2015 International Nuclear Atlantic Conference - INAC 2015
São Paulo, SP, Brazil, October 4-9, 2015
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
ISBN: **978-85-99141-06-9**

HUMAN EYE ANALYTICAL AND MESH-GEOMETRY MODELS FOR OPHTALMIC DOSIMETRY USING MCNP6

Lucas V. Angelocci[1], Gabriel P. Fonseca[1] and Helio Yoriyaz[1]

[1] Instituto de Pesquisas Energéticas e Nucleares (IPEN / CNEN - SP)
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP
hyoriyaz@ipen.br

ABSTRACT

Eye tumors can be treated with brachytherapy using Co-60 plaques, I-125 seeds, among others materials. The human eye has regions particularly vulnerable to ionizing radiation (e.g. crystalline) and dosimetry for this region must be taken carefully. A mathematical model was proposed in the past [1] for the eye anatomy to be used in Monte Carlo simulations to account for dose distribution in ophthalmic brachytherapy. The model includes the description for internal structures of the eye that were not treated in previous works. The aim of this present work was to develop a new eye model based on the Mesh geometries of the MCNP6 code. The methodology utilized the ABAQUS/CAE (Simulia 3DS) software to build the Mesh geometry. For this work, an ophthalmic applicator containing up to 24 model Amersham 6711 I-125 seeds (Oncoseed) was used, positioned in contact with a generic tumor defined analytically inside the eye. The absorbed dose in eye structures like cornea, sclera, choroid, retina, vitreous body, lens, optical nerve and optical nerve wall were calculated using both models: analytical and MESH.

1. INTRODUCTION

The use of radiation as an effective treatment for malignant melanoma of the choroid is emphasized in ophtalmic literature for some time, but photon beam therapy (teletherapy) is an option with little advantage due to the damage caused to the eye structures sensitive to radiation and close to the tumor [3].

Applicators containing ^{60}Co plaques and ^{125}I seeds are most commonly used today, in a surgical procedure consisting of suturing the applicator on the patient's eye for a specified period of time [3,4]. In this procedure, the applicator is placed at the base of the neoplasm, ensuring that the majority of the dose is absorbed in the region of interest, without causing further damage to radiosensitive structures of the human eye (e.g. crystalline).

Based on studies found in the literature that used Monte Carlo simulations to estimate the distribution of dose in the human eye [1,4], this study aims to compare a model of the human eye modeled using CSG (Constructive Solid Geometry) with the same model built with UM (Unstructured Mesh geometry). The MCNP6 (Monte Carlo N-Particle 6) Transport Code, from Los Alamos National Laboratory [5], is able to perform simulations with hybrid geometries, uniting the most intuitive and well known method of CSG, with UM geometries that presents several advantages for modeling complex structures, such as the use of CAD (Computer-Aided Design) tools [6].

These tools, such as ABAQUS/CAE (3DS SIMULIA Dassault Systems [7]) allow easy representation of complex structures and conversion to Mesh geometries, as well as exporting these files into a MCNP6-compatible format. While the human eye model was rebuilt with both methods, the other structures (such as the applicator) were defined only by CSG, for two different simulations: one CSG-pure and one with hybrid geometry (CSG and UM) to determine the effect of using only the Mesh geometry for the eye model itself.

2. MATERIALS AND METHODS

The eye model equations were obtained from literature [1] and defined analytically in MCNP6 (CSG case), as well as drawn structure-by-structure in ABAQUS/CAE, which was also used to build the MESH and to generate files compatible with MCNP6 for the hybrid case (UM).

2.1. The Eye and Tumor Geometry Model

The mathematical model for the human eye was obtained from an article by Yoriyaz [1], and adapted to fit ABAQUS restrictions. As the software uses revolution and extrusion as the main methods to create solid structures, tri-axial ellipsoids were difficult to model. Yoriyaz's equations for the human eye have two cells that were defined as tri-axial ellipsoids: namely the cornea and anterior chamber. Both of them were adapted, so than, one of the main axes was altered to become identical as the other. This result in a change of about 0.5 mm in the radii of these axes, a minor change to the model that allows these structures to be changed to spheroids (ellipsoids with two identical main axes), thus allowing them to be defined as revolution solids. The final model used for this work is described by the following equations:

Sclera, choroid, retina and vitreous body. These four structures comprise the main body of the eye, and are defined as three concentric spherical shells (1 mm thick) and a sphere, respectively, according to the expressions:

$$x^2 + (y + 1.6)^2 + z^2 \leq {R_i}^2 \tag{1}$$

Where R_{sclera}=1.35; $R_{choroid}$=1.25; R_{retina}=1.15; and $R_{vitreous}$=1.05.

