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Full Length Research Paper

Depth Dose Distribution in Several Human Organs during Boron Neutron Capture Therapy Using Monte Carlo Simulation

Ahmed A. Taha and E. Massoud
Nuclear and Radiological Regulatory Authority Radiation Protection Department, Egypt.

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Corresponding Author:
E. Massoud
Nuclear and Radiological Regulatory Authority Radiation Protection Department, Egypt.

Abstract
Boron Neutron Capture Therapy (BNCT) is a promising radiotherapy for tumor cancer for its ability to concentrate the major damage due to radiation in localized area that does not exceed the radius of the infected cell. So healthy cells around may be safely receive acceptable dose. BNCT technique that have been widely used for tumor brain, should be applied for various cancers such that, lung, liver and pancreas. Depth dose distribution in these soft tissues is an essential issue in treatment plane. The neutron beam has to be determined and adjusted to have the thermal neutron required for the BNCT reaction since the main component for these tissues is water which has high effect in neutron moderation, many trials should be repeated to have the required beam intensity using different materials in filters to absorb gamma flux and keep neutron flux in order 1E+09 n.cm^{-2}.s^{-1}.Existing of theoretical models for human body with its different organs presents a valuable tool to calculate the effect of different factors in applying BNCT facility. In this study, MCNP4C was used to simulate the human organs with different tumors in lung, liver and pancreas and compare it with that for ADAM and EVA, the ICRU models to evaluate depth dose distributions in each during BNCT.The results suggest that BNCT using an epithermal neutron beam could be applied for lung, liver and pancreas cancer treatment. Also good agreement was found for the stated model and that given by ICRU.

Keywords: *BNCT, Monte Carlo simulation, depth dose*

Introduction

Theory of BNCT

Boron neutron capture therapy (BNCT) is an ideal technique to kill cancer cells selectively without harming healthy cells nearby, which is based on the reaction of boron-10 nuclei capturing neutrons to yield high-LET alpha particles, recoiling lithium-7 nuclei and gamma rays(Barth R.F. et al. 2006). High energy alpha particles (He^4) have path lengths of approximately one cell diameter; their lethality primarily is limited to boron containing cells. BNCT, therefore, can be regarded as both a biologically and a physically targeted type of radiation therapy (Fig. 1).

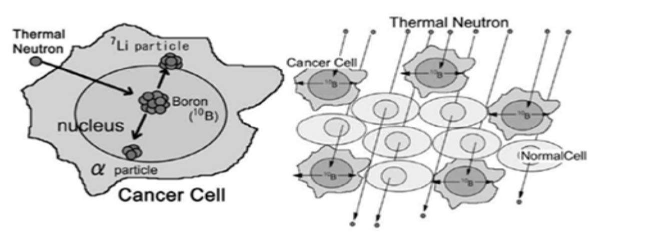


Fig 1: Nuclear reaction utilized in Boron neutron capture therapy (Shinji et al., 2011).

Its success is in the selective delivery of sufficient amounts of B^{10} to cancer cells with only small amounts localized in the surrounding normal tissues (Shinji K. et al. 2011). In BNCT technique, the patient is injected with a boron-10 carrier compound, which has the ability to trace tumor cells and accumulate therein. After a certain time (30 minutes to 2 hour), the boron-carrier compound washes out from the body leaving a high difference in boron concentration between healthy and tumor cells (3.5: 1 tumor/blood). Patient is then exposed to epithermal neutron beam, which is thermalized and highly absorbed by boron (Eid M. 2008). The capture of the thermal neutrons by boron leads to one of the following reactions.

$$^{10}B + n_{th}\ (0.025\ eV) \longrightarrow [^{11}B] \begin{cases} {}^{4}He + {}^{7}Li + 2.79\ MeV\ (6\%) \\ {}^{4}He + {}^{7}Li + 0.48\ MeV\ \gamma + 2.31\ MeV\ (94\%) \end{cases}$$

Boron neutrons capture therapy based on two phenomena; First one, Non-radioactive boron drug was delivered through injection to the tumor tissue and the next one, patient was irradiated with epithermal neutron until the normal tissue dose limit is reached. The advantage of the boron is it has large cross section (3840 barn) for slow thermal neutron (IAEA, 2001).

