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MONTE CARLO DOSE CALCULATIONS FOR BREAST RADIOTHERAPY USING ^{60}Co GAMMA RAYS

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The present study aims to assess radiation dose received by the target tumor cells and non-target organs during breast radiotherapy. The human body with its details, was modeled using three dimensional Monte Carlo Nuclear Particles Code (MCNP-4B). The dose distribution from ^{60}Co γ-rays, with average energy 1.25 MeV, in two fields in human theoretical model was calculated at selected points using the same code. Monte Carlo computer calculations of the photon spectra and the ratios of doses at the surfaces and in some of the internal organs of the model were also performed. In order to validate the calculated data, dose distribution at the same selected points were measured during a real radiotherapy practice using ARP phantom and TLD. Moreover, depth dose distribution was established by modeling water phantom with capacity 80 cm^3 and measured by ion chamber 0.125. Both measured and calculated data were compared. The comparison showed that the calculated and the measured data have the same behavior in different organs. The correlation coefficient of both sets of data (R) was found to be = 0.9126. The comparison between calculated and measured depth dose gives fair agreement.

Keywords: *Breast Radiotherapy, MCNP-4B in Radiation Therapy, MCNP in Medical Physics.*

INTRODUCTION

For the scope of protection against undue exposure to ionizing radiation it is necessary to determine radiation dose to specific body organs and tissues. It is impossible to produce an analytic expression to describe the transport of particles through the body due to the multitude and the complexity of its interactions. Monte Carlo simulations are needed to solve accurately this kind of complexity [1].

Series of models of the human body were designed, together with computer codes simulating the radiation transport and energy deposition in the body. Most of the computational body models used are the so-called mathematical models; the most famous of these is the MIRD-5 phantom developed at Oak Ridge National Laboratory. Mathematical models are constructed analytically via 3D surface equations representing internal organ boundaries and outer body surfaces and shapes. In the 1980s a new generation of human body models (Tomographic models was introduced. These are represented by voxelized geometries through segmentation of 3D CT or MRI medical image data sets [2]**.** Although the voxel phantoms are more realistic than the MIRD mathematical phantoms, yet they reflect individuals and are only applicable to a population with similar physical shape.

The mathematical phantoms on the other hand allow the actual simulation of individuals through the variation of input parameters of the phantom surfaces or a specific organ. Various methods have been employed to calculate the dose deposited within the patient. Almost all the codes of practice (analytical codes) for absolute dose determination in radiotherapy beams now use Monte Carlo calculations to describe the transport of particles through the body [1].

In this study a general-purpose Monte Carlo N-Particle code (MCNP version 4B), was used for photon transport. The principle of a Monte Carlo simulation, is to simulate the radiation transport knowing the distribution probability governing each interaction of particles in materials [3]. The physics photon, and electron interactions is the very essence of MCNP-4B. For photons, the code takes account of incoherent and coherent scattering, the possibility of fluorescent emission after photoelectric absorption, absorption in pair production with local emission of annihilation radiation and bremsstrahlung [1]. For each single particle history, the parameters influencing its actual course are selected randomly from their probability distributions. The code includes libraries of cross section data for the radiation interaction processes [4] for all elements from which the cross section data for body tissues are then evaluated according to their elemental composition and density.

During radiation treatment process, the MCNP-4B code can be applied to provide the desired dose to the target volume while minimizing exposure to adjacent normal tissues [5]**.** The accuracy of dose calculations in treatment planning for radiation therapy is very important and the overall error in dose delivered to patients should not exceed 5% [6,7]. Most of the commercial systems, named Treatment Planning Systems (TPS), use an analytic calculation and errors near in homogeneities in the patient can reach 10 to 20%. Such methods are less accurate for practical complex situations, such as small irradiated volumes limited in lateral and/or forward directions; interface regions,…etc. In alternative, Monte Carlo calculations can solve problems of real life that are otherwise difficult or even impossible. Its ability to simulate any 3D geometry enables its use for clinical routine radiotherapy treatment planning.

A photon virtual source model was developed for simulating arbitrary, external beam, intensity distributions using the Monte Carlo method by Chetty *et al.,* [8]. In 2000 [9] a new Monte Carlo (MC) algorithm, the "Dose Planning Method" (DPM), and its associated computer program for simulating the transport of electrons and photons in radiotherapy class problems employing primary electron beams was presented.

