REPRESENTING RANGE COMPENSATORS IN THE *TOPAS* MONTE CARLO SYSTEM

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1. Introduction

Double scattering-based proton therapy systems often use patient-specific range compensators for beam modulation. Range compensators adjust the depth in the tissue at which protons reach their Bragg peak. Accurately representing range compensators in Monte Carlo particle transport simulations is a vitally important problem for clinical treatment planning. This paper proposes two new computational geometry range compensator representations.

The authors have implemented the proposed range compensator representations in Tool for Particle Simulation (TOPAS) [1][2]. TOPAS aims at making Monte Carlo simulation faster and easier to use for clinicians and researchers. TOPAS employs the Geant4 [3] simulation toolkit for the underlying physics processes, and TOPAS offers numerous features that enable radiation therapy simulations. TOPAS includes a collection of customizable geometries for radiation therapy systems.

2. Methods and Materials

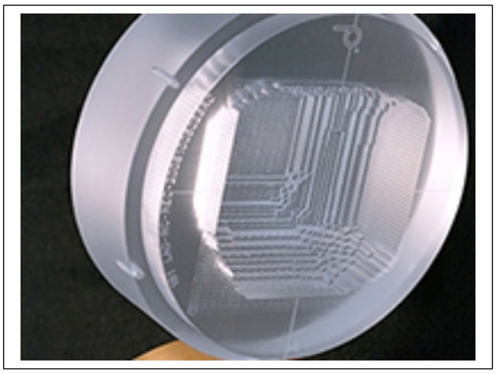

Figure 1: Example range compensator

Treatment planning systems such as Eclipse [4] and XiO [5] design patient-specific compensators. XiO and Eclipse output text or XML files containing a series of positions and drill depths to represent cutouts from a solid cylinder of water-equivalent plastic such as Lucite. A milling machine produces the compensator by drilling these of holes out of a cylinder of a plastic cylinder. Each drill hole may have a unique depth, such as in Figure 1. Unique drill hole depths allow the compensator to reduce the proton energy by different amounts in different (x,y) positions, thus shaping the distal end of the beam.

For Sections 2.1 and 2.2, we assume that the only knowledge of the compensator design is provided by an Eclipse or XiO output file.

2.1. Exact Compensator Representation with Boolean Solids

To precisely represent a compensator in TOPAS, we simulate a plastic cylinder with a number of holes drilled out. We represent these holes as cylinders of air inside the larger plastic cylinder. To achieve this, we use a Geant4 geometrical construct called the *boolean solid* [6]. Boolean solids are primitive geometries (e.g. cylinders) that are allowed to overlap. We construct an exact representation of a range compensator by producing a union‡ of all the drill holes and then subtracting this union from the plastic cylinder. Figure 2a

