Iran. J. Radiat. Res., 2003; 1(3): 143 - 149

Application of MCNP4C Monte Carlo code in radiation dosimetry in heterogeneous phantom

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ABSTRACT

Background: In treating patients with radiation, the degree of accuracy for the delivery of tumor dose is recommended to be within ± 5% by ICRU in report 24. The experimental studies have shown that the presence of low-density inhomogeneity in areas such as the lung can lead to a greater than 30% change in the water dose data. Therefore, inhomogeneity corrections should be used in treatment planning especially for lung cancer. The usual methods for inhomogeneity correction are the Tissue-Air Ratio (TAR) method, the power low tissue-air ratio (Batho) method, and the Equivalent Tissue-Air Ratio (ETAR) method. But they are not able to calculate the dose with required accuracy in all cases. New and more accurate methods are based on Monte Carlo methods. They are able to account for all aspects of photon and electron transport within a heterogeneous medium. The focus of this paper is the application of MCNP (Monte Carlo N-Particle) code in radiotherapy treatment planning.

Materials and methods: Some special test phantoms were made of cork and Perspex instead of lung and normal tissue respectively (with electron densities relative to water equal to 0.2 and 1.137 respectively). Measurements were obtained using cobalt-60 radiation for four different fields. Then the results of RTAR, Batho and MCNP methods were compared to the measurements.

Results: RTAR method has an error equal to 10% approximately. Also Batho method has an error especially in the low-density material. At least, MCNP method calculates correction factors very accurately. Its average error is less than 1% but it takes a long time to calculate the dose.

Conclusion: Monte Carlo method is more accurate than other methods and it is currently used in the process of being implemented by various treatment planning vendors and will be available for clinical use in very near future. *Iran. J. Radiat. Res., 2003; 1(3): 143 - 149*

Keywords: *Monte Carlo, inhomogeneity correction, radiotherapy.*

INTRODUCTION

A long-standing problem in radiotherapy treatment planning has been the calculation of dose distribution in a patient. In treating patients with radiation, the degree of accuracy for the delivery of tumor dose is recommended to be within ±5% by ICRU in report 24(ICRU 1976). To satisfy this recommendation, each step involved in dose delivery (machine calibration, dose calculation, acquisition of patient-specific tumor information, patient positioning, patient motion, etc) must be performed with accuracy much higher than 5%. For the important step of dose calculation in treatment planning, the necessary accuracy may be set at 2%-3% so that an overall accuracy of 5% can be attained (Cunningham 1982). The experimental studies have shown that the presence of low-density inhomogeneity in

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areas such as the lung can lead to a greater than 30% change in the water dose data (Batho 1964). Therefore, inhomogeneity corrections should be used in treatment planning especially for lung cancer (Papnikolaon *et al.* 2000). There are some inhomogeneity correction methods that can be used in radiotherapy treatment planning. However most of them are not able to calculate dose with required accuracy in all cases.

Recently, the Photon Treatment Planning Collaborative Working Group has produced a comprehensive document evaluating the role of three-dimensional treatment planning for eight different anatomical sites (PTPCWG 1991[a]). The study evaluated various feature related to three-dimensional treatment planning such as dose calculation algorithms, imaging systems, dose volume histograms, numerical evaluation and scoring in treatment planning, uncertainty analysis and inhomogeneity corrections (PTPCWG 1991[b]). Some of the main conclusions of the inhomogeneity correction evaluation were: (a) significant differences occurring mainly for the lung tumors, and less dramatically for the other sites; (b) dose corrections are higher dependency on the beam energies and geometries; (c) one-dimensional Effective Path Length (EPL) corrections despite their limitation, as the only practical options available at present; (d) large dose perturbations in regions where electronic equilibrium is disrupted, not predicted by any of the current methods used in treatment planning and remaining a major problem (PTPCWG 1991[c]).

The usual methods for inhomogeneity correction are the Tissue-Air Ratio (TAR) method (Khan 1992), the power-law tissue-air ratio method (Sontag and Cunningham 1977), the Equivalent Tissue-Air Ratio (ETAR) method (Sontag and Cunningham 1978), and Differential Scatter-Air Ratio (DSAR) method (Cunningham 1972).

Among current dosimetry algorithms for radiotherapy treatment planning, only Monte Carlo method is able to take into account for all aspects of photon and electron transport within a heterogeneous medium. So this method will be able to calculate the dose in electron disequilibrium regions (Demarco *et al.* 1998).

