Modelling Dental X-ray Examinations for Assessment of Radiation Doses to Patients

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***Abstract*—**The work is connected with modelling dental radiographic examinations for evaluating absorbed and effective doses to patients. The X-ray set model with the source of radiation and the models of irradiated objects (the reference voxel phantoms of an adult male and female) were constructed. Monte Carlo simulation of X-rays transport in the patient body during dental radiography was performed. Radiation doses to organs and tissues and effective doses for different types of dental examinations and features of X-ray tube were obtained.

***Keywords*—** Dental radiography, Monte Carlo method, radiation doses, voxel phantoms, X-ray tube.

I. Introduction

Currently X-ray examinations became the leading and widely used method in identifying many dental system diseases. The tendency of fast dental radiology development causes to treat with special attention to observance of radiation safety during dental examinations. For example, medical exposure is the second most important source of irradiation after natural sources for the population of Belarus. Meanwhile its contribution to the radiation exposure of the population is almost entirely formed by diagnostic and preventive medical examinations embracing all age groups [1].

In this context the problem of determining the radiation burden to patients from medical X-ray examinations becomes of current interest. And there exist a very convenient tool for comparing different exposure methods and procedures. It's the effective dose proposed by the International Commission on Radiological Protection (ICRP) at a modified interpretation [2].

In practice radiologists receive the effective dose to a patient using special tables that in very common form take into account the impact on dose from X-ray unit model, procedure type and X-ray field dimensions. But in recent years new types of X-ray sets are widely used in dental practice. They have different workload, various anode voltage and different radiation output. Thus revising these tables, reassessing radiation field distribution and preparing more reliable dose estimations are required. Also all these new data must be received considering exposure séance parameters, radiation output and patient anthropometric characteristics.

As it is rather difficult or in most cases impossible to estimate doses to patient organs and tissues then the only appropriate way of evaluating these doses is modelling the exposure procedure. The simulation allows receiving the distribution of absorbed and equivalent doses in human body, estimating the effective dose for particular examination type and exposure set, or determining desired X-ray set parameters combination.

In this work the Monte Carlo method was applied to simulate the X-ray radiation transport in the environment. Currently method Monte Carlo is widely used for dosimetry of radiological examinations in medicine [3]. There are some computer codes (EGS, MCNP, FLUKA, GEANT, etc.) that implement method Monte Carlo for solving the task of various particles transport in different media [4-7]. These programs require such input data as the X-ray source model and the irradiated object model for calculating doses in the human body.

Thus all work connected with estimating doses to patients from dental X-ray examinations can be divided into several stages:

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1. Development of a diagnosis dental X-ray set model with a source of radiation;
2. Constructing human body model taking into account the geometry of exposure;
3. Calculation of the absorbed dose distribution in patient's body and determining the effective dose with Monte Carlo method.

In this work the software MCNP (Monte Carlo N-particles Transport Code, Los Alamos National Laboratory, USA) version 4B was used for Monte Carlo modelling.

II. Dental X-ray Set Model

The important element of modelling is obtaining radiation spectrum of X-ray set. Nowadays there are three basic directions of radiation spectrum measuring, modelling and calculating: experimental methods, theoretical methods (Monte Carlo simulation) and semi-empirical methods [8]. Each of these techniques has its advantages and disadvantages, but the Monte Carlo method provides more appropriate results primarily because it uses realistic representation of radiation interaction with matter and detailed description of problem geometry.

Unfortunately, it is difficult to implement the detailed X-ray tube model because of the lack of manufacturer detailed information about tube constituent elements and their material composition. Furthermore, simulating such a model takes much computer time as it takes into account all physical processes included in generation of bremsstrahlung radiation although most of them will not be used for final spectrum. Therefore, the X-ray emitter was modelled by a point source with predetermined energy spectrum in this work.

To obtain the X-ray tube energy spectrum the TASMIP (Tungsten Anode Spectral Model Interpolating Polynomials) model was used. It is considered to be the most appropriate one for modelling typical X-ray examinations using X-ray tube with a tungsten anode that operates in the anode voltage range from 30 to 140 kV [9]. TASMIP model based on polynomial interpolation of experimentally measured emission spectra of X-ray tube with a tungsten anode actually acts as X-ray tube model as it considers spectrum dependence on the anode voltage, ripple and total filtration.