Tumor. The tumor was defined as an ellipsoid limited by the spherical surface of the sclera, resulting in an irregular structure located in the inner most part of the eye:

$$0.444(x)^2 + 0.04(y - 3.6)^2 + 0.444(z)^2 \leq 1 \tag{2}$$

$$x^2 + (y + 1.6)^2 + z^2 \leq 1.35^2 \tag{3}$$

Lens. The lens is formed by the region defined inside the spherical surface of the sclera (equation 3) and an ellipsoid defined as:

$$2.04(x)^2 + 2.04(y + 1.6)^2 + 8.16(z - 1.18)^2 \leq 1 \tag{4}$$

Cornea. The cornea is an elliptical shell limited by two concentric ellipses (equations 5 and 6) and the outer surface of the sclera (equation 7).

$$1.45(x)^2 + 1.45(y + 1.6)^2 + 1.59(z - 0.73)^2 \geq 1 \tag{5}$$

$$1.35(x)^2 + 1.35(y + 1.6)^2 + 1.49(z - 0.73)^2 \leq 1 \tag{6}$$

$$x^2 + (y + 1.6)^2 + z^2 \geq 1.35^2 \tag{7}$$

Anterior chamber. The anterior chamber is the region between the cornea (equation 7) and the outer surface of the sclera (equation 8).

$$1.45(x)^2 + 1.45(y + 1.6)^2 + 1.59(z - 0.73)^2 \leq 1 \tag{8}$$

Optic nerve and wall. The optic nerve and wall are represented by a concentric cylinder and cylindrical shell, respectively (equations 9 and 10). Both arise from the outer surface of the sclera (equation 7) and are limited by the plane y=2.

$$(x)^2 + (z)^2 \leq 0.35^2 \tag{9}$$

$$(x)^2 + (z)^2 \leq 0.4^2 \tag{10}$$

Then, both were rotated 30° in relation to the coordinate system.

The tridimensional complete geometric model is shown in Figure 1, as drawn in ABAQUS.

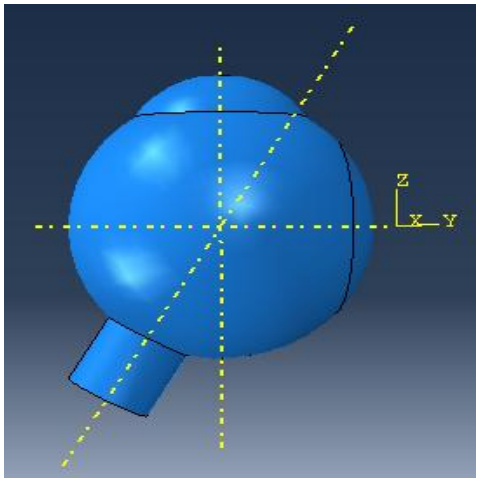

Figure 1: Human eye model as drawn in ABAQUS following the equations from [1].

2.2. Meshing in ABAQUS/CAE

ABAQUS/CAE (CAE standing for Complete Abaqus Enviroment, but also a backronym for CAE as in Computer-Aided Engineering) is a powerful software for geometrical modeling and physical analysis, developed by ABAQUS Inc. and further acquired by Dassault Systèmes Simulia Corp. As the software presents tools for many applications, it was used in this work only to drawn the eye structures (following the above equations) and to Mesh them. The version used is *Abaqus 6.14 Student Edition*, with a student license that limits the creation of Mesh geometries to instances up to 1000 nodes. These nodes are defined as the vertex points of each element of the Mesh. For this work, the element type used to Mesh is a first-order tetrahedral, abbreviate as C3D4.

Due to the limitation of the student edition, each structure of the eye was Meshed separately (or in a set of two or more structures that together don't surpass 1000 nodes). Then, for each one, an *.inp* file was generated. These files are compatible with MCNP6, that imports the UM geometry with the EMBED card and create a universe that contains the Mesh geometry, to be inserted inside any MCNP regular cell (called then the '*fill cell*'). As MCNP6 can only import one *.inp* file, all the files generated with Abaqus were merged manually in one file with the same format, following the *.inp* file organization presented in [6].

The number of nodes and elements used to represent each eye structure is shown in Table 1.

