Head Modeling for Monte Carlo Dose Estimation in Diagnostic Radiology

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Abstract- A model for dose estimation to parts of a head in diagnostic radiology, based on Monte Carlo technique, is presented. It can be adapted to any type of x-ray examination. The absorbed dose per unit kerma in air during conventional x-ray examination for different parts of a head has been analyzed. Numerical experiment has been performed for mathematical model of head based on ADAM phantom and x-ray spectrums of various qualities (60-80 kV).

INTRODUCTION

The x-ray examinations of skeletal system are one of the most frequent medical x-ray examinations. Head and head bones are x-rayed in the presence of anti-scatter grid. Focus to film distance ranges from 80 cm to 100 cm, exposure time is measured in seconds and field size in the image receptor plane is 24x30 cm

Depending on the type of x ray generator, the loading factors range from 60 to 80 kV and from 40 to 120 mA. The appropriate choice of loading factors implies good image quality as well as acceptable dose level for exposed organs [1].

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The last few decades have seen increasing interest for examination of harmful effects of radiation on human tissues. This has imposed to greater need for quantification of radiation dose to patient in diagnostic radiology. The appropriate quantity for this purpose is the effective dose, which implies determination of the doses to critical organs. Since this cannot be obtained in real patients, the most common method is determination of the patient entrance surface dose (by measuring with thermoluminescent dosimeters or calculating from the output of the x ray unit) and dose-area product. This approach is more closer to quality control of the process of obtaining diagnostic image than information about detriment brought to patient. In an attempt to overcome this problem, Monte Carlo techniques for dose estimation to organs have been developed.

In this paper a method for dose estimation for different parts of a head is presented. The method, based on Monte Carlo technique, is integrated in a flexible software capable to estimate the absorbed dose when possibility of application of other actual methods does not exist [2].

Software package FOTELP can be generalised for any medical x-ray examination or view. It has been developed for photon, electron and positron transport for numerical experiments in dosimetry, radiation protection, radiotherapy, for absorbed dose distribution determination in organs and tissues, etc. Programs from this package work in 3D geometry with optional particle spectrums from 1 kev to 100 MeV, in solid angle of 4π. The geometrical configuration of the irradiated object can be described using planes and second order surfaces [3].

METHOD OF CALCULATION

A. Mathematical model of the head

The skull x-ray examination in latheral projection using software package FOTELP was simulated. As a result of a compromise between accuracy and computer resources a mathematical model of head was constructed. The orientation of the mathematical model in three-dimensional space is given by cartesian coordinates, whose origin is situated at the center of the head. To describe parts of the head we used the following expression for geometrical objects:

\[ \alpha \left( \frac{x-x_0}{a} \right)^2 + \beta \left( \frac{y-y_0}{b} \right)^2 + \gamma \left( \frac{z-z_0}{c} \right)^2 \leq 1 \]  \hspace{1cm} (1)

where \( \alpha, \beta, \gamma \) and \( a, b, c \) are constants that may take the values 0 or 1 and determine the type of organ geometry. The boundary surfaces of geometrical object are centered at the point \((X_0, Y_0, Z_0)\) while \( a, b, c \) are sectors in positive and negative directions \( x, y, z \), respectively. The ellipsoids are concentric for the center of the coordinate system. These geometrical forms characterize six anatomic regions (brain, skull, jaw, skin and eyes) consisting of four different materials (brain, bone and soft tissue and skin) of appropriate chemical composition. The parameters in equation (1) are chosen that dimensions of mathematical model represent the dimensions of reference man (see Table I).

| Table 1 | Values of the parameters describing the geometrical objects of the mathematical model of the head |
Mathematical model of head is based on the ADAM phantom [2]. It consists of three ellipsoids, two half ellipsoids (defined for y<0) and two 1x0.5x2 cm³ parallelepipeds (see Fig. 1).

For the purpose of dose estimation, the mathematical model of the head was embedded in a 36 cm edge virtual cube. The cube was divided into 2x2x2 cm³ voxels.

FOTELP includes program module RFG that allows modular geometric description of space occupied by geometrical zones used in numerical experiment. Input data for RFG module have to be noted according special algorithm [4].

B. Numerical experiment

Software package FOTELP is very flexible and allows modifications of actual experiment conditions varying dimensions and forms of radiation source and relative position of beam to irradiated object. In photon transport, in our case, the following processes are considered: photoelectric absorption, Compton scattering and coherent scattering [3]. The atom relaxation in six atom shells, the Auger electron and fluorescent photon creation are treated after photoelectric absorption and ionization. Considering actual photon energy range and low Z materials, we concluded that pair creation and delta electrons and bremsstrahlung productions should be neglected.

![Fig. 1. Schematic representation of the mathematical model of the head in plane Y0Z.](image)

The exact x-ray spectrum in real conditions as hardly known, so we used calculated polyenergetic beams for the numerical experiment [5].

The main characteristics of the used beams are presented in Table 2. The spectrums are generated with tube potentials from 60 kV to 80 kV and tabulated in histogram form at interval of 1 keV.

The rectangular crossection incident beams were perpendicular to XOY plane with beam axis collinear to z-axis, passing trough the center of the mathematical model of the head. Radiation field size was 24x30 cm². Backscatter radiation from the cassette holder was not taken into account, since the intensive attenuation in the left side of the head (the side which is facing the beam).