The model of typical X-ray set comprising TASMIP was developed with the help of MCNP and Mathematica. This model does not require simulating the X-ray tube internal structure and operation mode but nevertheless it takes into account:

- anode voltage (V);
- total beam filtration (d);
- beam size;
- distance from radiation source focus to the surface of the irradiated object (FSD);
- anode voltage ripple;
- characteristics of the forming system.

The necessary spectra were obtained by setting definite anode voltage, filter thickness and ripple.

All dental X-ray sets use systems that form the field of irradiation. Usually it is a lead director cone with a round or rectangular diaphragm at the end. 20 cm or 30 cm director cones are often used in modern dental X-ray sets. They form either a round field having a diameter of 6 cm or a rectangular field with dimensions (3-3.5) cm × (4-4.5) cm on a flat surface. In this work simulation was performed for the X-ray set having a tube with director cone length of 20 cm and forming a rectangular field of 3 cm × 4 cm.

III. Model of the irradiated object

As mentioned above the MCNP program requires a computational model of human body (phantom) with detailed description of the internal structure, organs positions, tissues density and composition for calculating the absorbed dose distribution in the human body.

According to the ICRP recommendations one should use the reference voxel adult male and female phantoms for dosimetric calculations [10]. These phantoms correspond to standard anatomical data presented in ICRP Publication 89 [11].

The voxel phantom is a computer model of the human placed in a rectangular parallelepiped and divided into equal-size cells (voxels). Each voxel has a number that attributes it to a particular organ or tissue. Voxels that do not belong to phantoms are filled with air. The reference phantoms contain more than 140 different structures, which consist of 50 types of tissues. It allows achieving maximum conformity to the reference individual not only in organs shape and location but also in chemical composition of organs and tissues. There are more than 14 million voxels in the female voxel phantom. Voxel dimensions are 1.78 mm × 1.78 mm ×4.8 mm. The male phantom contains more than 7 million voxels having a size of 2.14 mm× 2.14 mm × 8 mm.

These reference phantoms were found to be too detailed for modelling dental X-ray examinations. Therefore, the phantoms adjustment to the MCNP code was made, i.e. the part of phantom that was directly within the radiation field and the penumbra region located at a distance of 20 cm from the field edge was included into the irradiated zone (see Fig. 1).

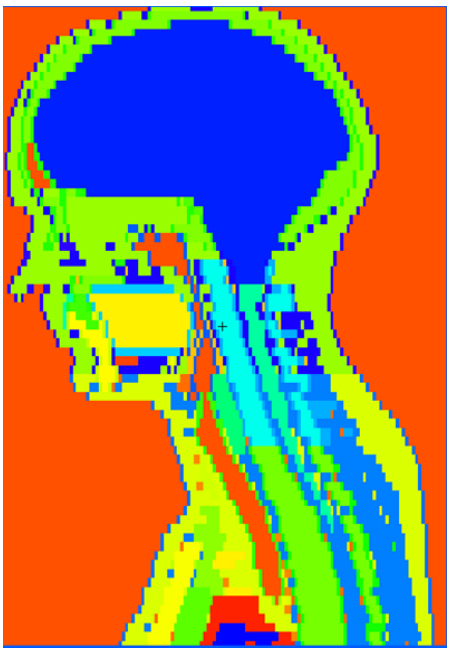

Fig. 1 The phantom part located within the radiation field and the penumbra region

As mandible and maxilla teeth were not distinguished in the voxel phantoms, it was necessary to modify these phantoms by performing separation of the teeth. For this purpose, the images of transverse sections that passed through the bite plane of male and female phantoms were obtained using the MCNP code. Then the jaw curve points array was obtained with the help of GetData software. These points were processed by a specially developed program in Mathematica. This program segregates the teeth of mandible and maxilla using biometric data on the adult patient average teeth size.

