Lakshay Seth

Adam Glick

Dose Rate Calculation in Waveguide using Neutron Transport

Introduction:

An ideal therapy for cancer would be one that guarantees only tumor cells, rather than normal tissues, are damaged. Most of the cancer cells should be destroyed by the treatment, else the danger exists that tumor may return. Even though current cancer treatments which comprise of chemotherapy, surgery etc., have been effective, there are still many treatment disappointments. Since, these treatments do not selectively target cancerous cells there is risk that tumor may return (Harling, 2009). This has resulted in a growing focus on alternative cancer treatments that selectively destroy cancerous cells. Boron Neutron Capture Therapy (BNCT) is one of this alternative treatment (Hickey, et al., 2010).

In BNCT, a Boron-10 compound is inserted in the blood of the patient. The two compounds currently used to deliver Boron-10 atoms only to the tumor cells are Sodium Borocaptate (BSH) and Boronophenylalanine (BPA). After inserting the compound in the bloodstream, the body (tumor area) is irradiated with epithermal neutrons to yield excited Boron-11 state, which alpha decays into Lithium-7. Thermal neutron (energy less than 1 eV) have highest neutron capture probability in Boron-10 (Barth, Soloway, & Brugger, 1996). The nuclear reaction is shown in Figure 1.

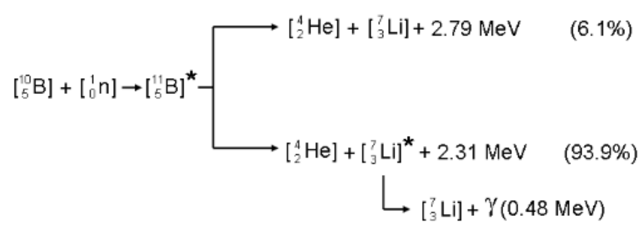

Figure 1: Nuclear Reaction of Boron-10

Since ranges of the Alpha (α) and Lithium-7 particle is 5-9 μm, equivalent to the diameter of the cell nucleus, all the energy of the reaction is released inside the tumor cell, causing considerable damage to the DNA. This results in the target cell being killed with high probablity while bordering cells are not damaged. For tumors where surgical operations are not probable, especially for neck and brain region, BNCT can be very successful (Sauerwein & Moss, 2009).

A problem in BNCT application is to attain a suitabale neutron source. The neutron source can come from spalation (linear proton accelerators) or reactor cores. Each has its advantages. For spalation sources you can tune the neutron energy more easily and precisely which allows for less aperatures necessary in the beamline. However these sources require a lot of maintenance and take a lot of energy, causing an increase in the cost of treatment. University of Washington, Seattle using a linear accelerator to create neutrons by bombarding a beryllium target with protons. For reactor based neutron beams there is little required in the way of maintaining the beamline. Natural sources such as these are usually maintained as the reactor core is maintained. However in natural neutron sources the energy spectrum achieveable is much different than for spallation sources which limits the types of treatments you can perform. An increasingly popular type of treatment is intensity modulated radiation therapy (IMRT) which modulates the dose rate and treatment field shape during beam delivery. With natural sources this is unachievable in terms of the neutron source dose rate, but can be overcome with more aperatures inbetween the beam and the patient.

For the purposes of this project, the neutron source considered will be a reactor core for a micromodular fast reactor modeled in Serpant.

Dose calculation of BNCT are complex. This is due to dose absorbed being the sum of various radiation dose components which emerge from other reactions that occur during BNCT. Along with thermal neutrons, epithermal (1 ev – 10 keV) and fast neutrons (energy greater than 10 keV) are also produced by the source (Joensuu, et al., 2003). With these neutrons available, BNCT application results in other reactions inside normal tissue. These other reactions are:

$$^{14}N + {}^{1}_{0}n \rightarrow {}^{14}C + {}^{1}_{1}p \tag{1}$$

$$^{1}H + {}^{1}_{0}n \rightarrow {}^{2}H + \gamma \tag{2}$$

$$^{1}H + {}^{1}_{0}n \rightarrow {}^{1}H + {}^{1}_{0}n \tag{3}$$

The radiation produced by these reactions is remarkably lower than level of radiation produced by the α and Lithium-7 particles.

