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ASSESSMENT OF THE ABSORBED DOSE TO ORGANS FROM BONE MINERAL DENSITY SCAN BY USING TLDS AND THE MONTE CARLO METHOD

by

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Nowadays, dual energy X-ray absorptiometry is used in bone mineral density systems to assess the amount of osteoporosis. The purpose of this research is to evaluate patient organ doses from dual X-ray absorptiometry by thermoluminescence dosimeters chips and Monte Carlo method. To achieve this goal, in the first step, the surface dose of the cervix, kidney, abdomen region, and thyroid were measured by using TLD-GR 200 at various organ locations. Then, to evaluate the absorbed dose by simulation, the BMD system, patient's body, X-ray source and radiosensitive tissues were simulated by the Monte Carlo method. The results showed, for the spine (left femur) bone mineral density scan by using thermoluminescence dosimeters, the absorbed doses of the cervix and kidney were 4.5 (5.64) and 162.17 (3.99)(μGy), respectively. For spine (left femur) bone mineral density scan in simulation, the absorbed doses of the cervix and kidney were 4.19 (5.88) and 175 (3.68)(μGy), respectively. The data obtained showed that the absorbed dose of the kidney in the spine scan is noticeable. Furthermore, because of the small relative difference between the simulation and experimental results, the radiation absorbed dose may be assessed by simulation and software, especially for internal organs, and at different depths of otherwise inaccessible organs which is not possible in experiments.

Key words: absorbed dose, Monte Carlo method, TLD chip, bone mineral densitometry

INTRODUCTION

Osteoporosis is not just a health problem. It is also a serious economic issue as the disease costs, including the expenses of hospitalization, outpatient care, nursing services, medical treatment and lost workdays. Thus, the diagnosis and treatment of this disease are very important.

The only reliable way to diagnose osteoporosis and to determine bone density is via the bone mineral density (BMD) test. BMD provides the detection of osteopenia and osteoporosis before fractures occur, predicts the risk for the development of osteoporosis later on and determines the efficacy or failure of therapy.

Several methods are available to measure BMD, such as dual-energy X-ray absorptiometry (DEXA), single photon absorptiometry (SPA), quantitative computed tomography (QCT), radiographic absorptiometry (RA), and quantitative ultrasound (QUS), but currently the most widely used technique is DEXA [1]. In the DEXA technique, BMD at the spine, hip, forearm, heel, as well as the whole body is measured. Older methods, such as single photon absorptiometry (SPA), measure BMD just at the wrist and heel. The diagnosis of osteoporosis and the prediction of bone fracture risk greatly depend on the region of study and the number of measured sites [2].

Nowadays, DEXA systems have evolved from the use of pencil and fan beams to that of cone beam densitometers, which allow for the examination to occur with a short acquisition time and high-resolution images [3].

The DEXA system is not only used to study and diagnose osteoporosis, but also in research studies, including clinical trials of new treatments for bone cancer and epidemiological studies.

Because of the importance of this field of study, several research groups have reported some relevant data. Bandirali *et al*. [4], assessed the absorbed dose in lumbar and femoral organs of an anthropomorphic phantom by a DEXA test. Their study was limited to the dosimetry of only two region means, lumbar and

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femoral. They used a phantom and TLD in their study. The aim of their study was the evaluation of lifetime attributable risk (LAR) of cancer due to radiation. They estimated the lifetime dose absorption and LAR for cancer of a male and a female patient undergoing 36 DEXA studies (18 lumbar, 18 femoral) every 21 months for 32 years. They found that the DEXA scan involves a negligible increased risk of developing cancer. In another study which was done by Thomas *et al*. [5], the effective dose to children as a function of age in the DEXA scan was evaluated. They estimated the effective dose of DEXA (Hologic QDR 4500A) scan to hip, lumbar spine, total body and forearm of children aged 1,5,10 and 15 years and also for adults. They used pediatric phantom models. In all scans the effective dose decreased as age increased.

In this research, the Hologic Explorer (Discovery model, Hologic Inc., USA) BMD system was used. The system is an example of second generation DEXA scanners with a fan beam and a linear array of detectors [6].