IV. Geometry of exposure

For obtaining an undistorted tooth image on an X-ray field it is necessary for radiologists to abide two following techniques for intraoral examinations: the bisecting angle technique (isometric technique) and the tangent technique. Therefore, these two techniques must be taken into consideration during simulation.

Thus, in this work the source position and the central beam direction were chosen in such a way that the central beam could hit perpendicularly the plane dividing the angle between the tooth axis and the radiographic field plane (the isometric technique). Simultaneously, the central beam was directed toward the tangent to the targeted tooth arc (the tangent technique). In this case the upper teeth roots were projected on the Camper plane while the lower teeth roots were projected on the plane located 0.5 cm above the lower jaw edge [12].

In order to apply the tangent technique envelope curves were plotted to each dental arch (for the mandible and the maxilla). Then normal to the middle of certain tooth was drawn (see Fig. 2).

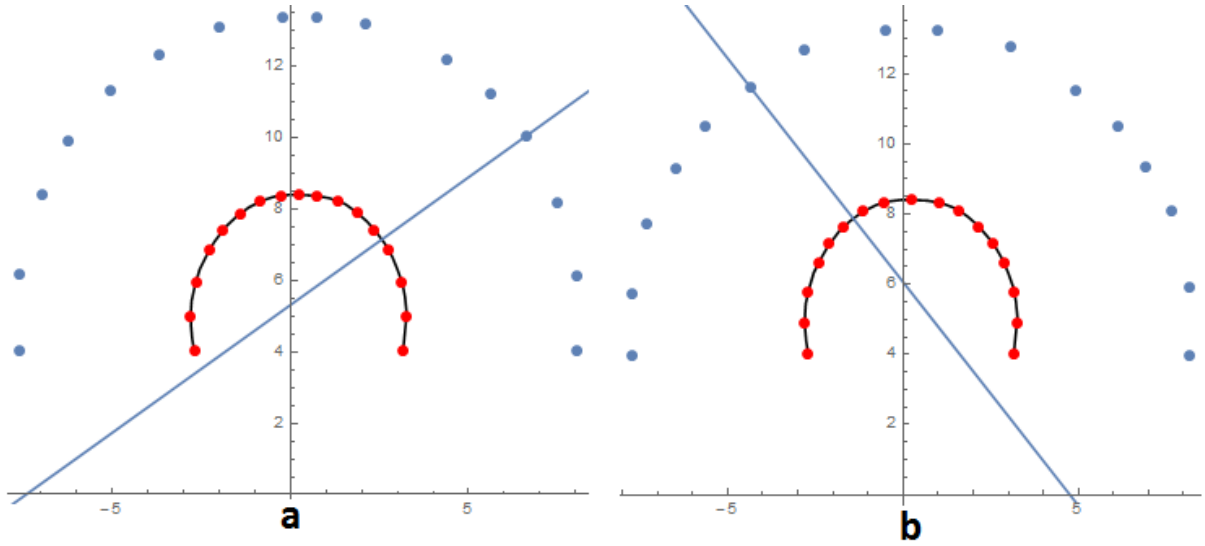

Fig. 2 The tangent technique applications for the mandible teeth (a) and the maxilla teeth (b) of the female phantom

The equations that describe the Camper plane and the corresponding plane for the mandible were derived to apply the isometric technique. The inclination angles of these planes to the horizontal plane were calculated. The direction of the central X-ray beam was chosen so that the beam could be normal to the tangent and form the proper angle (see Table 1) with a certain plane.

TABLE I
Inclination Angles for Intraoral Contact Radiography [12]

Teeth	Maxilla	Mandible
Incisors	+55°…+65°	-20°
Canines	+45°	-15°
Premolars	+35°	-10°
Molars	+25°…+30°	-5°…0°

V. METHODOLOGY OF CALCULATING RADIATION DOSES

Calculating the effective dose and radiation doses to organs and tissues was performed in accordance with the ICRP recommendations [2].

In order to find the absorbed dose to an organ or a tissue, the dose values obtained with the help of MCNP were summed up and averaged over the organ or tissue volume

$$\overline{D}_{T,R} = \frac{\sum_{i=1}^{N} D_{i,T}}{N_T}, \tag{1}$$

where $D_{i,T}$ is the value of the absorbed dose in the *i*th voxel of the organ/tissue *T*; N_T is the number of voxels in the organ/tissue *T*.