Factors Affecting in BNCT Facility

- *Boron concentration*

The primary factor for successful BNCT relies on the boron 10-delivery agents. These are the types of tumor cell-finding boron 10-containing agent which are injected into the human body, which then accumulates in the tumor through blood transportation system within a period of time. The most important aspect is strong selectively accumulative ability to achieve high ratios of (concentration of boron-10 in tumor cells)/(concentration of boron-10 in normal cells) the ratios should be greater than 3- 4.

- *Neutron Sources*

Thermal neutrons with energies of approximately 0.025eV are used in BNCT. They are well below the threshold of ionizing tissue components (Zamenhof R.G. et al. 1994). However, thermal neutron beam cannot penetrate into deep tumors due to only 2.5cm penetration range of them within the tissue's surface (Sweet W.H. et al. 1960). Also regarding that the human body has water as a main component of it, epithermal neutrons produces the required thermal neutron for BNCT reaction. Epithermal neutron (1 – 10,000eV) beams can deeply penetrate the tissue 3-6cm below the surface (Soloway A.H. et al. 1998).

- *Doses Associated with BNCT Facility*

Dose calculations in BNCT facility is considered to be difficult task since there are 4 main doses that contribute to BNCT: (1) the "boron dose"-dose from boron neutron capture reaction, D_b; (2) the proton dose from nitrogen capture reaction, D_p; (3) the neutron dose, D_n; (4) the gamma dose, D_r (Chen D. 2003
and Junjie Huang, 2009)

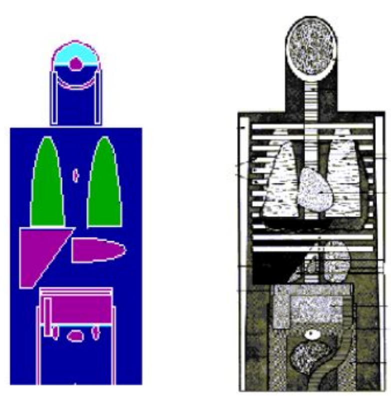
Materials and Methods

Monte Carlo Codes

MCNP is a well-known general purpose Monte Carlo code for the transport of neutrons, photons and electrons developed at the Los Alamos National Laboratory. The user can apply up to second order surfaces (boxes, ellipsoids, cones, etc.) (J.F. Briesmeister 1993) and fourth order tori to build a three-dimensional (3D) geometry, which can be filled with materials of arbitrary composition and density. Point, surface or volume sources of radiation can be defined, from which the mentioned particles are emitted with user specified probability distributions for energy and direction. The code then simulates the particle tracks and interactions with the materials, according to probability density distributions implied by particle and material properties. Taking a comprehensive account of the underlying physics of radiation-matter interaction, it creates secondary particles (which are also transported) and keeps a record of quantities like particle fluence, energy deposition and dose (Massoud E. et al. 2014).*MCNP4C* -Monte Carlo code is One of the codes recommended for the BNCT dosimetric calculations (Hanna Koivunoro, 2012 and Voorbraak W. et al. 2003) was used as a simulation tool or as reference dose calculation method.

The Mathematical Model

MCNP4C was used to simulate the human body with all its organs as shown in fig. 2



(a) (b)

Figure 2: Anterior view of the principal organs in human body.

The body is represented as erect with the positive *z*-axis directed upward toward the head. The *x*-axis is directed to the phantom's left, and the *y*-axis is directed toward the posterior side of the phantom. The origin is taken at the center of the base of the trunk section of the phantom. As composition and tissue density are important parameters in determining the transport of photons in the body, geometric shape of each organ in human body is very essential in preparing the input of the code concerning with the relation between all these organs and they must not intersect. Cristy, M (Cristy M. et al. 1987) gave these mathematical representations for different ages. Some modification in the adult male of age 15 year for expressing adult female which is represented in (E. Massoud 2005).

Liver. The liver is defined by an elliptical cylinder cut by a plane as follows:

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 \leq 1,$$

$$\frac{x}{x_m} + \frac{y}{y_m} - \frac{z}{z_m} \leq -1,$$

and $z_1 \leq z \leq z_2$

Lungs. Each lung is represented by half an ellipsoid with a section removed. Note that the section removed from the left lung is larger than that removed from the right lung because of the position of the heart. The right lung is defined as follows:

$$\left(\frac{x + x_0}{a}\right)^2 + \left(\frac{y}{b}\right)^2 + \left(\frac{z - z_0}{c}\right)^2 \leq 1$$

and $z \geq z_0$;
if $z_{1R} \leq z \leq z_{2R}$ and $y < y_{2R}$, then $x \leq x_{1R}$ must also hold.