The aim of this research is to evaluate the patients absorbed dose during spine and hip regions study in BMD. Two methods were used in this research. In the first step, the absorbed dose was calculated by the experimental method and using thermoluminescence dosimeters (TLD) located at the surface of some regions of the body. In the second step, the absorbed doses of those regions were calculated by the Monte Carlo method. In the simulation stage, the Hologic Explorer BMD machine, X-ray source, the patient's body and its more radiosensitive tissues such as the cervix and thyroid were simulated. Finally, the calculated absorbed doses of simulation were compared with experimental data.

MATERIALS AND METHODS

Bone mineral density system

Figure 1 shows the Hologic Explorer fan beam scanner which has been used in this study. Fan beam scanners reduce the scanning time and increase image resolution, but also deliver a higher absorbed dose than pencil beam DEXA scanners. In this system, the X-ray high voltage tube is rapidly switched between two specified energy means, 100 kVp and 140 kVp. More useful specifications of the Hologic system are shown in tab. 1.

The preferred sites for DEXA measurements of bone mineral are the lumbar spine and femur, regions of the body which were used in this research, too.

Thermoluminescence dosimeters measurement technique

In order to achieve the experimental data means absorbed dose, TLD were used in this study. TLD may be used on the patient during examination procedures because of their small sizes [8].

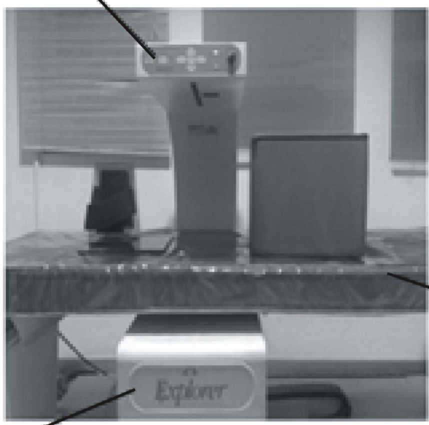

Figure 1. Hologic explorer fan beam scanner and its components

Table 1. Hologic explorer specifications [7]

Specification	Definition
X-ray system	Tungsten target switched pulse dual energy X-ray tube, operating at 100 kVp and 140 kVp
Scanning site	AP lumbar spine, proximal femur (hip), forearm and whole body
Scan region (at pad surface)	1.97 m (77.5 in) × 0.65 m (25.6 in) maximum
X-ray system geometry	Source-to detector distance 883.4 mm Source-to-patient distance 424 mm Beam size at detector 226 mm 4.4 mm

One of the most advanced thermoluminescent detectors is LiF:Mg,Cu,P. Its main advantages are high-sensitivity, quicker turnaround time of readout and good tissue equivalence.

TLD are available in various forms *i. e.*, thin films, powder, sintered circular chips, cylindrical chips and square chips [9].

In this research the LiF: Mg, Cu, P, usually named TLD – GR200, was used. The used TLD were in the form of cylindrical chips with the dimensions of about 2.25 mm in radius and 0.9 mm in thickness.Also their useful dosimetry range is from 0.1 μGy to 10 Gy [10].

Before using the TLD, they were calibrated by X-ray energy of about 100 keV. Then the calibrated TLD were annealed at 240 °C in the Thermolyne oven (model 47900) for 10 min. This procedure reduces the uncertainties of TLD measurements.

Since the absorbed dose of an organ is determined by the dose of TLD, to reduce the uncertainties, two TLD were applied for each organ [11]. Also, to increase measurement and calculation accuracy, seven groups of TLD were considered. Each package of

Figure 2. Used TLD packages, each package consisting of two TLD tablets

Table 2. The adjusted values of time and temperature to read data from TLD reader

Parameter	Value
Preheating temperature	160 °C
Duration time of heating	25 s
Maximum used temperature	300 °C
Duration time of heating	30 s
Duration time of cooling	20 s
Total time	75 s

TLD consisted of two TLD tablets, as shown in fig. 2. In the spine scan, four groups of TLD were placed at following locations: the first group consisting of two tablets at the location of the cervix, the second group of two tablets at the location of the thyroid, the third and fourth group of two tablets at the location of the kidney, and the other two tablets at the location of the abdominal region. In the femur scan, three groups of TLD were placed at the following locations: two tablets at the location of the cervix, two at the location of the kidney, and the other two tablets at the location of the abdominal region.