‡ G4UnionSolid in Geant4 terminology

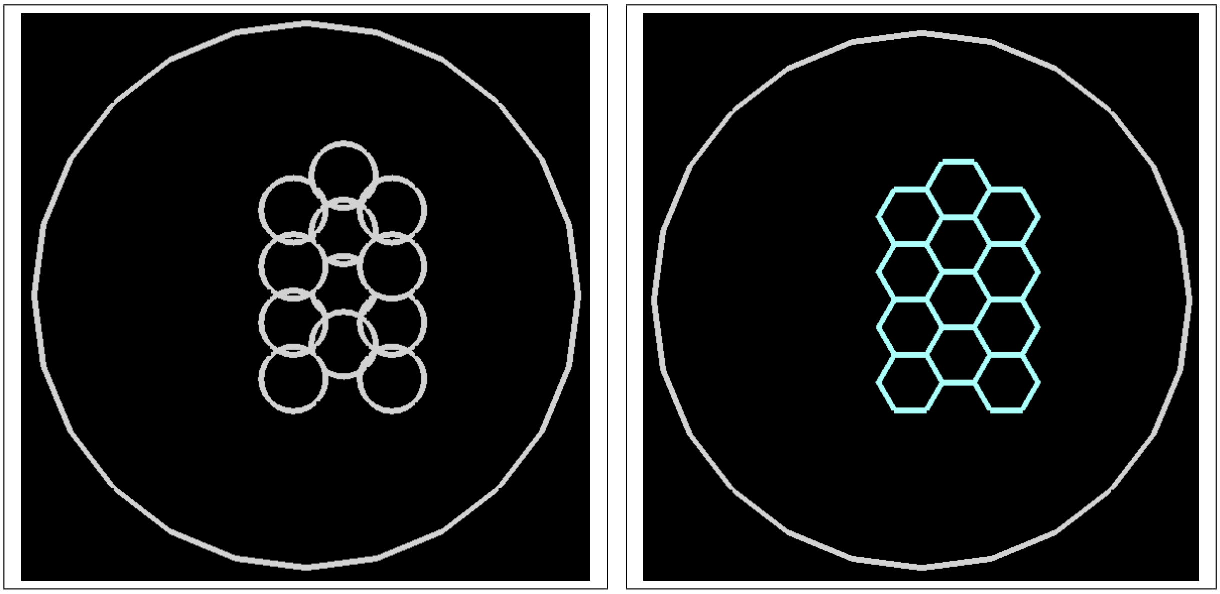

Figure 2: Left: Range compensator modeled with boolean solids. Right: Range compensator modeled with hexagonal prisms.

presents a Geant4 visualization [7] of how we use boolean solids to model a simple compensator with a 4 cm outer diameter and drill holes with a diameter of 0.475 cm.

Unlike most Geant4 solids, boolean solids are allowed to overlap. Therefore, for the example in Figure 2a, Geant4's ability to track particles is not impaired even though the cylinders overlap. If a particle moves into the large plastic cylinder, Geant4 checks whether the particle's new location is inside any of the air holes in the cylinder. Checking every air hole can be time consuming, as we will see in the Results section.

In contrast, Geant4's navigation system employs performance numerous optimizations in order to only explore nearby geometries when tracking particles through non-boolean solids.

2.2. Fast Compensator Approximation with Hexagonal Prisms

The compensator representation presented in Section 2.1 uses boolean solids and therefore requires significant computational overhead for particle tracking. Our next goal is to develop a more efficient compensator representation that does not use boolean solids. Thus, to avoid using boolean solids, we must design a compensator representation that has no overlap among geometric pieces.

To avoid overlap, we approximate each drill hole as a hexagonal prism. We choose hexagons, because they can be clustered without overlap or gaps (Figure 2b). We fill each simulated hexagonal prism with air and place it inside the plastic cylinder.

The benefit of this representation is that it avoids overlaps, which allows us to avoid using computationally-expensive boolean solids. However, unlike the precise compensator model produced with boolean solids, the hexagonal prism model does not correctly represent the drill hole depth in regions where drill holes overlap. Thus, the clustered hexagonal prisms form an approximation of the real compensator's shape.

2.3. Simulation Design

To compare the compensator representations in Figure 2a and 2b, we simulate particle tracking through each representation. We use the same patient-specific compensator for all simulations. This patient-specific compensator is comprised of a Lucite cylinder with a 14 cm diameter, which has 84 holes drilled out. Each drill hole has a 0.475 cm diameter.

To test the *computational efficiency* of our compensator representations, we use a beam of uncharged, non-interacting simulation particles called Geantinos. This allows us to focus on the efficiency of particle navigation in these compensators. Although we use Geantinos instead of protons, we select a realistic beam energy, spread, and spot size for a proton therapy system.

To test the *accuracy* of the compensator representations, we use a simulated version of the Massachusetts General Hospital Francis H. Burr Proton Therapy Center (FHBPTC) beamline in TOPAS. We simulate ten million protons through the FHBPTC beamline, and we capture all particles in phase space immediately before they pass through the compensator. Next, we begin each simulation with this phase space. We position a box-shaped water phantom at the end of the beamline, two centimeters downstream of the compensator. For scoring the particles, we partition the phantom into small bins, which each have a 0.0475 cm width ($\frac{1}{10}$ of the drill hole diameter), 0.0475 cm height, and 0.2 cm depth. For the accuracy results in the next section, we focus on the bins located at the distal portion of the beam. By studying the fluence through these bins in several experiments, we compare beam profiles generated by each of the compensator representations.