The Monte Carlo method provides a numerical solution to a problem obtained through modeling objects interesting together or with their environment following simple rules of interactions (Bielajew 2001). The Monte Carlo simulation of the radiation transport in an absorbing medium is the most accurate method for dose calculation in radiotherapy. Despite its accuracy, the Monte Carlo method is not widely used for treatment planning due to the long computing time, especially in the case of photon beams, to get dose results of reasonable statistical accuracy. Several Monte Carlo simulation codes are currently being tested and modified with respect to radiotherapy treatment planning calculations. Some of the more important codes are MCNP (Briesmeister 1997, Hendricks *et al.* 2000), PEREGRINE (Hartman *et al.* 1996), EGS (Nelson *et al.* 1985), ITS (Halblieb 1984), … The focus of this paper is applications of MCNP code in radiotherapy treatment planning.

MATERIALS AND METHODS

In this study, calculations using Ratio of TAR (RTAR), modified power-law (Batho) and Monte Carlo methods of inhomogeneity correction were compared with measurements in order to examine some of their abilities and limitations.

A. Monte Carlo simulation

We employed the Monte Carlo code system MCNP for the simulation. MCNP is a general purpose Monte Carlo N-Particle code that is used to calculate coupled neutral / charged particle code. This code uses a three-dimensional heterogeneous geometry and transports photons and electrons in the energy range from 1 KeV to 100 MeV. Low energy phenomena, such as characteristic x-ray and Auger electrons, are also accurately modeled. MCNP requires the source for a particular problem to be specified in a user-defined input file. The source includes distributions of the position, energy and angle of starting particles. In this study we used of 4c version that was released in 1999. The results of

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MCNP were benchmarked with standard depth dose and profile measurement. Four field size were tested; 6×6, 10×10, 15×15 and 20×20 cm^2. The depth dose calculations utilized a cylindrical tally cell with a grid spacing of 2 mm along the beam central axis and a cylinder radius based upon one-tenth the size of open field. This produced a tally radius of 6, 10, 15 and 20 mm for the 6×6, 10×10, 15×15 and 20×20 cm^2 field size respectively. The photon and electron low-energy cutoff was 0.01 and 0.5 MeV respectively for the Monte Carlo calculation. For decrease of statistical error about 100 million photons were simulated. It takes about 12 hours by a Pentium III (CPU 866 MHz) computer.

B. Phantoms

Some phantoms were designed for this study. These phantoms were made of Perspex and cork slabs. Their dimensions were 30×30 cm^2 and with various thicknesses. The Perspex and cork slabs had electron densities relative to water equal to 1.13 and 0.2 respectively. Also Perspex and cork had mass densities 1.175 gr/cm^3 and 0.21 gr/cm^3 respectively. The real lung had various mass densities in any case and it differed from 0.05 to 0.35 gr/cm^3. A hole was drilled in one of them to fit exactly the cylindrical chamber dimensions. Figure (1a) represents the simple heterogeneous phantom and beam passed through one lung equivalent. Figure (1b) is a simple simulation of chest lateral and beam passed through the two lungs equivalent. In order to investigate the influence of lateral scatter, phantom shown in figure (1c) was designed.

C. Dose measurement

Measurements have been made using radiation from a cobalt unit with a source to surface distance (SSD) of 80 cm. The cobalt unit was Teratron 780 model. The dose values were measured by using a Farmer cylindrical ionization chamber with a nylon wall coated with graphite and a cavity volume of 0.6 cm^3. The chamber was connected to an electrometer. Measurements were done for four field sizes; 6×6, 10×10, 15×15 and 20×20 cm^2. The experimental inhomogeneity correction factor for each point was taken as the ratio of readings with and without the presence of the inhomogeneity with the same geometric conditions. Uncertainties of the correction factors were related to geometrical set-up. It can be estimated to be around 0.5%.