All badges were placed at the surface and on the anterior side of the patient to measure the surface dose. To assess the kidney absorbed dose, two tablets were placed on the posterior side of the patient, too. These measurements were performed on 12 women as patients. The TLD were read out by using a reader (TLD reader, Hungary). This TLD reader has a three-phase heating cycle. The first phase is the preheating period to fade low temperature traps. The second phase is the reading period in which the light output is integrated as the raised temperature. The final stage is the cooling-off period. The used time duration and temperature specifications of each stage are shown in tab. 2. The TLD were then annealed for 10 minutes at 240 °C [12].

Simulation study

Monte Carlo method

Monte Carlo calculation is used for dosimetry studies in medicine [13]. The method is used to assess the radiation absorbed dose of internal tissues and in different depths of each organ. In this research, the Monte Carlo method (MCNPX) was used to simulate the Hologic Explorer BMD machine, its X-ray source, the human body and its radiosensitive tissues in order to assess the absorbed dose of radiosensitive tissues of the human body.

Description of X-ray source

To perform a spine scan, the DEXA system usually measures the lumbar spine from L1 to L4 in either posterior or anterior projection, as shown in fig. 3.

Approximately, the vertebra has the dimensions of 4 cm in height, 4 cm in width and 5 cm in thickness. So, for the spine scan, the X-ray source was simulated as a rectangular source with the dimensions of 4 cm × 20 cm.

In the femur (hip) scan, BMD measurements were obtained for several regions of interest, including the femoral neck, trochanter, and Ward's triangle, as shown in fig. 4. So, the dimensions of the simulated source for the femur scan in this study were considered to be 7 cm ×12 cm in rectangular source geometry.

Also, the distance from the X-ray tube to the patient and the distance from the source to the detector were determined as 42.4 cm and 88.34 cm, respectively.

Description of mathematical phantom

The exterior view of the body phantom used is shown in fig. 5. The body phantom consists of three cubic principal sections means: a cube to represent the

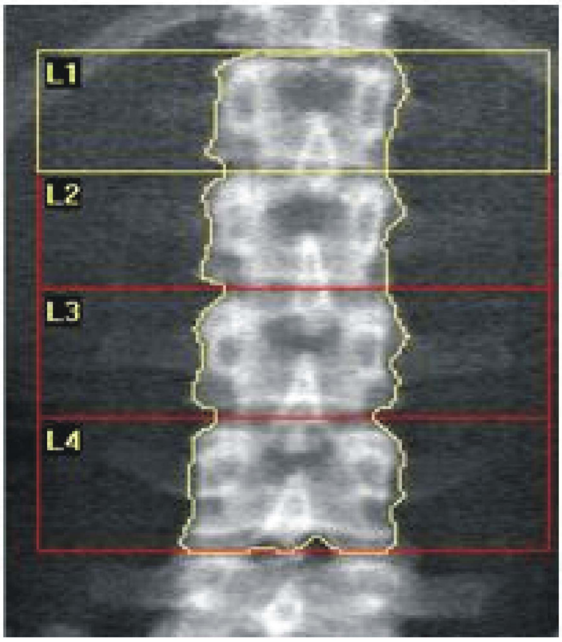

Figure 3. The lumbar spine from L1 to L4 [12]