Table 1: Number of nodes and elements in each eye structure for the Mesh-model.

Structure	Nodes	Elements
Sclera	970	2762
Choroid	818	2319
Retina	828	2350
Vitreous Body	946	4271
Lens	159	520
Anterior Chamber	134	314
Cornea	232	621
Optic Nerve	64	181
Optic Nerve Wall	336	863
Tumor	265	994
Total	**4752**	**15195**

2.3. Simulation with Monte Carlo code MCNP6

MCNP6, by Los Alamos National Laboratory, is a well known Monte Carlo (MC) code that transports particles in a medium. In the actual version, it has received compatibility with unstructured mesh (UM) geometries, reading an *.inp* file generated by ABAQUS. Each instance of the ABAQUS assembly (or a set of elements in the instance that share the same statistical characteristics and materials) is named pseudo-cell, to be related to one regular cell of MCNP. A background cell (to fill the gaps between two structures) and a fill cell (to define the region in the main universe of MCNP where the Mesh is located) are also defined.

The EMBED card is used to access *.inp* file information, as well to relate each pair instance/cell. These Mesh structures were given the same composition and density as the cells used in the CSG model, defined analytically in the MCNP6 input for the pure CSG case. Information on the parameters used in the simulations is given in Table 2.

Table 2: Parameters used in MCNP6 simulations for both models.

Material	Density (g/cm^3)	Composition (Fraction by Weight)	Composition from
Seed (Silver Rod)	10.5	100% **Ag**	--
Seed (I-125 adsorbed)	0.013	100% **I**	--
Seed (Air)	$5.03e^{-5}$	0.01% **C** 75.53% **N** 23.18% **O** 1.28% **Ar**	NIST (STAR Database) [8]
Seed (Titanium)	4.54	100% **Ti**	--
Soft Tissue	1.06	10.2 % **H** 14.3% **C** 3.4% **N** 70.8% **O** 0.2% **Na** 0.3% **P** 0.3% **S** 0.2% **Cl** 0.3% **K**	NIST (STAR Database) [8] obtained from: ICRU-44 [9]
Applicator (Silastic)	1.12	8.1% **H** 32.1% **C** 22.35% **O** 37.45% **Si**	[4]
Applicator (Gold Coating)	19.3	100% **Au**	--
Water Box (Surrounding)	1.00	100% **H_2O**	--

2.3.1. MC Simulation Setup

Both cases were simulated with the same setup. The applicator is placed in the geometric center of the setup, so the central seed is located at the origin (0, 0, 0), and the others seed are axially distributed around the y axis. The geometric center of the eye is at (0, -1.6, 0), the front of the eye (cornea) "looking" at +z axis. The entire setup is surrounded by a water box, 6x6x6 cm^3 in volume, concentrically with the eye. Figure 2 and 3 represents this setup as obtained with MCNP Plot, for UM case and CSG case, respectively.

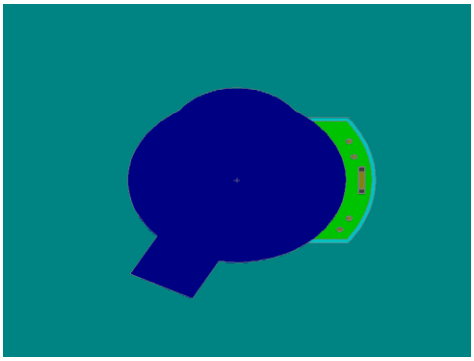

Figure 2: Simulation setup for the Mesh model. Indigo region indicates the fill cell, where the Mesh geometry is inserted into. Green region indicates the applicator.

The eye model was built in ABAQUS taking into account the placement of the structures in the relation to the coordinate system, so that, translation and rotation of every structure was done in the CAE program before exporting to MCNP.