In applications for medicine a minimum dose rate of 2 Cobalt Gray Equivalent (CGE) per minute is necessary. This is due to radiobiological effects and interplay effects of target motion and beam shape. As targets move superiorally and inferiorly they can sometimes move partially or completely out of the neutron field. This is thought to be remedied by delivering a higher dose rate so that there is less probability for tumor motion to effect the treatment.

To calculate the rudimentary dose and dose rate, an ion chamber is usually placed at a 10 cm depth in a water phantom with a neutron beam incident in a 10x10 cm square field. However, we can use empirical data and analytical models to predict what the dose rate will be by neutron interactions in water. The reason we use water is due to the similarity in neutron and photon attenuation coefficients between water and tissue. In this paper, we will be discussing the calculation of the dose rate at isocenter (100 cm from the neutron port). We will use deterministic and analytical methods to model the neutron transport in the waveguide and we will use empirical data and analytical models to calculate the dose rate at a 10 cm depth in water for a 10x10 cm neutron field.

Geometry:

The waveguide we are considering will consist of 3 main components: a capture section, a multiplying target, and a beam shaping section. In the capture section we consider a diverging vacuum tube with reflecting walls made from HT9 stainless steel. This section diverges from the core at 30^{o} from the orthogonal plane in the radial direction and 47.9^{o} in the azimuthal direction. The reflecting material is solid HT9 with a thickness of 30 cm. In this region, outside of the reflecting material is lead-bismuth eutectic (LBE) coolant which provides additional reflection to bring neutrons into the vacuum section, however this is not being considered in this project.

The second region consists of a multiplying target made from Beryllium where (n,2n) reactions are used to increase the neutron fluence into the shaping region. The thickness of this target is optimized such that 75% of neutrons have $E_N > 2$ MeV and that the dose rate at isocenter in the treatment room is 2 Gy/min. The energy condition is arbitrary and can be changed based on location of tumor for treatment and different thicknesses of multiplying material can be used to increase dose rate and decrease mean energy.

In the third region the neutron beam is shaped into a 40x40 cm field using HT9 stainless steel with thickenss optimized to increase dose rate. This thickness will be determined based on the neutron current leaving the multiplying material. The angle of convergence for the beam will also be optimized depending on the initial results we get. For starting conditions we consider the Washington State research reactor with BNCT room which has an orthogonal length of 0.466 meters. However because we expect higher energies we predict that the length of our shaping region will have a greater orthogonal length.

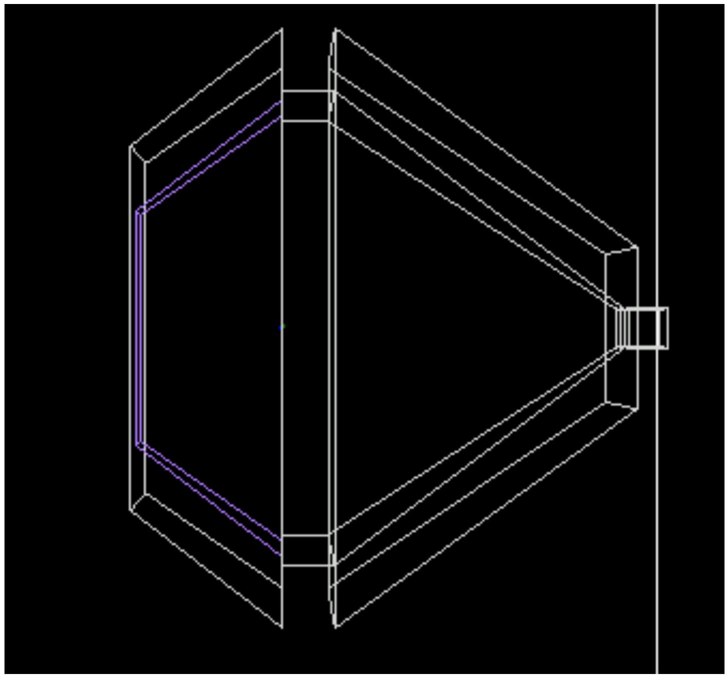

Figure 2: Geometry of waveguide generated using TopasMC.