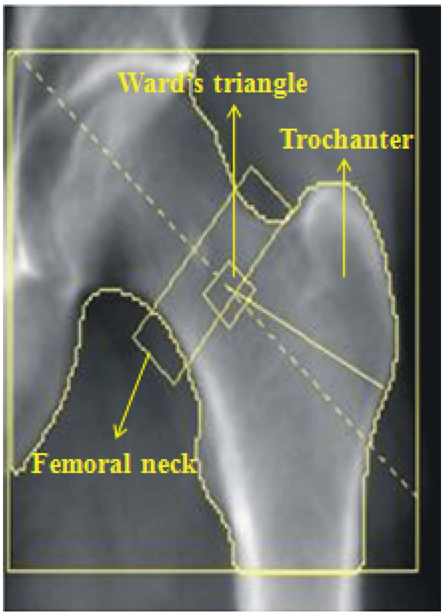

Figure 4 . The femoral neck, trochanter and Ward's triangle [14]

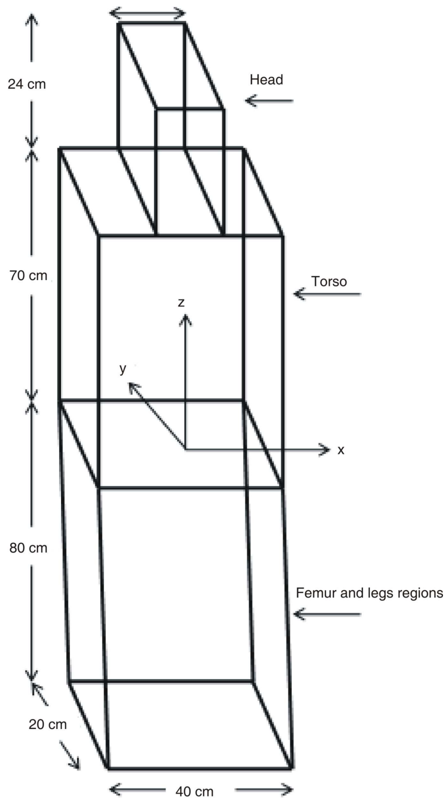

Figure 5. Exterior view of the adult phantom

head, the other cube to represent the torso and the last cube to represent the femur and two legs.

The phantom consists of two kinds of materials means bone and soft tissue to simulate the skeletal and soft tissues. The densities of the skeleton and soft tissues were considered as, 1.5 and 1 g/cm^3, respectively [15].

Table 3. Dimensions of the used body phantom and part center co-ordinates in simulation study

Part of body	Dimension [cm] (height × width × thickness)	Part center coordinates (x , y , z)
Torso	70 × 40 × 20	(0 , 0 , 35)
Head	24 × 14 × 20	(0 , 0 , 82)
Legs	80 × 40 × 20	(0 , 0 , –40)

Table 4. Dimensions of skeletal regions and their co-ordinates center in the body phantom used in the simulation study

Skeleton	Dimension [cm] (height × width × thickness)	Part center co-ordinates (x, y, z)
Spine	56.5 × 4 × 5	(0 , 5.5 , 50.25)
Pelvis	10 × 24 × 18	(0 , 0 , 17)
Legs	91.5 × 7 × 6	(8.5 , 4 , –33.8)[a]

[a] Left leg co-ordinates' center

The body was represented as a standing person, with the z-axis directed upward to the head. The x-axis was directed to the phantom's left and the y-axis was directed toward the posterior side of the phantom. The torso, head and legs are cubes with different dimensions. The dimensions of these parts and their center co-ordinates have been specified in tab. 3 [16].

Description of skeletal system

The skeletal system consists of 3 parts: spine, pelvis, and leg bones, that have been simulated by cubic geometries. The spine, pelvis, and leg bones were simulated by cubic geometry. The dimensions of each cube and their coordinates' center have been specified in tab. 4.

Description of organs

In this study, the medical internal radiation dose (MIRD) pattern (standard) that specifies the shape and location of the different organs was used. The cervix, kidney, thyroid, and abdomen were simulated by cubic geometry. The dimensions of organs and their co-ordinates' centre have been specified in tab. 5 and fig. 6.