Charlie (2001) [10] investigated practical methods for source modeling and beam commissioning for Monte Carlo treatment planning. Various source models have been developed based on the detailed knowledge of clinical photon and electron beams. The Monte Carlo method has been an excellent tool for obtaining the particle phase space and analyzing the beam characteristics.

Gual and Valle 2002 [11] modeled the ORNL mathematical phantom designed by Cristy and Eckerman in 1987 [12] using the MCNP-4B code with the objective of validating the systems of patient specific dosimetry used in the hospitals. The mathematical phantoms modeling with Monte Carlo guarantee estimates doses more exact in the therapy of the cancer with radionuclides because of difference of the anthropomorphic phantoms, are free of engines that are one of the reason of present errors in the experimental measurements.

In the present study the mathematical phantom, designed by Cristy and Eckerman in 1987 [12], was modeled using the MCNP-4B code in order to study the radiation dose distribution in the target (breast) and non target organs. This study is planned not only to assess the radiation doses received by the target organ and non-target organs in external radiation treatment but also to demonstrate the advantages of the using the MIRD mathematical phantoms over other homogenous phantoms or that of fixed sizes (voxel phantoms). In the mathematical phantoms, many parameters can be change such as volume, mass, length and fatness,…etc. Results of the calculated and measured data will be compared. This will be of great importance to validate this code as a standard method of calculation for radiotherapy.

MATERIALS AND METHODS

Mathematical Model and MCNP Calculations

Most of the commonly used computational models of the human body are the so-called mathematical models. Mathematical expressions representing planes, cylindrical, conical, elliptical or spherical surfaces are used to describe idealized arrangements of body organs. In this work, the mathematical model for the human body was used to calculate the photon spectra as well as the dose ratios at the surfaces and in some of the internal organs of this model. The mathematical model is designed, according to Cristy and Eckerman in 1987 [12], to represent whole populations. For this model, the organ volumes are in accordance with the ICRP data on Reference Man [13] However, individuals can be simulated by the mathematical model through the adjustment of surface parameters. Also a model of water phantom with 80 cm^3 was performed to calculate the depth dose distribution for field size 10 *10 cm^2. The radiation transport in the human phantom is calculated using MCNP-4B Monte Carlo code following individual photon histories.

In the MCNP-4b radiation transport code used in this work, the energy transferred at a point of inelastic photon interaction (1.25 MeV) is modeled as being deposited at that point, without considering the energy transport by secondary particles "Kerma approximation". This approach is valid as long as there is approximate secondary electron equilibrium, which can be supposed in most cases due to the moderate differences of the photon cross sections for the tissues in the human body. Furthermore, according to Maigne *et al.,* [3], the ranges of secondary electrons for the photon energies below approximately 1-3 MeV are small compared to the dimensions of the organs, especially in view of the macroscopic approach considering mean organ and tissue doses. Figure 1. shows the horizontal cut of the computerized model at the center of the target (breast) and the selected TLD locations. Figure 2A. and Figure 2B. show the horizontal cut of the computerized model at the center of the target (breast) and the shape of field size for the two treatment fields.

Experimental Measurements

In order to validate the calculated data, a parallel experimental measurements were carried out. For this purpose, The LiF Thermoluminescent Dosimeters (TLD) (Harshaw TLD-100 LiF:Mg Ti, Harshaw Chemical, Solon, USA) were placed at different selected sites inside the Alderson Rando Phantom (ARP) as shown in Figure 1. Left breast was irradiated at Department of Medical Physics, Mansoura University by 1.25 MeV γ-ray from ^{60}Co. The total dose to the breast (the chest wall was included) was 50 Gy over 25-treatment session, the daily dose fraction was 2 Gy during the treatment session. After the irradiation process the TLDs were removed and readout by TLD reader (Harshaw 4000,USA) at the Radiation Protection Department, NCNSRC Atomic Energy Authority, Cairo.

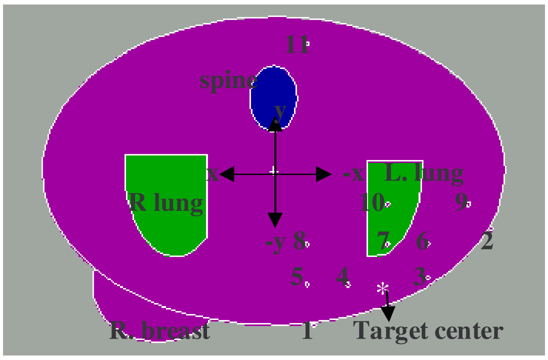

Figure 1. Horizontal section of phantom showing the position of the TLDs from number 1 to 11.

