MONTE CARLO SIMULATION OF HETEROGENEOUS ORNL WOMAN PHANTOM UNDERWENT MAMMOSITE OR MULTICATHETER INTERSTITIAL LEFT BREAST BRACHYTHERAPY 1500

Mahmoud Suleiman A. Dahoud*

Iskandar Shahrim Mustafa**

ABSTRACT: Monte Carlo simulation plays a key role in both research and clinical practice; it has become an essential tool in dosimetry in modern brachytherapy to determine dose distributions around radioactive source. The measurements of absorbed doses in organs are required to protect it against any type of ionizing radiation, but implantation dosimeters inside human body organs is impossible that makes the dose measurements not measurable. The use of mathematical human body phantom with exact description of organ geometry, tissue chemical constitution, and appropriate computer program can predict the amount of doses delivered to each organ inside human body. The virtual patient is ORNAL woman heterogeneous phantom and other with homogeneous phantom, both two phantoms underwent MammoSite balloon brachytherapy for left breast with 11 dwell positions.

KEY WORDS: MCNP5, Homogeneous, Heterogeneous, MammoSite, Brachytherapy.

* **Mahmoud Suleiman A. Dahoud holds Ph.D. degree, School of Physics, Universiti Sains Malaysia, Malaysia, Penang**

** **Iskandar Shahrim Mustafa is currently a staff at School of Physics and holds PhD in radiation physics in Universiti Sains Malaysia, Malaysia, Penang,**

Introduction: Monte Carlo Simulation Method

MCNP is computational software package used for simulating nuclear process in different applications especially in radiation physics. It was developed by Los Alamos National Laboratory (LANL, USA). Medical physicist needs to simulate radiation transport inside human phantoms by the use of MCNP code. MCNP has an input file, by which the user can define the problem to be solved; it describes the geometry, specific radiation sources and materials, and types of wanted results. Cells, surfaces, material data, source information, and the output format are all designed by the user himself (Alexis, 2007). MC computer code can be used in the estimation of the effect of inhomogeneity on dose distribution in brachytherapy delivered from some radioactive seeds. The result was that bone decreased the dose by 2% by the use of Ir^{192} seed, by 84% by the use of I^{125} seed, and by 83% by the use of Pd^{103} (Slate et al., 2004). MC can assist to find a new approach to source design used in brachytherapy (Rivard, Reed, and DeWerd, 2014). The use of parameterized representation of the source can allow easy setup in brachytherapy dose planning for the parallel computing to design a compact job of MC; it can reduce the memory consumption and keeps accuracy and speed (Zhang et al., 2014). MCNP5 technique represents a numerical computer simulation to solve a complex system by statistical resampling. It was developed by radiation physicists and has witnessed wide use in radiation therapy applications such as in the simulation of imaging process, modeling in treatment source, and to get optimal estimation of delivered doses. It's computer codes had grown since its biginnings which was captured in 1983 about solitaire (Eckhardt, 1987). MCNP can be used for photon, neutron, electron, or coupled photon/ neutron/ electron transport. MCNP codes treat arbitrary 3-D material configuration in geometric cells which bounded by surfaces in its 1^{st} and 2^{nd} degree, and 4^{th} degree of the elliptical tori. Photon code deals with coherent and incoherent scattering, pair production absorption with local annihilation radiation emission, bremsstrahlung, and the fluorescent emission occurred after photoelectric absorption with photon energy regime from 1 keV to 1000 MeV. The use of MCNP standard features make it easy to use with multiple purposes. It obtains answers by the simulation of individual particles and record of some tallies of the average behavior of these particles which is inferred from simulated particles. MCNP provides information about tallies requested in the problem, it solves integral transport equation by using the simulation of particle histories. Monte Carlo can solve complicated 3-D time-dependent problems. The detailed representation of physical data is allowed because there is no