Table 5. Dimensions and co-ordinates' center of the organs in body phantom used for simulation study

Organ	Dimension [cm] (height × width × thickness)	Organcenter co-ordinates (x, y, z)
Cervix	2 × 3 × 0.1	(0 , –2 , 14)
Thyroid	5 × 5 × 0.1	(0 , 4 , 72.5)
Kidney	11 × 9 × 0.1	(6 , 6 , 32.5)
Abdomen region	16 × 8 × 0.1	(8 , –4 , 35)

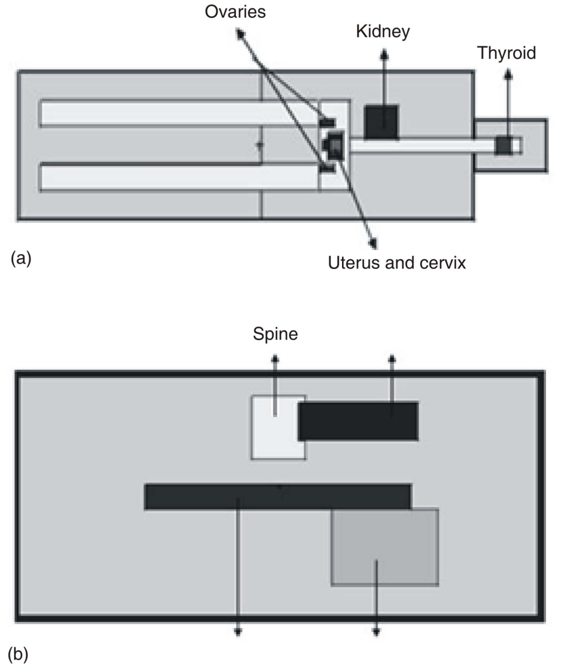

Figure 6. Samples of simulated organs, (a) x-z view of body phantom and (b) x-y view of body phantom

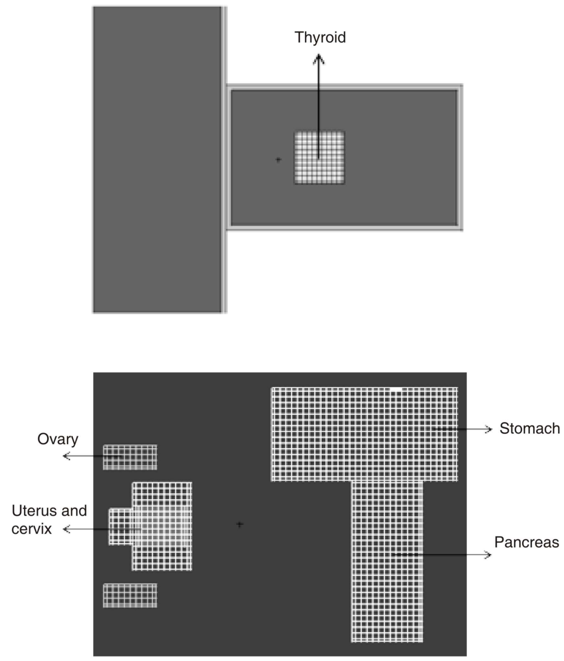

Figure 7. Division of tissues into equal parts (TLD dimensions)

RESULTS

Patient dosimetry was done, using two different protocols for the spine and femur, respectively. The mean height, preferred size of the abdomen region and thickness of patients were 161.82 cm, 94.77 cm, and 22.1 cm, respectively.

In the experimental study, to measure the dose for the tissues, TLD packs were prepared and placed on the body surface. Moreover, two TLD were used to measure the background radiation of the room. After applying the correction and calibration coefficients for each TLD, the dose of each region was calculated in μGy.

Surface doses of the cervix, kidney, thyroid, and abdomen regions in the spine and femur scan modes for 12 patients (women) have been calculated and shown in tab. 6.

In the simulation study, to cover the most experimental conditions, organs were simulated at the surface of the patient's body and all of them were filled with a cubic lattice of 0.5 cm × 0.5 cm × 0.1 cm, as shown in fig. 7.