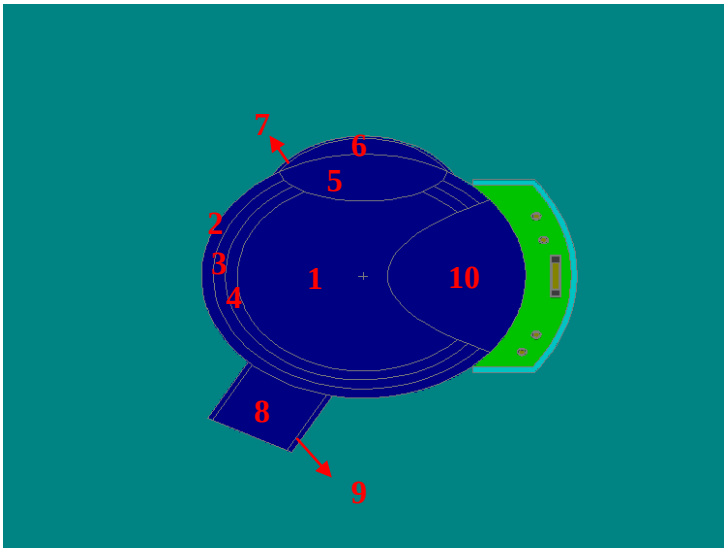

Figure 3: Simulation setup for CSG case. Green region indicates the applicator (seeds can be viewed inside it); light-blue indicates the gold coating; indigo region indicates the eye, with red numbers indicating each structure as it follows:
1- Vitreous Body; 2- Sclera; 3- Choroid; 4- Retina; 5- Lens; 6- Anterior Chamber; 7- Cornea; 8- Optic Nerve; 9- Optic Nerve Wall; 10- Tumor.

Although the Mesh model cannot be exported as a whole, Abaqus 6.14 Student Edition does show the complete meshed assembly, thus allowing the user to fully visualize the Mesh model, as shown in Figure 4.

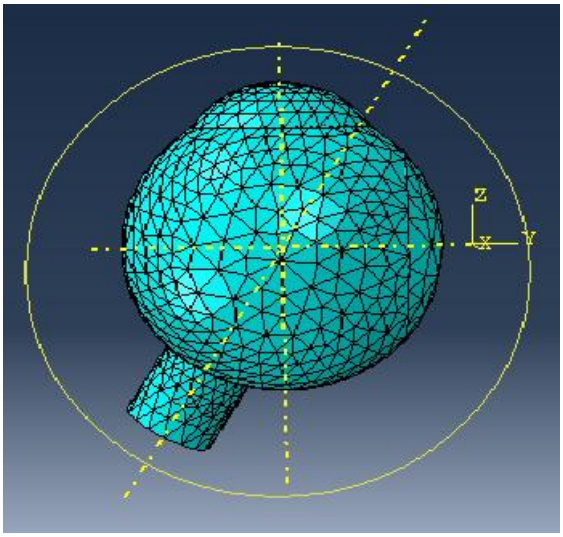

Figure 4: Complete Mesh model of the human eye as created in Abaqus/CAE 6.14 SE, already translated to fit analytical equations [1]; total of 15195 elements.

3. RESULTS

The average absorbed dose was evaluated for each structure and for the entire eye, for each one of the models. So far, the results show differences up to 20% for the same structure in different models. As this value was not expected to be this high, is also important to notice that the geometry can still be improved, and better results are expected to be evaluated.

Part of the discrepancy is also explained by the difference in the masses used for evaluating the absorbed dose, as they are obtained in different ways for each model. The mass in the UM case is obtained by the density defined by user and the volume calculated in MCNP6 using the EMBED card, summing the volume of every element in the Mesh. In the CSG case, as the volume is hard to be calculated due to the structures being irregular, a '*volume calculator*' was used, creating a spherical surface source irradiating each of the structures separately. The VOID card is used, so all the materials are treated as vacuum. Each structure, one-at-a-time, is placed inside this sphere, and the F4 Tally (track-length estimator) is asked in the structure volume. As the source sampling is considered to be equal all over the spherical surface, the F4 value is expect to converge to the real volume of the structure inside the source, as the number of stories increase. Table 3 compares the masses obtained for each part of the eye, in the two cases.

Table 3: Eye structure masses calculated for the CSG model (by a MCNP Track Length Estimator F4 volume calculator) and for the UM model (evaluated by MCNP EMBED card to account for the mass of each Mesh element).

Structure	Mass (g)		Relative Difference (%)
	CSG	UM	
Sclera	1.834	1.793	2.236
Choroid	1.554	1.497	3.668
Retina	1.310	1.251	4.504
Vitreous Body	4.329	3.952	8.709
Lens	0.502	0.473	5.777
Anterior Chamber	0.176	0.163	7.386
Cornea	0.068	0.059	13.24
Optic Nerve	0.276	0.260	5.797
Optic Nerve Wall	0.088	0.085	3.409
Tumor	1.395	1.823	30.68
Total	**11.53**	**11.36**	**1.474**

Most of the mass values are in good agreement, except for the tumor with differences of 30% and should be further investigated. Other factor may be arising from the fact that the *.inp* file was manually modified to merge all the Mesh instances, which means that could exist errors in the file being read by MCNP that can compromise the simulation; these files are to be recreated and checked for errors.