use of phase space boxes and no averaging approximations wanted in time, energy and space by MC method (Briesmeister, 2000). Monte Carlo simulation is considered as the most accurate method in radiation transport. It is used to predict absorbed doses from external or internal radiation sources inside human phantom. The MC idea is to prepare a similar model to real system to be simulated with radiation interactions within this virtual system. It is based on the probabilities of random event occurrences. The statistical uncertainties can be decreased and the system quality of the average behaviors can be improved by increasing the number of histories (Zaidi, 2003). MC simulates individual probabilistic events which are statistically sampled in a purpose of describing the total phenomenon. The simulation needs a digital computer due to the large number of trials which are needed to describe the phenomenon. It is based on the random numbers-analogous selection (Briesmeister, 2000). The total cross section gives the interaction probability of the incident particle through material. The result of interactions can be calculated also by MC software. The interaction types for a photon with energy less than 1 MeV passes through tissues that may occur are: photoelectric effect (photon energy is totally transferred to atomic electron), coherent or Rayleigh scattering (change in the direction of scattered photon with no energy transfer occurs), and incoherent or Compton scattering (fraction of photon energy is transferred to atomic electron), so the summation of linear attenuation coefficients is

$$\mu(cm^{-1}) = \mu_{photo} + \mu_{coh} + \mu_{incoh} \quad (1)$$

which represents the probability of photon interaction with tissue (Z) but for a heterogeneous phantom with different densities, the probability of interaction should equals the summation of all mass attenuation coefficients $(\frac{\mu}{\rho})_i$ of all mediums with weighting factor (w_i) and density (ρ) of radiation traverse through as the following equation

$$\mu = \rho \sum_i w_i (\frac{\mu}{\rho})_i \quad (2)$$

The interactions of photons with tissues will continue until they either absorbed, escape, or energy fall down under threshold (Zaidi, 2003).

Dosimetry and HDR Brachytherpy

Dosimetry is the practical part of measuring or calculating absorbed doses in a medium. In brachytherapy, it is used to determine the distribution of used radioactive source (Ir192) in

defined volumes to achieve acceptable dose distributions, calculate patient doses, and to provide a prescription dose system (Rivard, Venselaar, and Beaulieu, 2009). The interest is increased in the improvement of the accuracy of dosimetry in brachytherapy purposes by the use of remote afterloading, CT scan data, MRI for volume definition, dose calculation by Monte Carlo methods, the use of low energy gamma radiation sources, and the possibility of real time biological and dosimetric optimization led to improve the accuracy of dose distributions and dose calculations in tissue equivalent materials to modify the algorithms (Bidmead et al., 2004).

Methodology

The dose distribution inside the phantom can be measured by using TLD-100H dosimeters. Each dosimeter has its own location inside the phantom slices with its own dose value and isodose curve. There were seven slices that contained TLDs. The radioactive source (Ir^{192}) changed its location inside breast by 11 times in MammoSite balloon brachytherapy (dwell position).The input files for the research phantom which has its own dimensions developed by referring to ORNL female phantom. Medical Internal Radiation Dose committee (MIRD) is a standard formalism used in the calculation of doses for different types of radiation of individual organ doses that distributed by radionuclide sources. The use of cell cards, surface cards, and material cards taken from the ORNL (Oak Ridge National Laboratory) phantom for adult female which was developed by Korean authors at Hanyang University in 1996 makes it an accurate output data (Krstic and Nikezi, 2007). Phantom is mathematical model has different shapes like discs, spheres, and circular cylinders and represents tissues and organs of the body to allow radiations to interact with. The use of MCNP5 is to simulate the transport of particle inside human chest phantom. The most important data must be considered are the activity of the radioactive source (10.303 Ci) and the location of used TLDs inside organs. The input file in MCNP describes the geometry of a problem by defining cells filled with material or not (void) and bounded by surfaces, specifies the source and materials, and defines results needed from the calculation. The input file has three sections starts with cell cards, surface card, and end with data card. The first card in the input file is the title card which contains information about the problem and can be used among input files and it can identify the output files (Reed, 2007). The input cards took into account the dwell positions. The source step was about 0.5 cm. The microSelectron-HDR Ir^{192} source consists of cylindrical iridium core of 3.6 mm length and 0.7 mm diameter, and

