EGS_Mesh: accurate radiation transport simulations in CAD meshes with EGSnrc

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Introduction

EGSnrc is a reference software for Monte Carlo simulation of radiation transport [1]. In medical physics and related fields, there is growing interest for tetrahedral mesh models as an alternative to conventional rectilinear voxel grids for modelling the human body with fewer, better conforming, and deformable geometrical elements.

The general-purpose tetrahedral mesh library EGS_Mesh was implemented in EGSnrc to simulate radiation transport in such phantoms. This new library has immediate applications for simulating radiation transport in any mesh derived from industrial CAD models as well.

CAD models can be meshed with a mesh generator and used as direct inputs to EGS_Mesh without requiring simplification, allowing for more realistic radiation transport simulations using complex CAD geometries. EGS_Mesh simulations can improve modelling accuracy of fundamental quantities such as product sterilization dose uniformity ratios (DUR) compared to constructive solid geometry phantoms.

Background

EGSnrc can simulate a wide range of phantom geometries. As computing power has grown over time, phantoms have become more sophisticated. The earliest phantoms (ca. 1960) were simple shapes such as spheres and slabs [2]. These “stylized” phantoms are straightforward to model in software but are limited by their simplicity [2]. Voxel phantoms emerged in the 1980s and remain a widely-used format today [2]. A voxel is a hexahedron of fixed size, and voxel phantoms are made of many voxels with varying media and densities. Recently, tetrahedral mesh phantoms have become an alternative to voxel phantoms. Unlike voxels, tetrahedral mesh elements can vary in resolution, so complex features can have a higher local resolution without greatly increasing the total number of elements. This improved modelling power means tetrahedral mesh phantoms can use fewer total elements for very accurate models, improving simulation efficiency. These three types of phantoms are shown in **Figure 1**.

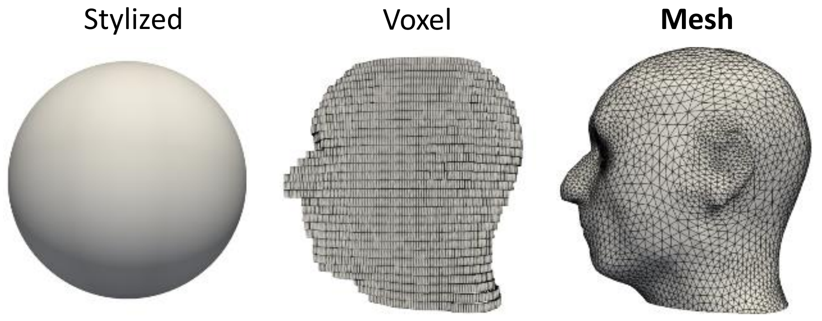

Figure 1. Three adult male head phantoms. The stylized phantom, a sphere, is the simplest but it can only roughly approximate the geometry. The voxel phantom is more detailed but the uniform element resolution has problems modelling thin and curved geometries. The mesh phantom has varying element resolution, meaning it is better able to model complex geometries.

Methods

To simulate CAD geometries, the geometry is first exported as a STEP file from the CAD program. Then, the STEP file is meshed using the mesh generator Gmsh [3]. After assigning EGSnrc media names to the STEP entities, the resulting mesh file can be directly simulated using EGS_Mesh. An example CAD model and resulting mesh is shown in **Figure 2**.

EGS_Mesh is implemented as part of the egs++ class library. Standard ray-plane and ray-triangle intersection algorithms from the literature are employed [4]. Particle transport is accelerated using an octree spatial partitioning scheme, following the PHITS tetrahedral mesh implementation [5].

To verify the EGS_Mesh implementation, the recently released ICRP 145 reference adult tetrahedral mesh phantoms [6] were simulated and results were compared to Geant4 [7].

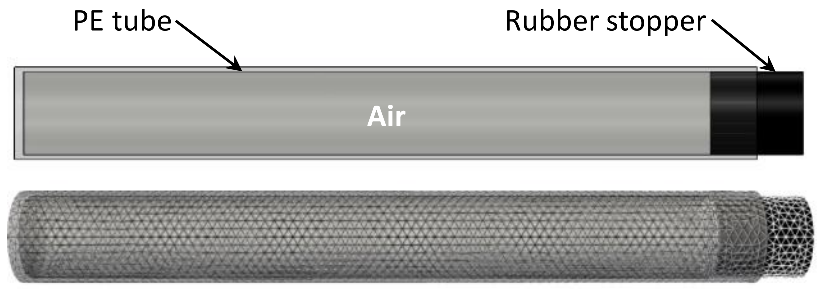

Figure 2. A CAD model of a test tube (above) and the resulting mesh. Compared to a constructive solid geometry model using cylinders, the mesh allows for more accurate dose uniformity ratio calculations.