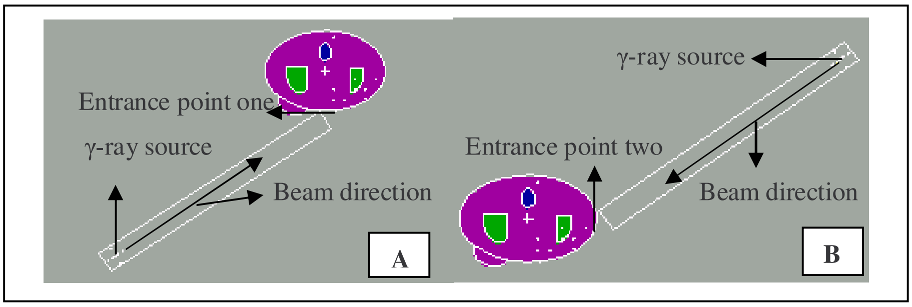

Figure 2. A: gantry angle 303° and B: gantry angle 126°

RESULTS AND DISCUSSION

In the theoretical study, the code calculates the photon flux multiplying by the dose conversion factors to give the dose in rem/hr then it converted to the dose in gray. The source direction biasing was established with high efficiency in order to guarantee that the most of radiations emitted from the Co-60 source are directed toward the target. For this reason the dose was calculated around the source in four directions at about 2.5 cm from the source.

The calculated average doses over the specified volume for some organs around the target (left) breast are shown in Table 1. It is obvious that tissues outside the treatment field are exposed to scattered radiation. For example, the non-target opposite breast received about 14.3% of the given dose. This result goes with the finding of many studies regarding dose distribution during breast radiotherapy [14,15,16]. The left lung received high dose of radiation (0.268 Gy). This is because it is included in the lateral radiation field. In this respect several studies noticed that breast radiotherapy can cause pulmonary damage [17,18]· Furthermore, Rubino *et al.,* (2005) [19] noticed that the risk of soft tissue and bone sarcoma increased after breast radiotherapy. Therefore, such risks should be considered during treatment and certain precautions, as shielding, should be done to reduce the treatment- related complications.

Table 1. Calculated average doses over the specific volume for some organs around the target (left) breast**.**

Organs	Dose (Gy) ± st. error
R. Breast	0.2864 ± 0.0025
L. Lung	0.26838 ± 0.003
Thyroid	0.21312 ± 0.005
Liver	0.13999 ± 0.0018
R. Lung	0.08907 ± 0.0035
L. Kidney	0.0782 ± 0.006
R. Kidney	0.0467 ± 0.008
Uterus	0.0331 ± 0.0178
L. Ovary	0.0181 ± 0.0427
R. Ovary	0.0167 ± 0.0419

Table 2. shows the comparison between the calculated doses and the corresponding measured data for the selected points. From the comparison it was found that the relative differences between the measured and calculated doses [(Measured–calculated)/Measured] are from –0.376 up to 0.269.

As shown in Figure 3., the calculated and the measured data are drown as a ratio relative to the given dose (2 Gy). The correlation coefficient of the calculated and measured data were carried out and are shown in Figure 4. The result revealed that the correlation coefficient R equals 0.9126, and this means that there is good agreement between the measured and calculated data.

Table 2. Comparison between the measured and the calculated doses in different places in breast radiotherapy.

Location No	Measured (Gy) ±SD	Calculated (Gy)	Relative difference
1	1.5735 ± 0.0539	2.1008	-0.335
2	1.7596 ± 0.0494	1.9597	-0.107
3	1.9451 ± 0.0131	1.9995	-0.028
4	1.9659 ± 0.0657	1.4744	0.25
5	0.9141 ± 0.018	0.9747	-0.066
6	2.85 ± 0.0087	2.36	0.0024
7	1.4386 ± 0.0146	1.5539	-0.08
8	0.3644 ± 0.0497	0.5015	-0.376
9	2.1026 ± 0.0351	1.5376	0.2687
10	0.4063 ± 0.0111	0.525	-0.292
11	0.1204 ± 0.0159	0.1593	-0.323
	R=0.9126		

It is important to point out the causes of the observed differences, in some sites, obtained from the code calculations and TLD measurements. These differences are very small for all points apart from points 1, 4 and 9. Point 1 shows a higher value for the calculated data than the measured data. This may be due to the high statistical error in this point. The dose at point 9 is the maximum reading dose at the TLD detectors (105.13% from the given dose). This is may be due to the formation of the "hot spot" or maximum target dose (which is an area outside the target that receives a higher dose than the specified target dose) [20]. This idea is supported by the fact that the hotspot is formed near this point in both code calculations and the isodose distribution estimated in the treatment planning system. However, the variations between calculated and measured dose distribution are accepted in the common practice to be in good agreement.

