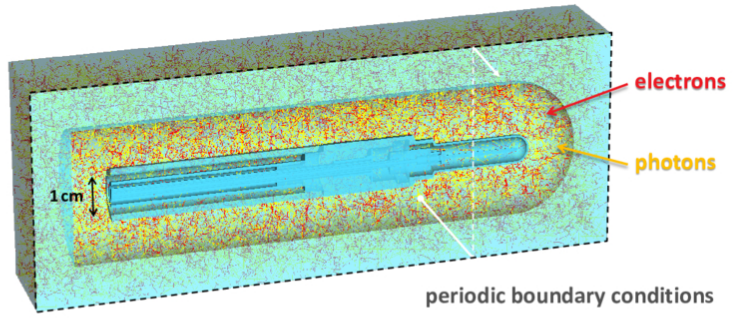

Figure 3. Cross sectional view of the Fano test performed on the Exradin A12 chamber using the custom **egs_fano** application, showing a few particle tracks (transparency around the chamber is for illustration purposes only). As required by the Fano condition, all regions are set to the same material (here water) but with the original material bulk mass density; **periodic boundary conditions** create an infinite simulation space.

4) Validate the chamber models

The dose to the chamber cavity can be calculated efficiently with the **egs_chamber** application [8]. Results for proprietary chamber models were compared to the public versions, in order to find an acceptable compromise between modelling accuracy and vendor confidentiality.

For example, dose calculated in a crude PTW 30012 chamber geometry differed by 0.3% compared to the fully detailed one. Further refinements to the public model **reduced this discrepancy to 0.02%,** appropriately below the typical EGSnrc accuracy (0.1%) and the primary standard uncertainty (0.3%).

Results

Fano test results for the Exradin A12 ionization chamber are shown in Figure 4. The Monte Carlo calculation is found to be **accurate within 0.1% in most geometrical regions,** including the air cavity regions, which are relevant for dosimetry. Verified models enable reliable Monte Carlo simulations of deposited dose. This plays a key role in dosimetry, where we need to calculate perturbations due to the detector's presence inside the measurement medium. Indeed, Figure 5 indicates that **dose to chambers in this work differ by as much as 1%,** owing solely to differences in materials and geometry.

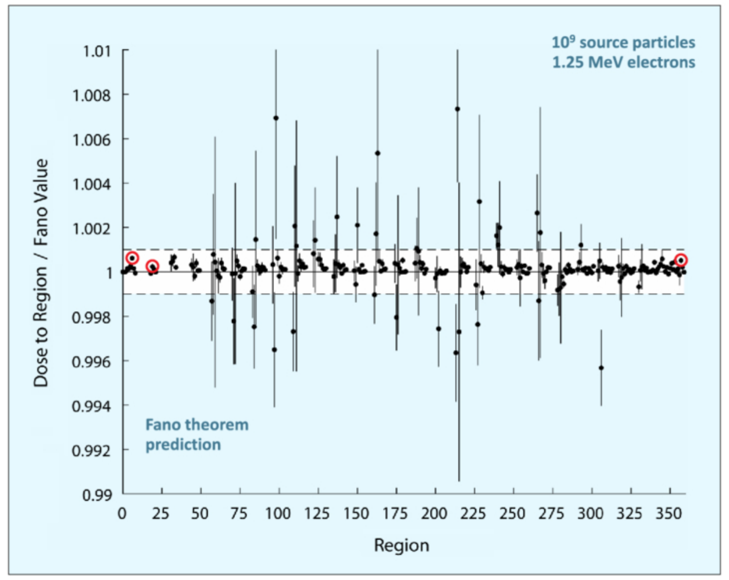

Figure 4. Dose deposited in each region of the Exradin A12 geometry, relative to the theoretical Fano value. The three regions of interest (forming the chamber air cavity) are circled in red, and the dashed lines highlight the 0.1% accuracy range. Regions with data points outside this range are very small (volumes less that 1.5 mm³) and register fewer energy deposition events; hence the large uncertainties (k = 1).

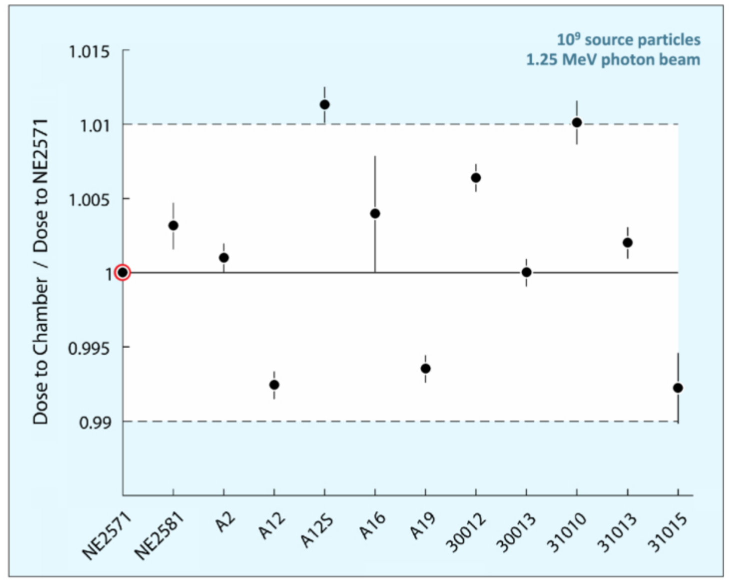

Figure 5. Air cavity dose for all ionization chambers modelled in this work, relative to the standard Phoenix Dosimetry NE2571 chamber, circled in red. The dashed lines show a range of 1% around this reference value.

Conclusion

We built accurate EGSnrc simulation models for 12 ionization chambers from three manufacturers. Incorporating these in the EGSnrc 2021 release is a concrete step towards a **public repository of computational models for dosimetry research.** We trust that this initial effort will prompt other vendors to disclose data for their detectors, and inspire developers of the other Monte Carlo packages to contribute equivalent models.

References

1. Andreo P, et al. *Fundamentals of ionizing radiation dosimetry.* Wiley-Vch (2017).
2. Almond PR, et al. *Medical Physics* **26,** 1847–1870 (1999).
3. Andreo P, et al. *IAEA Technical Report Series* **No. 398** (2000).
4. Kawrakow I, et al. *The EGSnrc software,* https://doi.org/10.4224/40001303.
5. Agostinelli S, et al. *Nucl. Instrum. Methods A* **506,** 250–303 (2003).
6. Salvat F, et al. *Informes Tecnicos* CIEMAT **799** (1996).
7. Fano U. *Radiation Research* **1,** 237–240 (1954).
8. Wulff J, et al. *Medical physics* **35,** 1328–1336 (2008).

National Research Council Canada
Conseil national de recherches Canada