We conducted all of our simulations on a system with 8 GB of memory, using one core of a 2.6 GHz AMD Opteron processor. To ensure the repeatability of our results, each simulation was the only user process on the system.

3. Results

3.1. Computation Time

As we mentioned earlier, Geant4 has particle navigation optimizations that improve the performance of the hexagonal prisms representation. However, these optimizations do not apply to the boolean solids representation. Therefore, it is significantly less time-consuming to track particles through hexagonal prism compensator than it is for the boolean solid-based compensator.

To focus on the computation time of only the compensator, the results in Figure 3 represent the time for the particles to travel through just the compensator (and not through the entire beamline). Each data point in Figure 3 is the average of 20 simulations. We notice in Figure 3 that the boolean solid's computation increases exponentially with the number of drill holes used in the compensator. In contrast, the hexagonal prism's computation time is approximately constant without regard to the number of drill holes.

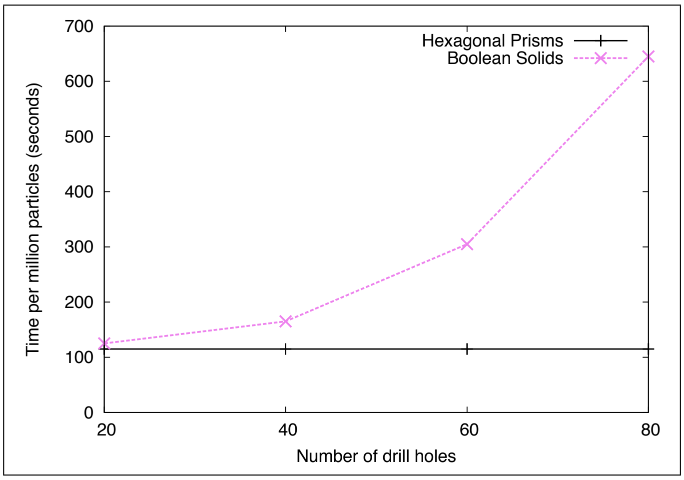

Figure 3: Relationship between number of drill holes and computation time.

3.2. Accuracy

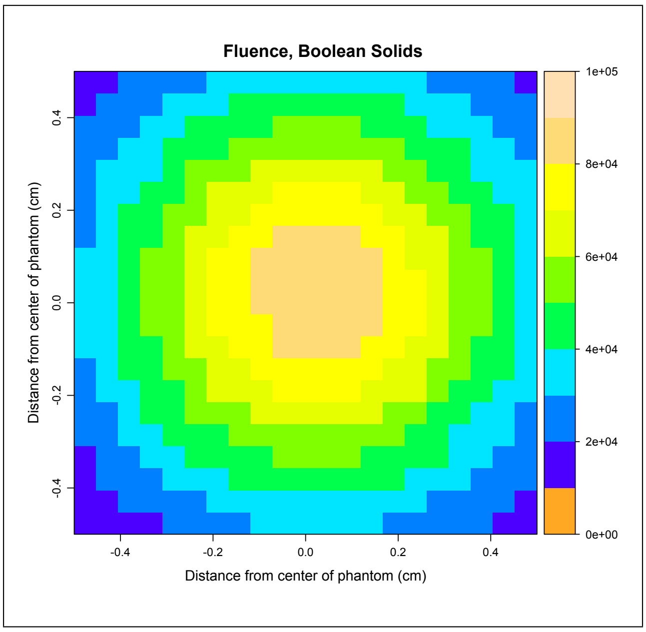

Figure 4: Boolean solid fluence map.