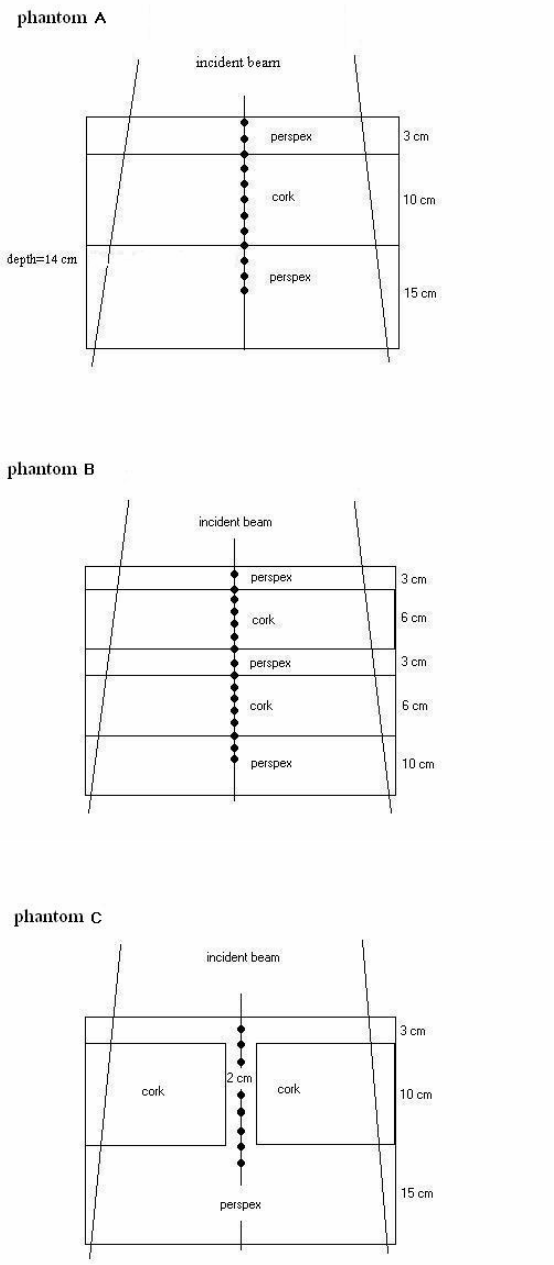


Figure 1. Diagrams of phantoms designed for investigate inhomogeneity correction factor. All dimensions are shown on diagrams.

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RESULTS

The results for the different phantoms are reported in figures (2, 3 and 4). In each phantom correction factors were calculated by four methods for points located on the beam axis as a function of depth. On the other hand, in order to investigate the effect of field size on correction factors, they were calculated for four different field dimensions. Results for phantoms 1a and 1b are illustrated in figures 2 and figures 3 respectively. Clearly Monte Carlo method is more accurate than other methods in all field sizes. RTAR method can calculate correction factor as inaccurate method and this method overestimates correction factor in most points. Batho method, in small field size, can calculate correction factor very accuracy but in a large field and in low density material underestimates correction factor. Results for phantom 1c are illustrated in figures 4. In this phantom effect of lateral inhomogeneity on correction factor were investigated. Clearly RTAR and Batho methods cannot take into account it, so both RATR and Batho methods calculate correction factor equal to one. But Monte Carlo is able to take into account effect of lateral inhomogeneity correction factor because this method is a three dimensional method. The results show that Monte Carlo method also can calculate correction factor in this case very accurately.