encapsulated by a tube of stainless steel that's length is 4.5 mm and its outer diameter is 0.9 mm, and connected to a 0.7 mm diameter drive cable. The source has atomic number of 77 and emits gamma radiation with average energy value of 0.360 MeV, and its location inside breast is changing as dwell positions due to treatment plan. MCNP5 simulation methods track the interaction of incident radiation through the radioactive source taking into account the probability of statistical cross-section for used materials. The phantom which was used is ORNL woman heterogeneous phantom, with Ir^{192} radioactive source which has an impact positions by the use of CT images and moving locations as dwell positions. Thirteen Phantom slices with thickness of 2.5 cm each were used in the study with certain locations for TLDs at its pinholes. The distance between each pinhole and the adjacent one is 3 cm in both horizontal and vertical directions. TLD-100H chips had a dimensions of $3.2 \times 3.2 \times 0.89$ mm^3, nearly tissue equivalent with effective atomic number of 8.2, density of 2.48 g/cm^3, and mass of 0.0226 g for each one. The output results are pulse height distributions and energy depositions through tallies F8:p and *F8:p respectively for all required cells, but dose can be calculated as equation 3, where *F8:p is in unit of MeV, mass in gram, and dose in cGy (rad).

$$D(rad) = \frac{{}^{*}F8 \times 1.602 \times 10^{-8}}{m} \qquad 3$$

The energy bin tally gives result of total energy deposited in a cell detector by each history. The number of particle histories (nps) used in MCNP5 input files reached the value of 3.9585×10^{13}, which was calculated as the number of disintegrations from the radioactive source and depends on each of its activity and dwell time to examine its affect on the output files data.

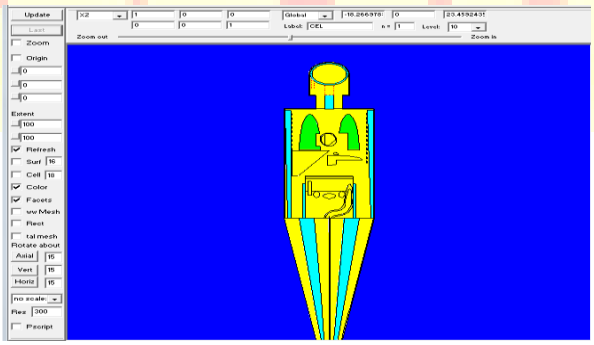

Figure 1: ORNL phantom as simulated by MCNP5 VisEd (Visual Editor).

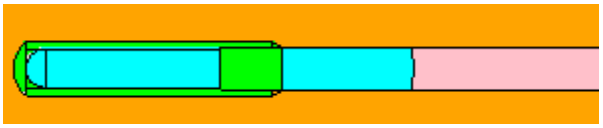

Figure 2: Radioactive source (Ir^{192}) as simulated by MCNP5 VisEd (Visual Editor).

ORNL Phantom has its own dimension for the external border, trunk, ribs, lungs, and left breast. Materials used here were soft tissue (M3 density -1.04 $g.cm^{-3}$), skeleton (M5 density -1.4 $g.cm^{-3}$), lungs (M4 density -0.296 $g.cm^{-3}$), woven steel capsule (M21 density -4.81 $g.cm^{-3}$), source (M20 density -22.42 $g.cm^{-3}$), steel capsule (M10 density -8.02 $g.cm^{-3}$), breast (M7 density -0.93 $g.cm^{-3}$), and saline inside balloon (M280 density -1 $g.cm^{-3}$). The number of particle histories (nps) used was 1×10^{9} particles.

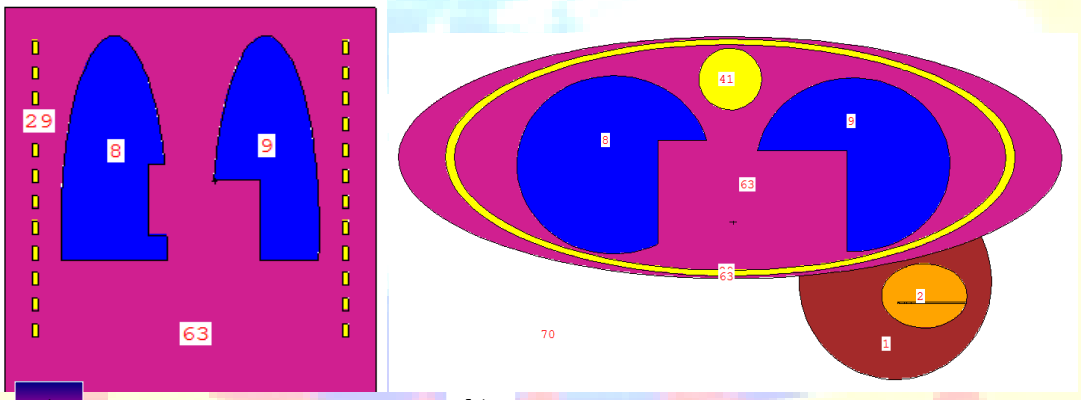

Figure 3 ulated phantom by MCNP5 some cell numbers in a) x-z axis, and b) x-y axis.