An essential step in the dose calculation system is to establish depth dose variation along the central axes of the irradiation beam. Figure 5. shows the comparison between the calculated, measured and Khan [20] depth dose distribution in water phantom.

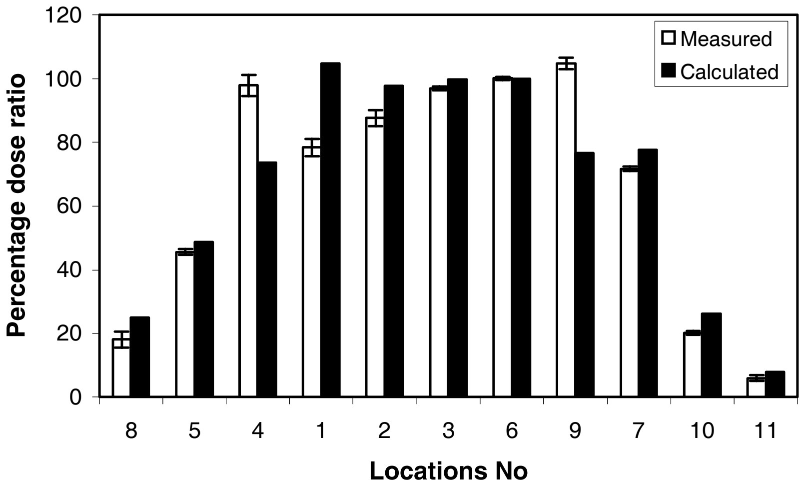

Figure 3. Comparison between the calculated and measured doses in different organs during breast radiotherapy, see Figure 1.

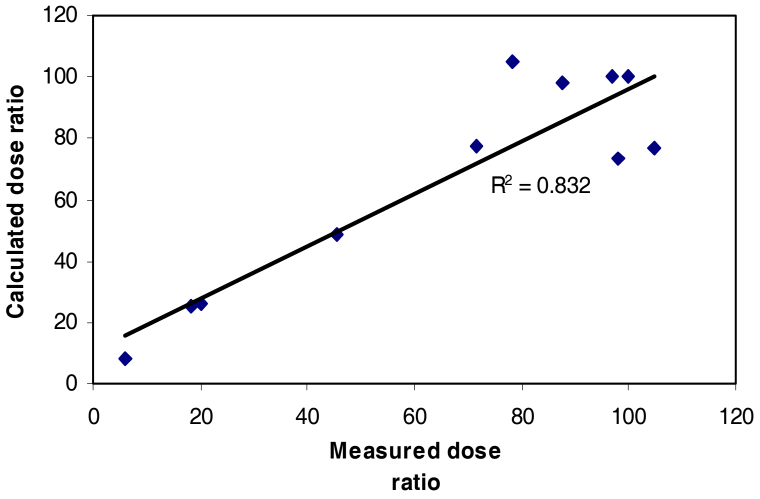

Figure 4. Correlation coefficient of the calculated and measured data.

As the beam incident on a patient (or phantom), the absorbed dose in the patient varies with depth. This variation depends on many factors: beam energy, depth, field size, distance from the source, and beam collimation system. Thus the calculation of the dose in the patient involves considerations in regard to these parameters and others as they affect depth dose distributions [20]. It is clear that the dose near 0.5 cm is the maximum value along the central beam. The build up area is clear from 0 up to 0.5 cm then the dose rate decreased rapidly with the depth inside the computational model. The comparison indicates good agreement between the compared data.