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>c</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
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<tr>
<td>brain</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>8.4</td>
<td>8.4</td>
</tr>
<tr>
<td>skull</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>9.5</td>
<td>9.5</td>
</tr>
<tr>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>10.5</td>
<td>11.0</td>
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<tr>
<td>1st</td>
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<td>10.0</td>
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<td>7.8</td>
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</table>

| 60 kV | 2 mm Al | 0.125 | 122.7 | 36.3 | 1.94 |
| 70 kV | 2 mm Al | 1.191 | 113.7 | 39.0 | 2.36 |
| 80 kV | 2 mm Al | 2.267 | 128.6 | 40.7 | 2.52 |
| 65 kV | 2.5 mm Al | 2.654 | 144.1 | 42.5 | 2.69 |
| 75 kV | 2.5 mm Al | 0.125 | 122.7 | 36.3 | 1.94 |

| | 90 kV | 2 mm Al | 0.125 | 122.7 | 36.3 | 1.94 |
| | 1.191 | 113.7 | 39.0 | 2.36 |
| | 2.267 | 128.6 | 40.7 | 2.52 |
| | 2.654 | 144.1 | 42.5 | 2.69 |

| 1st | 0.125 | 122.7 | 36.3 | 1.94 |

Statistical errors in dose estimation can be constrained by increasing the number of followed photon histories. To reach the optimal relation between accuracy and required CPU time, the simulation was carried with 5·10⁵ photon histories. Cutoff energies were 5 keV for photons and 10 keV for electrons and positrons.

RESULTS

Five numerical experiments with 5·10⁵ incident photons and different beam qualities were performed. For 70 kV x-ray beam the simulation was carried for 10⁵ incident photons. Depending on computer characteristics and incident photon number the total CPU time for one simulation ranged from 200 to 800 min. All numerical experiments were performed on minimum 200 MHz, Pentium, 32 MB RAM computer. It may be concluded that the value of CPU time depends on complexity of geometrical configuration of irradiated object.

Monte Carlo calculation of photon transport through mathematical model of the head was used to estimate absorbed dose per slice in beam direction and equivalent doses per unit kerma in air in head parts (material zones). FOTELP provides the total absorbed energies in all material zones for defined incident photon number. The mean equivalent dose in all material zones was calculated using values for absorbed energy per photon and masses of material zones. Dividing equivalent dose values by kerma in air on the entrance surface (see Table 2) we obtained the values for equivalent dose per unit kerma at the entrance surface H/Kₑ (mSv/Gy) versus tube potential. Also, applying the real loading factors to calculated doses per photon, the dose to patient’s head parts can be obtained.

The absorbed dose per incident photon along the beam axes is shown on Fig. 2. Slices are perpendicular to the beam axis and their thickness is 2 cm. Intensive absorption in bone tissue (jaw and skull regions between 10 and 12 cm from virtual cube edge) can be noticed.

On Fig. 3 the absorbed dose distribution in XOY plane which crosses the mathematical model of the head in the left eye level (z=-2). The slice
thickness in z direction is 2 cm. On Fig. 4 is presented the aside distribution in X0Z plane, which crosses the mathematical model of the head in the level of both eyes (y=-9.5). The slice tickness in y direction was also 2 cm. Fig. 5 presents the equivalent dose per unit kerma in air at the entrance surface versus tube potential, for different head parts. Lower values in the inner region (brain) are due to intensive absorption in bone tissue in the outer parts (jaw and skull). This implies more critical doses to left eye than the right one.

Concerning available computer resources simulations were not performed for incident number of photons higher than $10^6$. Statistical errors, so, were estimated to 2.5% for jaw, skull and skin regions, 5% for brain and up 50% for eyes. The pour statistic is due to the insufficient number of photon interactions in particular material zones (eyes).

![Fig. 2 Absorbed dose per photon along the beam axes](image)

**DISCUSSION**

The results obtained by simulation the lateral x-ray skull examination reveal the physical reality of low energy photon interaction with biological materials. Literature data, based on Monte Carlo methods, are available in table form for limited number of projections, loading factors, field sizes and focus to image receptor distances and different organs [6]. The direct comparison these values with our calculations was not possible, so we compared our result with interpolated table values for few organs exposed to primary beam and scattered radiation. The comparison showed the same order of magnitude.

![Fig. 3 3D absorbed dose distribution in X0Y plane (perpendicular to beam axes) of the mathematical model of the head at left eye level, slice tickness 2 cm along the z axis, 70 kV x-ray beam](image)

Correct validation would be possible only by results of experimental measurements under the same conditions as performed numerical experiment.

![Fig. 5 Equivalent dose for head parts per unit kerma at the entrance surface versus tube potential](image)

The abilities of the software package FOTELP are confirmed in previous papers by comparing the numerical experiment results with experiment measurements [7]. It is basis for statement that Monte Carlo is a method of choice when experimental conditions and analytical approaches are limited.

**CONCLUSION**

In view of the results, we can conclude that Monte Carlo can be successfully used for medical x-ray examination simulations. Software package FOTELP application enables fast and effective dose estimation in different parts of the head. Also, mathematical modeling of any organ could be improved from simple to complex algorithm using a
new program module for description of geometrical configuration. The advantages of described approach are in flexibility by adapting the numerical experiment condition to actual needs. In order to achieve optimal estimations, this method is more manageable than standard methods based on table values.

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REFERENCES