The final results for the absorbed dose, as well as their relative errors (taking the CSG case as the standard) are show in Table 4.

Table 4: Average absorbed dose in each eye structure calculated with both models.

Structure	Dose [x10^{-15} Gy/(Bq.s)]		Relative Difference (%)
	CSG	UM	
Sclera	5.951	6.217	4.481
Choroid	6.417	6.374	0.675
Retina	6.598	6.542	0.848
Vitreous Body	7.123	6.998	1.750
Lens	5.259	5.732	8.995
Anterior Chamber	3.491	4.382	25.51
Cornea	3.276	4.152	26.75
Optic Nerve	1.836	2.056	11.95
Optic Nerve Wall	1.842	2.202	19.52
Tumor	36.47	34.05	6.615
Total	**10.01**	**10.83**	**8.244**

4. CONCLUSIONS

Although further studies must still be conducted to improve results, Mesh geometries are clearly an option for modeling anatomical structures and importing them to MCNP. Its main advantage lies on the range of software that can be used to draw these structures, ABAQUS

itself being both a powerful drawing and meshing tool. Its student license limits the number of nodes by instance, though is recommended that the user acquires a full version, or use a different path to create the mesh. Another work on Mesh geometries for brachytherapy applicators [10] has shown a way for doing this, starting from ABAQUS Student Version and using Engrid and Meshlab (both freeware) to end up with the UM geometry on the MCNP6 (though the use of more than one software can lead to a greater uncertainty, due to error propagation).

Results for the eye show good agreement (<10%) between both models for the average absorbed dose, except for the outer-sclera structures. As the optic nerve and its wall are subject to a very low dose rate, the relative difference is negligible, as it actually represents a difference of only $0.4x10^{-15}$ Gy/(Bq.s). For cornea and anterior chamber, greater differences (up to 27%) are seen and will be subject of further investigation.

The next step of this project is to improve the methodology, thus improving results. When this technique shows better results, it will be implemented as a tool for AMIGOBrachy, a brachytherapy treatment planning system (TPS) in development by this workgroup, which has the capability of pre-processing medical images, simulating radiation transport with MCNP6 and analyzing dose distributions. The final model of the eye is to be implemented as the first tool of AMIGOBrachy that uses Mesh geometries instead of CSG.

ACKNOWLEDGMENTS

The authors would like to thank Fundação CAPES (MEC) and FAPESP for project funding, and CEN-IPEN for providing the environment that made this work possible.

REFERENCES

1. Yoriyaz, H; Sanchez, A; Santos, A. "A New Human Eye Model for Ophtalmic Brachytherapy Dosimetry" *Radiation Protection Dosimetry*, **Vol 115**, pp. 316-319 (2005).
2. Fonseca, G P et al. "A medical image-based graphical platform – Features, applications and relevance for brachytherapy" *Brachytherapy*, **Vol 13**, pp. 632-639 (2014).
3. Stallard, H B; "Radiotherapy for Malignant Melanoma of the Choroid" *British Journal of Ophtalmology*, **Vol 50**, pp. 147-155 (1966).
4. Chiu-Tsao S T et al. "Dosimetry for 125I seed (model 6711) in eye plaques" *Medical Physics*, **Vol 20 (2)**, pp. 383-389 (1993).
5. Goorley, J T et al. "MCNP6™ User's Manual Version 1.0", Los Alamos National Laboratory; Los Alamos, New Mexico, USA (2013).
6. Martz, R L; "The MCNP6 Book on Structured Mesh Geometry: User's Guide", Los Alamos National Laboratory; Los Alamos, New Mexico, USA (2012).
7. "Abaqus/CAE – Dassault Systèmes", *www.3ds.com/products-services/simulia/products/abaqus/abaquscae/* (2015)
8. Compositions of Materials used in STAR Database; *www.physics.nist.gov/cgi-bin/Star/compos.pl* (2015)
9. "ICRU Report 44", International Commission on Radiation Units and Measurements, Ann Arbor, Michigan, USA (1989).

10. Fonseca, GP et al. “The use of tetrahedral mesh geometries in Monte Carlo simulation of applicator based brachytherapy dose distributions” *Physics in Medicine and Biology*, **Vol 59**, pp. 5921-5935 (2014).