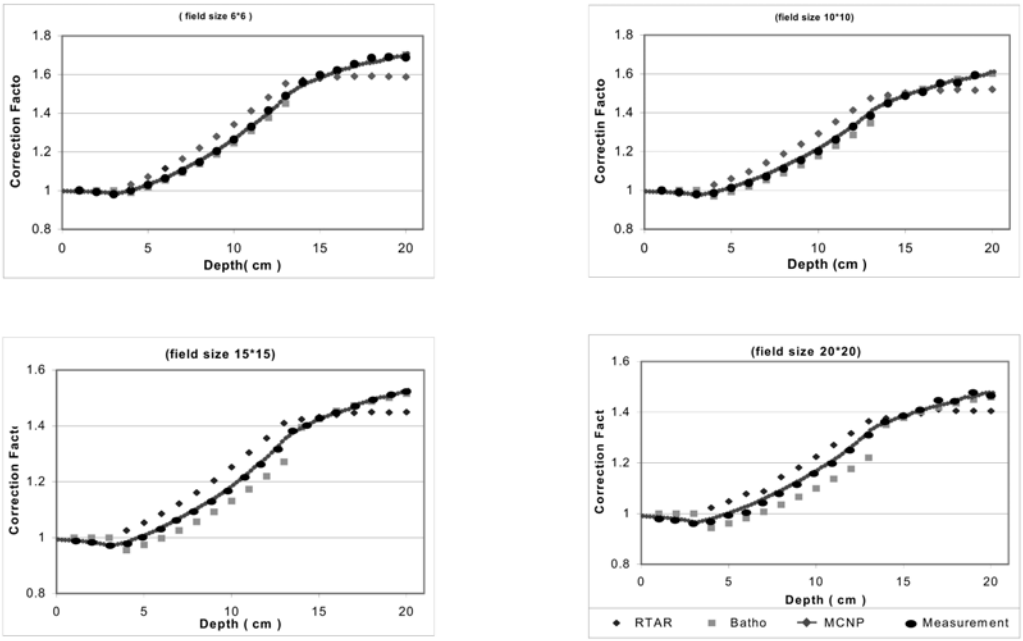


Figure 2. Comparison between correction factors calculated by different inhomogeneity correction methods and measurement for phantom (1a) for four field sizes.

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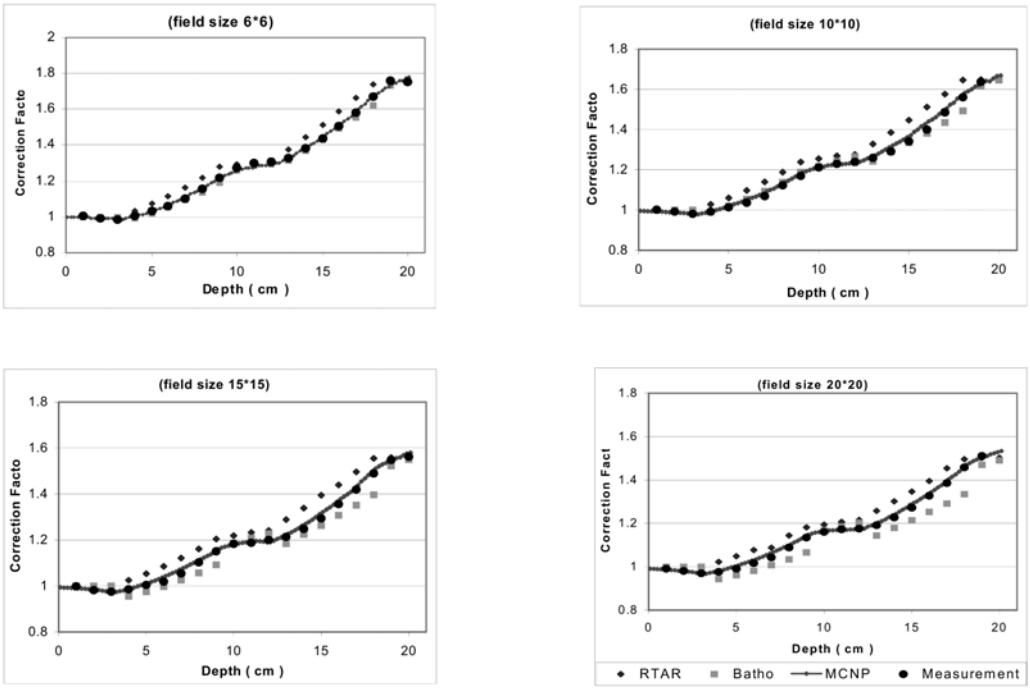


Figure 3. Comparison between correction factors calculated by different inhomogeneity correction methods and measurement for phantom (1b) for four field sizes.