The equivalent dose H_T to an organ or a tissue is numerically equal to the average absorbed dose $\overline{D}_{T,R}$ as the weighting factor for X-rays is $w_R = 1$

$$H_T = \sum_R w_R \cdot \overline{D}_{T,R}\,. \tag{2}$$

The effective dose *E* was calculated using average values of sums of equivalent doses to organs and tissues of the reference male and female

$$E = \sum_T w_T \cdot \left[\frac{H_T^M + H_T^F}{2} \right], \tag{3}$$

where w_T is the weighting factor for the organ/tissue *T*; H_T^M is the equivalent dose to the organ/tissue *T* of the reference male; H_T^F is the equivalent dose to the organ/tissue *T* of the reference female.

TABLE II
RECOMMENDED TISSUE WEIGHTING FACTORS [2]

Tissue	w_T	$\sum w_T$
Bone marrow (red), colon, lungs, stomach, breast, remainder tissue	0.12	0.72
Gonads	0.08	0.08
Bladder, esophagus, liver, thyroid	0.04	0.16
Bone surface, brain, salivary glands, skin	0.01	0.04
	Total	1

Remainder tissues: adrenals, extrathoratic region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate (only for male), small intestine, spleen, thymus, uterus/cervix (only for female).

It is worth noting that the equivalent doses to the organs and tissues from the remainder tissues category should be calculated according to [2] as

$$H_{other}^M = \frac{1}{13} \sum_T^{13} H_T^M \tag{4}$$

and

$$H_{other}^F = \frac{1}{13} \sum_T^{13} H_T^F \tag{5}$$

where *T* is a remainder tissue from Table 2.

As MCNP gives all simulation results per one emitted particle it is necessary to multiply the result by the number of emitted gamma-quanta to obtain real values of doses. As a result, the average radiation dose to the organ/tissue T ($\overline{D}_T$) is determined by the expression

$$\overline{D}_T = 2\pi \cdot \left(1-\cos\left(\frac{\theta}{2}\right)\right) \cdot R^2 \cdot \left[\frac{R_0}{R}\right]^2 \cdot N_\gamma \cdot \overline{D}_{T,R}, \frac{Gy}{mA \cdot s} \tag{6}$$

where $\overline{D}_{T,R}$ is the average value of the absorbed dose obtained by MCNP, $\left(\frac{Gy}{photon}\right)$; $N_\gamma = \int \Phi^*(E,d,V,\zeta)\,dE$ is the flux of gamma-quanta produced by TASMIP at a given distance R , voltage V, filtration d and ripple ζ and normalized to 1 A, $\left(\frac{photon}{mA \cdot s \cdot mm^2}\right)$; $\Phi^*(E,d,V,\zeta)$ is the interpolated function of the TASMIP source, $\left(\frac{photon}{mA \cdot s \cdot mm^2 \cdot keV}\right)$; $R_0 = 100cm = 1000mm$ is the distance at which TASMIP spectra are given; R is the distance between the source and the irradiated surface, (*mm*); θ is the angle of the cone with the vertex at the focus and circumscribed around the field of radiation, (°); $2\pi \cdot \left(1-\cos\left(\frac{\theta}{2}\right)\right) \cdot R^2$ is the surface area of the cone base at the distance R from its vertex, (mm^2).

In expression (6) the correction factor η should be introduced for a rectangular field with dimensions of a and b:

$$\eta = \frac{4 \cdot a \cdot b}{\pi \cdot (a^2 + b^2)}. \tag{7}$$

The result of calculating doses according to (6) is given per 1 mA and thus it cannot be used for estimating the effective dose from a particular X-ray set as this value does not include the specific characteristics of this set. Therefore, for calculating the effective dose E the following expression is used in practice [13]:

$$E = R \cdot I \cdot t \cdot K_e, \tag{8}$$

where R is the radiation output of the X-ray tube, $\left(\frac{mGy \cdot m^2}{mA \cdot s}\right)$; I is the X-ray tube current, (*mA*); t is the exposure time, (*s*); K_e is the conversion coefficient from the radiation output of the X-ray tube to the effective dose, $\left(\frac{\mu Sv}{mGy \cdot m^2}\right)$. The coefficient K_e takes into account a type of X-ray examination, the irradiation projections, field size, focus distance and anode voltage of the X-ray tube. This conversion coefficient is determined dividing the effective dose value by the radiation output.