Figure 4 illustrates the fluence of a beam that passes through our precise compensator representation. The hexagonal prisms-based compensator provides a nearly identical fluence distribution. We verify this

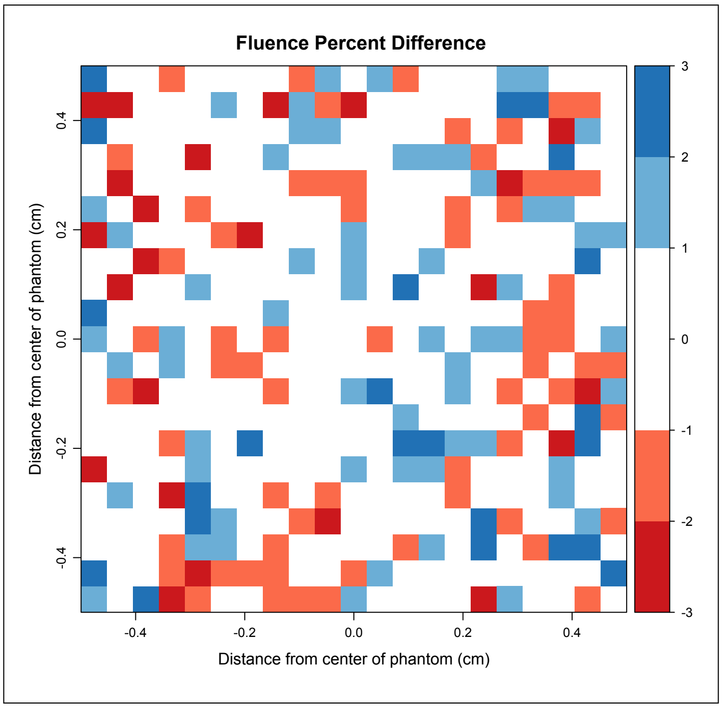

Figure 5: Percent difference between the fluence maps.

assertion in Figure 5, in which each pixel represents the percent difference between one bin of the phantom for each compensator representation. We take the precise boolean solids compensator as the reference data and the approximate hexagonal prism-based compensator as the experimental data. Figure 5 shows that our compensator representations agree to within 3%. Further, as we show in our forthcoming paper and presentation on this work, the differences shown in Figure 5 are largely due to statistics instead of geometry.

4. Conclusions

Developing flexible geometry components is a fundamental problem for Monte Carlo dose calculation. Therefore, we introduced two strategies for representing range compensators in the TOPAS proton therapy simulation. One of these strategies uses Geant4 boolean solids to precisely represent the overlapping drill holes in the real compensator geometry. A second strategy is to approximate the compensator's shape with hexagonal prisms instead of overlapping cylinders. We find that the hexagonal prism approximation offers a reduction in computation time, which enables faster clinical simulations. Further, since the hexagonal prism and boolean solids representations offer very similar fluence distributions, the hexagonal prism representation is suitable for clinical use.

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References

[1] Joseph Perl, Jungwook Shin, Jan Schümann, Bruce Faddegon, and Harald Paganetti. Topas – an innovative proton monte carlo platform for research and clinical applications. *Submitted to Medical Physics.*

[2] T. Akagi, T. Aso, B. Faddegon, A. Kimura, N. Matsufuji, T. Nishi, C. Omachi, H. Paganetti, J. Perl, T. Sasaki, D. Sawkey, J. Schümann, J. Shin, T. Toshito, T. Yamashita, and Y. Yoshida. The ptsim and topas projects, bringing geant4 to the particle therapy clinic. In *Joint International Conference on Supercomputing in Nuclear Applications and Monte Carlo (SNA + MC)*, October 2010.

[3] S. Agostinelli et al. Geant4–a simulation toolkit. *Nuclear Instruments and Methods in Physics Research Section A*, 506(3):250–303, 2003.

[4] Varian Medical Systems. Eclipse. `http://www.varian.com/us/oncology/radiation_oncology/eclipse`.

[5] Elekta. Xio. `http://www.elekta.com/healthcare_international_xio.php`.

[6] G. Cosmo. The geant4 geometry modeler. In *IEEE Nuclear Science Symposium (IEEE-NSS)*, volume 4, pages 2196–2198, October 2004.

[7] J. Allison, M. Asai, G. Barrand, Mark Dönszelmann, K. Minamimoto, J. Perl, S. Tanaka, E. Tcherniaev, and J. Tinslay. The geant4 visualisation system. *Computer Physics Communications*, 178(5):331–365, 2008.