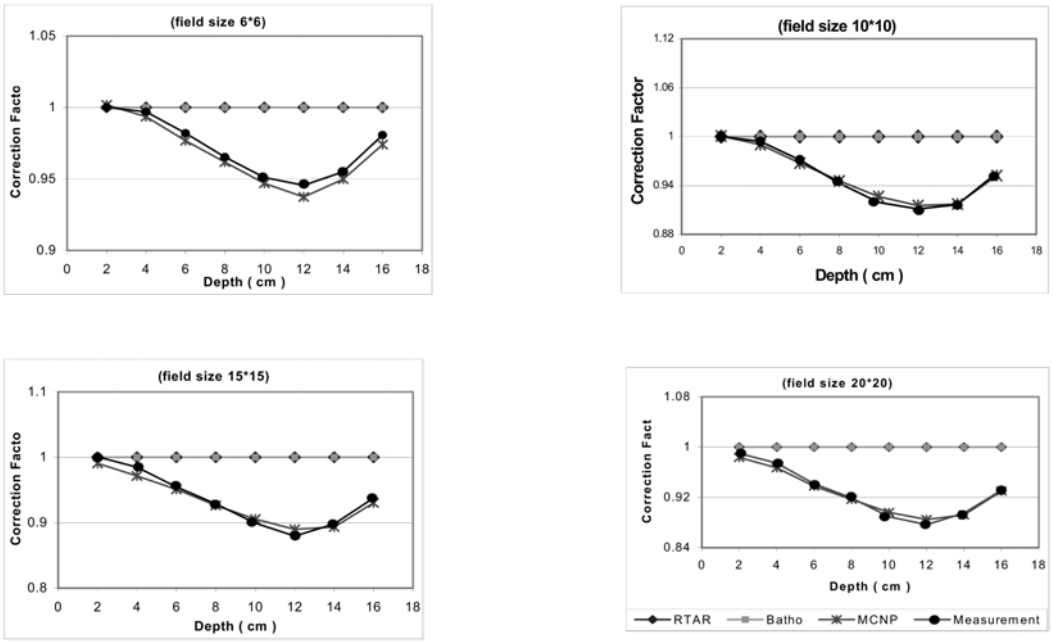


Figure 4. Comparison between correction factors calculated for lateral inhomogeneous by different inhomogeneity correction methoda and measurement for phantom (1c) for four field sizes.

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DISCUSSION

The results were analyzed from comparing calculations with measurements. The RTAR method in all field sizes had errors sometimes larger than 10% even for the simple situation (phantom 1a). This method overestimates correction factor in low density material and after inhomogeneity (with low density), it calculated correction factor almost constantly and it became smaller than real value. The RTAR method is a one-dimensional method and only models changes in the primary photon fluency. Therefore this method does not take into account the lateral inhomogeneities effect nor its position with respect to the point of calculation. In the near material interfaces there were not electron equilibrium and dose distributions were perturbed because of scatter and backscatter radiation. The RTAR method cannot calculate correction factor accurately in the near material interfaces and clearly after interface (depth equal to 3 cm), correction factor increased immediately and it was larger than 1.

The Batho method calculations provided better results than RTAR. It took into account one more factor, namely, the position of inhomogeneity with respect to the point of calculation. In this sense the configuration of scattered photons was considered. This method in small fields is an accurate method for points located on beam central axis. But with increasing field dimension, the accuracy of Batho method decreases, especially into low density material. It always underestimates correction factor in low density material and it has a benefit for this method; because, for example, as seen in figures 2 and 3 for points just inside the low density material the Batho correction factor drops below 1.0 as experiments confirm this behavior. While the previous mentioned method (RTAR) predicts correction factor greater than 1.0 in low density regions. The Batho method predicts a discontinuity in the dose that must not be real. This can be seen, for example, by considering points that are not overlain by an inhomogeneity. A correction factor of 1.0 is predicted, yet there must be a reduced amount of scatter coming from the low density region immediately beyond. It means no backscatter radiation originating from the material below the point is taken into account. This is observed in the experimental determination, as shown in figures 2 and 3. There is a similar discontinuity at the bottom of the low density region, where there are photons scattered back from the high density region below it, and this is not taken into account either. This can especially be seen in large field sizes in figures 2 and 3. This method only considers the material above the calculation point but does not consider the lateral inhomogeneities. As mentioned before no backscatter radiation originating from the material below the point is taken into account, then in the near material interfaces, Batho method is erroneously used to estimate correction factor.

Finally at last, Monte Carlo method is very accurate in all field dimensions and in all cases. This method is a three-dimensional method and it simulates all aspects of photon and electron transport in a medium. It also considers the lateral inhomogeneities effects on correction factor. In the lateral inhomogeneity case, with increasing of field size, correction factor decreased (less than 1.0) because in heterogeneous phantom less scatter ray reached to interest point on central axis beam relative to homogeneous phantom, so correction factors became more important. Only the Monte Carlo method can take into account the loss of electron equilibrium near interfaces between dissimilar structures. Undoubtedly it should be, the most accurate method discussed, but its application requires the generation of enormous number of photon histories and it takes a longer time. Then its application for treatment planning has not been practiced with present-day technology because the speed of today's computers are not enough to do it in a clinical routine time but it is currently used in the process of being implemented by various treatment planning companies and will be available for clinical use in the near future.

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ACKNOWLEDGEMENT

The authors would like to thank Medical Physics Group of Tehran University of Medical Sciences for valuable discussions throughout this study and staff of radiotherapy center of Imam Hospital. The authors are also grateful to SSDL center of Atomic Energy Organization of Iran for providing the phantoms.

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