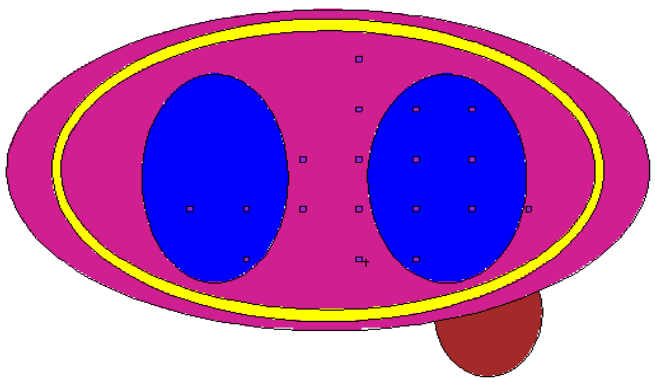

Figure 4: MC simulation for slice 13 and TLDs inside lungs and trunk.

Results

Doses inside organs were measured by three different ways; treatment plan, thermoluminescent dosimeters (TLD-100H), and Monte Carlo simulation methods. Tables 1 and 2 tabulate the final results at organs at risk.

Table 1: Percentage prescribed dose (%PD) for MIB by the treatment plan, TLD readings, and MCNP5 simulations.

Organ	TP data	TLD readings	MCNP5	average	SD
Heart	21.8	23	19.7	21.5	1.67
Left lung	21.8	23	19.7	21.5	1.67
Right lung	3.5	3.2	3.1	3.267	0.21
Left ribs	21.8	23	19.7	21.5	1.67
Spine	1.4	1.5	1.5	1.467	0.06
Sternum	5.9	5.9	5.9	5.9	0.00
Right ribs	3.5	3.2	3.1	3.267	0.21

Table 2: Percentage prescribed dose (%PD) for MBS by treatment plan, TLD readings, and MCNP5 simulations.

Organ	TP data	TLD readings	MCNP5	average	SD
Heart	25	25.1	22.3	24.13	1.59
Left lung	25	25.1	22.3	24.13	1.59
Right lung	3.5	3.3	3.8	3.53	0.25
Left ribs	25	25.1	22.3	24.13	1.59
Spine	6.5	3.3	2.1	3.97	2.27
Sternum	7.4	2.4	6.3	5.37	2.63
Right ribs	3.5	3.3	5.0	3.93	0.93

The relation between the dose inside the body and the radial distance from the radioactive source is illustrated in figure 5.