The statements for the left lung are similar, but replace ($x + x_0$) with ($x - x_0$), and z_{1R}, z_{2R}, and y_{2R} with z_0, z_{2L}, and y_{2L}, respectively; and replace the inequality ($x \leq x_{1R}$) with ($x \geq x_{1L}$). The letters *R* and *L* refer to right and left.

a	*b*	*c*	x_0	z_0	x_{1R}	y_{1R}	z_{1R}	z_{2R}	x_{1L}	y_{1L}	z_{2L}
4.09	6.98	20.55	7.33	39.21	-5.00	1.20	41.60	48.50	+7.00	0.70	49.00

Pancreas. The pancreas is half an ellipsoid with a section removed. It is defined by

$$\left(\frac{x - x_0}{a}\right)^2 + \left(\frac{y}{b}\right)^2 + \left(\frac{z - z_0}{c}\right)^2 \leq 1,$$

$x \geq x_0$, and $z \geq z_0$ if $x > x_1$.

a	*b*	*c*	x_0	z_0	x_1
13.32	1.14	2.87	-0.72	33.35	2.61

E. Massoud, 2014 described in details the appropriate energy that selected to achieve the required beam intensity. Also in this study many trials have been run to have the most effective moderator and reflector with different dimensions in order to conclude the last model construction giving the results as it should be. Also the theoretical model provided the most appropriate materials for moderator and reflector with suitable dimensions was given in this study.

A very useful study was presented in Japan by T. Matsumoto (T. Matsumoto, 2007) for some human organs depending on ICRU ADAM & EVA phantom to find out the possibility for applying BNCT technique on it using epithermal neutron flux 5E+8 n.cm^{-2} .s^{-1} for:

A lung tumor 2 x 2 x 2 cm^3, at a depth of 5 cm in a central region of left lung, was modeled. A liver tumor 3 x 3 x 3 cm^3 at the depth of 5 cm in a central region of liver. A pancreas tumor 2x2x2 cm^3 was also located at a depth of 5 cm in the right side of pancreas.

In this study the neutron flux was adjusted to be 1E+9 n.cm^{-2} .s^{-1} for same mentioned dimensions of tumors.

Results and Discussions

The dose observed is elevated over the tumor region in the lung. The average dose rate in the tumor was 4 Gy h^{-1} when irradiating with an epithermal neutron flux of 1E+9 n.cm^{-2} .s^{-1}.

The dose observed is higher over the tumor region in the liver. The average dose rate in the tumor was 4.8 Gy h^{-1} when irradiating with an epithermal neutron flux of 1E+9 n.cm^{-2} .s^{-1}.

The dose observed is elevated over the tumor region in the pancreas. The average dose rate in the tumor was 4.3 Gy h^{-1} when irradiating with an epithermal neutron flux of 1E+9 n.cm^{-2} .s^{-1}.

The tumor-to-normal tissue dose ratio was ranging between 2.4 to 2.6 in each case.

These results are very encouraging and seem to indicate that lung cancer could be treated by BNCT under the conditions of calculation.

Conclusions

For many years ago, BNCT had been approved as a selective method for tumor brain for its ability to deliver all the energy inside the target without reaching outside to the healthy tissues depending on the nature of α particles that produced in the reaction. The effectiveness of the process is illustrated in getting the appropriate beam that will be able to deliver the beam intensity required for the reaction since the main component of human body is water that can attenuate the neutrons. After many studies discussed in detail the device that passes the neutron beam into a collimator then filtered to get ride of gamma flux and thermalized the fast neutron flux to an epithermal, the researches in this method began to proof the success of the technique in all kinds of soft tissues cancers.

The depth dose distribution around the infected cell is the main parameter that grantee the safety of this technique for the surrounding cells.

In this study, the evaluated depth–dose distributions for liver, lung and pancreatic cancers were determined and then suggest that BNCT could be applied for treating those cancers under the conditions studied in the paper.

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