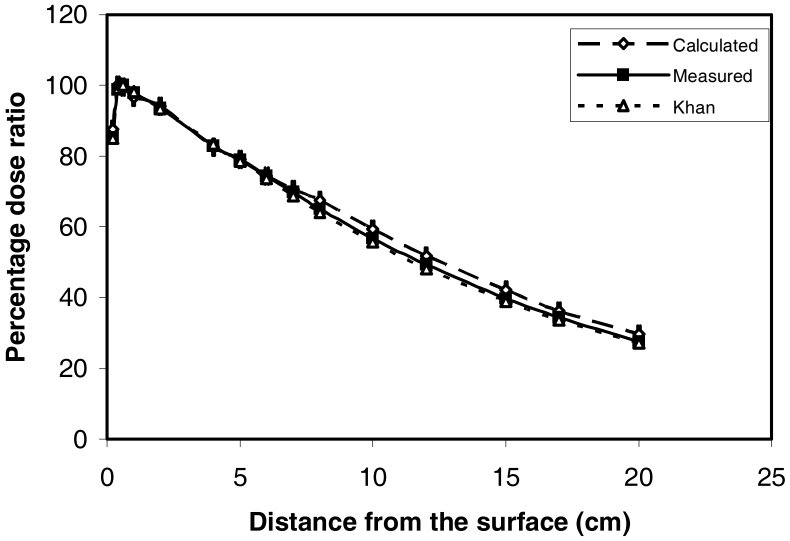

Figure 5. Depth dose distribution for ^{60}Co in water phantom. at SSD of 80 cm, and a field size of 10 *10 cm.

Quality assurance (QA) in the radiation therapy treatment planning process is essential for minimizing the possibility of undue exposure [21]. The Monte Carlo code MCNP version 4B used in this study was found to be a valid practical way of performing accurate calculations of 3-D dose distributions from particle interactions in a complex target such as the human body. This fact stemmed from the validation of the code by comparing its calculations by experimental measurements of dose distribution that showed good agreement.

CONCLUSION

The present study was initiated to measure and assess the radiation doses received by the target organ and the surrounding healthy sensitive organs in external radiation treatment of the breast. For this purpose we used the three dimensional Monte Carlo Nuclear Particles Code (MCNP-4B) along with the mathematical equations that presented the human organs to model all human body with its details. It was found that tissues outside the treatment field are exposed to scattered radiation. Therefore, such risks should be considered during treatment and certain precautions, as shielding, should be done to reduce the treatment- related complications.

In order to validate the theoretical results, MCNP calculations were compared with the measured experimental measurements. Fair agreement was found between the two sets of data. Thus, the present work provided a ready tool that accurately and fully describes radiotherapy planning system, and the theoretical model can predict the dose distribution in body organs during the treatment.

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محاكاة لتوزيع الجرعات الإشعاعية لأشعة الفوتونات الصادرة من الكوبالت-٦٠ باستخدام برنامج مونت كارلو أثناء العلاج الإشعاعي للثدي

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تهدف هذه الدراسة إلى قياس وتقويم الجرعات الإشعاعية في العلاج الإشعاعي لسرطان الثدي وذلك بعمل نموذج رياضي مكافئ لجسم الإنسان باستخدام كود MCNP-4b ثلاثي الأبعاد المعتمد على طريقة مونت كارلو .

في هذه الدراسة تم تعريض النموذج Alderson Rando المكافئ لجسم الإنسان إلى أشعة (كوبالت-٦٠) حيث متوسط طاقة الفوتونات ١,٢٥ مليون إلكترون فولت وذلك لحالة العلاج الإشعاعي لسرطان الثدي. و قد وضعت كواشف الوميض الحراري في أماكن محيطة بمركز المكان المعالج (الثدي) وتم قياس توزيع الجرعات الإشعاعية في هذه الأماكن. كما قيست الجرعات الإشعاعية في العمق على مسافات متتالية داخل نموذج مائي سعته ٨٠ سم^{٣} باستخدام (ion chamber 0.125).

قد تمت تغذية الكود MCNP-4b بكل البيانات المتبعة في عملية التشعيع لحساب توزيع الجرعات الإشعاعية في نفس الأماكن المحددة داخل النموذج المنوط بالدراسة. ثم قورنت القياسات العملية بالحسابات المعتمدة على النموذج الرياضي الموضوع المماثل لجسم الإنسان والنموذج المائي أيضا و قد وجد توافق مقبول بين النتائج العملية و الحسابات النظرية. كما قورنت بعض القياسات العملية والنظرية بتلك الناتجة من دراسات سابقة ووجد توافق بدرجة عالية.

تخلص الدراسة إلى أن الجرعات الإشعاعية الواصلة إلى بعض الأعضاء المجاورة لمكان التشعيع قد تسبب أضرار عالية مما يستلزم عمل درع واق للمريض أثناء عملية التشعيع. كما يعتبر أيضا النموذج الرياضي المماثل لجسم الإنسان أداة هامة من الممكن استخدامها لقياس توزيع الجرعات الإشعاعية داخل جسم الإنسان أثناء معالجته إشعاعيا.