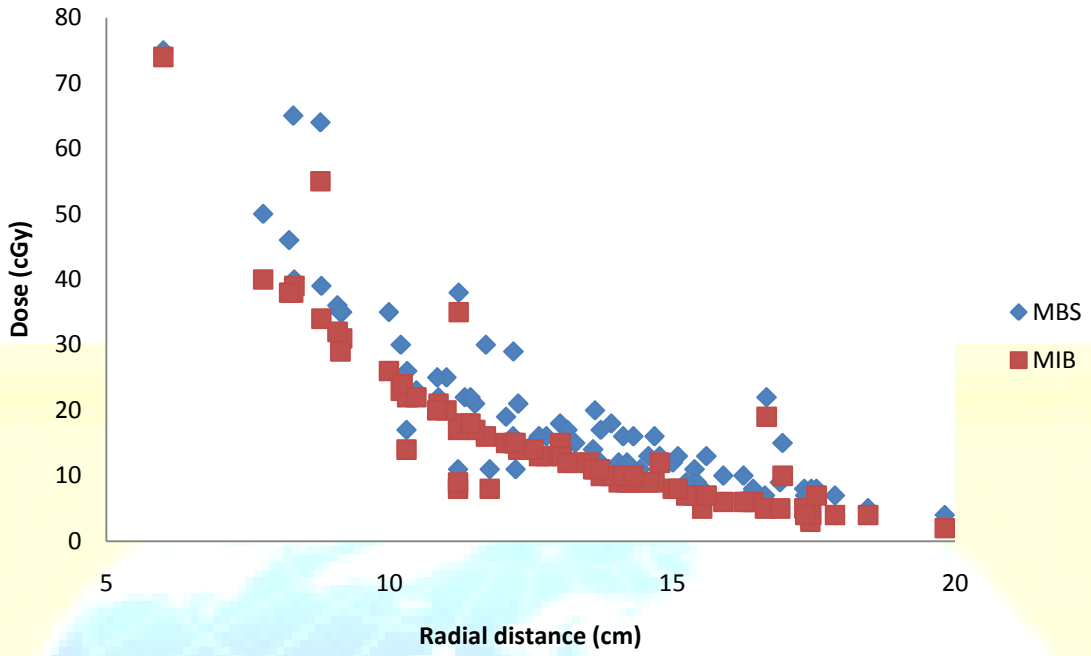

Figure 5: The relationship between dose value (cGy) and radial distance (cm) from the radioactive source for both multicatheter interstitial brachytherapy (MIB) and MammoSite brachytherapy system (MBS).

Conclusions:

The radiation dose to organs at risk, such as breast and PTV is affected by the number of dwell positions and catheters inside the breast used by the radioactive source to deliver radiation doses. Doses delivered by MBS to OARs have greater values than that of the MIB. The differences are not too much in some points, but in other points inside organs and tissues, can affect the recurrence of cancer in OARs, but MIB can cover the PTV with fewer doses for normal breast tissues.

Both MIB and MBS had an ideal dosimetric coverage of PTV, but MIB delivered higher dose (99.9%PD to 90% of PTV) more than MBS (98.99%PD to 90% of PTV), which means a noble goal to target the residual cancer cells by both MIB and MBS. Both satisfied brachytherapy protocol's recommendations. Both MIB and MBS spared organs at risk. The whole breast volume received higher dose in MBS, but did not exceed the recommended values.

References

1- Alexis, L. R. (2007). *Medical Physics Calculations With MCNP: A Primer* . Boston, MA: Summer American Nuclear Society Meeting , LA-UR-07-4133. Los Alamos National Laboratory.

2- Slate, L. J., Elson, H. R., Lamba, M. A., Kassing, W. M., Soldano, M., & Barrett, W. L. (2004). A Monte Carlo Brachytherapy Study for Dose Distribution Prediction in an Inhomogeneous Medium. *Medical Dosimetry , 29* (4), 271-278.

3- Rivard, M. J., Reed, J. L., & DeWerd, L. A. (2014). Monte Carlo Assessment of a New Approach to Brachytherapy Source Design. *Med Phys , 41* (1), 011716.

4- Zhang, M., Zou, W., Kim, L., Khan, A., Haffty, B., & Yue, N. J. (2014). Parameterization of Brachytherapy Source Phase Space File for Monte Carlo-Based Clinical Brachytherapy Dose Calculation. *Phys. Med. Biol. , 59*, 455-464.

5- Eckhardt, R. (1987). Stan Ulam, John von Neumann, and the Monte Carlo Method. *Los Alamos Sci , 15*, 131-143.

6- Briesmeister, J. F. (2000). *A General Monte Carlo N–Particle Transport Code*. California, USA: Los Alamos, University of California.

7- Zaidi, H. (2003). The Monte Carlo Method: Theory and Computational Issues. In H. Zaidi, & G. Sgouros, *Therapeutic Applications of Monte Carlo Calculations in Nuclear Medicine* (pp. 1-23). London: IOP Publishing Ltd.

8- Rivard, M. J., Venselaar, J. L., & Beaulieu, L. (2009). The Evolution of Brachytherapy Treatment Planning. *Med Phys , 36* (6), 2136-2153.

9- Krstic, D., & Nikezi, D. (2007). Input Files with ORNL—Mathematical Phantoms of the Human Body for MCNP-4B. *Computer Physics Communications , 176*, 33-37.

10- Reed, A. L. (2007). *Medical Physics Calculations with MCNP: A Primer* (Vols. LA-UR-07-4133). Los Alamos: Los Alamos National Laboratory.

11- Bidmead, M., Briot, E., Burger, J., Ferreira, I., Grusell, E., Kirisits, C., et al. (2004). *A Practical Guide to Quality Control of Brachytherapy Equipment* (1st ed.). (Venselaar, & P. Calatayud, Eds.) Belgium: ESTRO.