Mathematics:

The source of neutrons incident on our system is generated from a micro-modular fast reactor. The geometry of this reactor is a cylinder of height, *h* = 2.4 meters and radius, *R* = 0.56 meters with energy current generated from Serpent. To simplify the mathematics and geometry of the system we begin by taking the neutron current from the cylinder S_0 and transforming it to an equivalent neutron source given from an isotropic point.

(1) $S_{point} = \frac{S_0}{2\pi Rh}$

Once an isotropic point source is generated we can calculate the incident neutron flux incident on and anywhere in waveguide as

(2) $S_{waveguide} = (S_{point} \cdot A_{waveguide})\frac{R^2}{r^2}$

where *R* is the radius of the reactor core, *r* is the distance from the point source, and

(3) $A_{waveguide} = \iint_{\theta=0,\phi=0}^{\theta=30,\phi=47.9} 4R\frac{R}{\cos(\theta)}d\theta d\phi$

This information gives the starting information we need to operate our deterministic solver. The algorithms will be discussed in the next section. Since the neutrons traveling in vacuum are assumed to have no particle-particle interaction and the waveguide diverges with the beam we can then calculate the thickness of multiplying material for the first pass of our optimization algorithm. This is done using analytical methods where the thickness required to produce the necessary dose rate at isocenter is

$$(4)\ \ x_{Be} = \frac{-\ln\left(1-{}^{N}/_{N_0}\right)}{\rho_{Be}\sigma_{Be}^{(n,2n)}}$$

where we will tune the term ${}^{N}/_{N_0}$, which represents the fraction of particles not interacting with the target, according to our optimization parameters.

We will use ray tracing and optimization algorithms to track neutron groups as they propagate through the system we have designed. The source we are considering is already discretized in energy due to the output format of Serpent. From this grouping method we discretize the particle flux in angle, where we only consider angles that causes propagation through our reflecting material. Knowing the orthogonal distance from the core perimeter to the multiplying material, the distance traveled through the reflecting medium is given as

$$(5)\ \ r_{Reflector} = \frac{R_{waveguide}}{\cos(\theta)\cos(\phi)}$$

where $R_{waveguide}$ is the orthogonal distance of the waveguide from the reactor core to the multiplying target.

It must also be noted that to calculate the percent of particles that scatter in the energy group traveling through the reflector we employ a similar form of (4)

$$(6)\ \ N_{scatter} = N_0\left(1 - e^{-(\sigma_{scatter}\rho_{atomic}x)}\right)$$

and we discretize the ray into 30 spatial components for each (θ, ϕ) combination to determine where the particles are scattering along that ray. We also assume total elastic scattering for ease of computation. The scattering angle is given by Fresnel's law

$$(7)\ \ \alpha' = \arccos\left(\frac{1}{n}\cos(\alpha)\right)$$

$$(8)\ \ n = 1 - \frac{\lambda^2\rho}{2\pi}$$

where ρ is the nuclear scattering length density and λ is the particle wavelength.

Combining equations (5)-(8) gives us the information needed to model the full neutron transport in the waveguide particles in the first region.

Algorithms:

Plans for Completion:

During the initial stage of the project, we created timeline for each of our task. So far there haven't been any major reasons to deviate from this timeline. When we do encounter problems we do good job of communicating with each other about it. Following are the steps reaming on our timeline:

- *11/18* Determine angle of incidence on multiplying material, calculate (n,2n) reactions, determine exit angle of 2 particles (conservation of momentum)
- *11/25* Determine the shaping of the beam by calculating the interactions in the reflecting material to shape the beam into a 40x40 cm shape.
- *12/02* Calculate the dose rate at 100 cm from exit of beam port

Conclusion:

We have the deterministic part figured out, the part that is remaining modeling the geometry.

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