Results

The ICRP 145 mesh phantoms are a complex, realistic, test case. Each mesh has over eight million tetrahedrons and roughly 190 organs. **Figure 3** shows absorbed dose results for the ICRP 145 adult male phantom liver for two cases: a broad parallel beam of 5 MeV photons in vacuum, and the same for 5 MeV electrons. The photon dose is uniform throughout the liver mesh (as expected for penetrating radiation), while the electron dose is much less uniform. The highest dose is for the liver areas closest to the phantom surface, but drops off rapidly as expected for weakly-penetrating radiation. The liver curvature shown in **Figure 3** highlights the ability of tetrahedral meshes to model complex geometries.

Prior calculations comparing the ICRP 145 phantoms to the previous generation of voxel phantoms have found for photons, organ doses are mostly in agreement, but for electrons, there are large differences [6]. EGS_Mesh confirms this result. **Figure 4** shows liver dose results for an anterior-posterior broad parallel beam of electrons. Compared to the ICRP 116 voxel results [7], the EGS_Mesh and Geant4 [8] liver doses are roughly an order of magnitude higher at certain energies in the 1 to 10 MeV range. The EGS_Mesh and Geant4 liver doses of **Figure 4** agree within 2%. For all energies considered so far, organ doses agree within 10%.

In addition to the ICRP 145 results, EGS_Mesh has also passed theoretical tests, such as the stringent Fano test [9] at the 0.1% level using a thousand-element test mesh as well as comparisons against equivalent voxel phantom simulations.

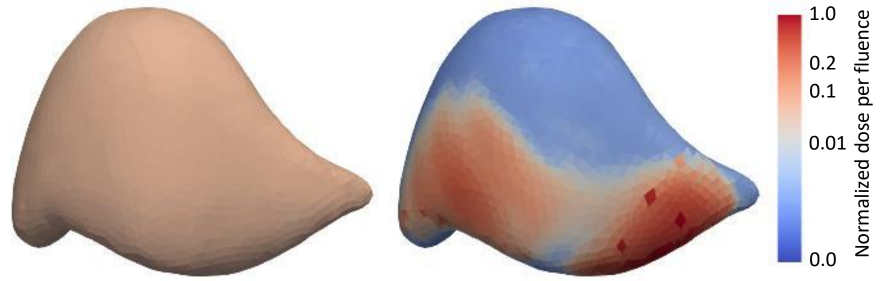

Figure 3. ICRP 145 adult male phantom liver absorbed dose distributions for 5 MeV photon (left) and electron (right) anterior-posterior parallel beams in vacuum. Results shown for 10^9 primary particles.

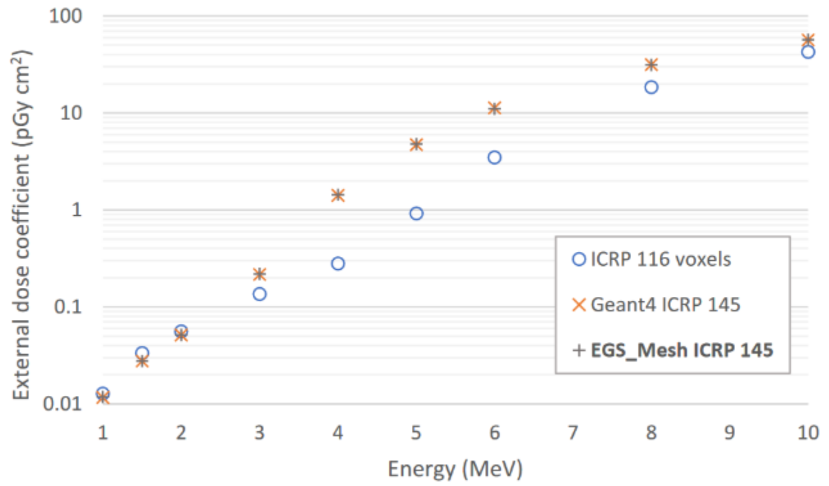

Figure 4. Adult male phantom liver doses from an anterior-posterior broad parallel electron beam in vacuum for energies from 1 to 10 MeV. All uncertainties are less than 1%. The voxel results are from [7] and the Geant4 results are from [8].

Conclusion

A tetrahedral mesh geometry library, EGS_Mesh, has been implemented for the radiation transport code EGSnrc. CAD geometries can be meshed and simulated using EGSnrc without further simplification.

EGS_Mesh also enables further verification of the other major transport codes capable of simulating tetrahedral meshes (Geant4, MCNP6, and PHITS).

Preliminary results using the ICRP 145 mesh phantoms show agreement within 10% with results obtained by the Geant4 tetrahedral mesh implementation.

Using EGS_Mesh, transport in complex CAD meshes using the trusted EGSnrc code is realized.

References

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