The radiation output of the X-ray set is calculated by means of the absorbed dose (or air kerma) multiplying by a squared distance of 1 m and dividing by the exposure setting 1 mA·s. This absorbed dose (or air kerma) is measured in free air on the primary X-rays beam axis at a distance of 1 m from the X-ray tube focus for a given anode voltage [13].

The radiation output for the TASMIP spectrum can be obtained using the following formula

$$R_{TASMIP}(d,V,\zeta) = \frac{R_0^2}{R^2} \int_{E_1}^{E_2} \Phi^*(E,d,V,\zeta) \cdot F(E) \cdot dE \tag{9}$$

where *F(E)* is the function that converts the flux to the kerma [13].

VI. Results and discussion

Dose distributions in a patient's body, doses to certain organs and tissues of male and female adult phantoms were obtained. The effective doses for different procedures of contact intraoral radiography were calculated.

The conversion coefficients calculated for three values of high voltage (60 kV, 65 kV and 70 kV) for a rectangular field of 3 cm × 4 cm are shown in Table 3. They represent well the effective dose dependence on the tube angle inclination but much less on anode voltage. For this reason the conversion coefficients proposed in different methodical documents should be divided into a larger number of gradations depending on the X-ray tube inclination angle.

TABLE III
THE CONVERSION COEFFICIENTS FOR DIFFERENT EXAMINATIONS OF MAXILLA

Parameters			Examinations			
V, kV	d_{Al}, mm	R, $\mu Gy \cdot m^2 / mA \cdot s$	Incisors	Canines	Premolars	Molars
60	3	0.028	29.5	27.3	14.7	14.
65	3	0.035	30.9	28.5	15.9	15.5
70	3	0.043	32.2	29.6	17.2	16.6

Table 4 shows the average effective doses to the male and female phantoms organs and tissues for contact intraoral radiography of the maxilla teeth for anode voltage of 60 kV. The calculations were performed for such typical parameters of dental radiography as FSD=20 cm, total aluminium filtration d_{Al}=3 mm, rectangular field of 3 cm × 4 cm, exposure setting 1 mA·s.

TABLE IV
DOSES TO ORGANS AND TISSUES FOR CONTACT RADIOGRAPHY OF MAXILLA TEETH

Organs and tissues	Examinations			
	Incisors	Canines	Premolars	Molars
Extrathoratic region, μSv	51.5	45.8	12.4	10.1
Oral mucosa, μSv	21.0	21.6	14.6	9.6
Bone surface, μSv	4.5	4.4	4.3	5.1
Salivary glands, μSv	1.5	1.7	2.2	5.9
Red bone marrow, μSv	0.6	0.5	0.6	0.7
Skin, μSv	0.5	0.4	0.4	0.4
Brain, μSv	0.4	0.3	0.5	0.7
Thyroid, μSv	0.2	0.2	0.2	0.1
Effective dose, μSv	0.9	0.8	0.4	0.4

Red bone marrow, skin and thyroid are irradiated in least. Wherein, doses to them are practically independent of the tube inclination angle. However, the effective dose increases linearly with increase of high tube voltage.

VII. Conclusion

Modelling different dental exposure procedures for assessment of absorbed and effective doses was presented in this work. The X-ray set model forming a rectangular field of 3 cm × 4 cm at a distance of 20 cm from the tube focus was created. The TASMIP model was used for simulating X-ray spectra. Doses estimation was performed based on the Monte Carlo method with the help of the MCNP. The results can be used for preparing methodical documents regarding doses assessment for different dental examinations and for various X-ray tube

characteristics. They also can be used for developing optimal irradiation procedures.

In the future we plan to evaluate effective doses to children and adolescents during dental X-ray examinations.

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