Table 6. Organs absorbed doses during spine and left femur scan by BMD Explorer system using TLD chips (experimental data)

Organ	Absorbed dose spine scan [μGy]	Absorbed dose femur scan [μGy]
Cervix	4.5 0.036	5.64 0.021
Thyroid	1.95 0.014	–
Kidney	162.17 ± 0.037	3.99 0.042
Abdomen region	8.45 0.01	3.55 0.041

Table 7. Organs absorbed doses during spine and left femur scan by BMD explorer system (simulation data)

Organ	Absorbed dose spine scan [μGy]	Absorbed dose femur scan [μGy]
Cervix	4.19 0.036	5.88 0.021
Thyroid	1.88 0.01	–
Kidney	175 0.037	3.68 0.039
Abdomen region	8.71 0.014	3.27 0.041

For the spine (femur) BMD scan in simulation, the absorbed doses of an adult patient have been tabulated in tab. 7.

The experimental and simulation results have a very good agreement, as is clear from tabs. 6 and 7.

It should be noted that the amount of the absorbed dose of the kidney in the femur scan is quite high in comparison to other organs.

CONCLUSIONS

In this study, the absorbed doses of some radiosensitive tissues such as the cervix, kidney, thyroid, and abdomen region were calculated by using TLD chips as well as the Monte Carlo simulation.

In this research, a very good agreement between the results of simulation and experimental data were found. The relative difference between the simulation results and experimental data was less than 8%. Therefore, the radiation absorbed dose may be assessed by simulation and software, especially for internal organs and inner parts of organs which are not easily accessible in experiments. A few differences between the simulation and experimental results may be a result of the difference between the real X-ray source in the BMD machine and its simulated form. These differences are a mere non-uniformity of X-ray radiation in the experiment, variance in location, dimensions of organs and also TLD precision.

During the spine scan, in the simulation study, the absorbed doses of kidney and abdomen regions were 175 0.037 μGy and 8.71 0.014 μGy, respectively.

The average surface doses of kidney and abdomen regions in the spine scan using TLD chips, in the experimental method, were 162.17 0.037 μGy and 8.45 0.01 μGy, respectively.

The measured surface doses of the organs in spine scan mode were bigger than for the other organs. So, to reduce the probable danger to these organs during BMD, these scans should be prescribed with more precision and sensitivity.

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AUTHOR CONTRIBUTIONS

The design and theoretical analysis in this work was carried out by A. Karimian. Experimental data was done by A. Hajarizadeh. The Monte Carlo simulation and the manuscript, including figures and text, were prepared and written by A. Karimian and A. Hajarizadeh.

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ПРОЦЕНА АПСОРБОВАНЕ ДОЗЕ У ОРГАНИМА ТОКОМ ПРЕГЛЕДА ГУСТИНЕ КОСТИЈУ ПРИМЕНОМ ТЕРМОЛУМИНИСЦЕНТНИХ ДОЗИМЕТАРА И МОНТЕ КАРЛО МЕТОДЕ

У данашње време уређаји за остеодензитометрију користе се за мерење густине минерала у костима ради процене нивоа остеопорозе. Циљ рада је одређивање дозе у органима пацијента током овог прегледа употребом термолуминисцентних дозиметарских чипова и применом Монте Карло симулације. У првом кораку апсорбована доза мерена је употребом TLD-GR 200 дозиметара постављених на различитим местима по површини цервикса, бубрега, абдомена и штитасте жлезде. Следећи корак била је процена дозе Монте Карло симулацијом мерног система, тела пацијента, извора X-зрачења и радиоосетљивих ткива. Резултати показују да су апсорбоване дозе измерене термолуминисцентним дозиметрима, у току прегледа кичме (леве бутне кости), за цервикс и бубрег биле 4.5 (5.64) μGy и 162.17 (3.99) μGy, респективно. Симулиране апсорбоване дозе биле су за цервикс и бубрег 4.19 (5.88) μGy и 175 (3.68) μGy, респективно. Подаци показују да је у току прегледа кичме, апсорбована доза за бубреге приметна. Такође, због мале разлике између измерених и симулираних резултата, апсорбована доза може бити процењена симулацијом, нарочито за унутрашње органе који се налазе дубље у телу и који нису доступни у експериментима.

Кључне речи: айсорбована доза, Монте Карло метода, термолуминисцентни дозиметар, дензиометрија костију