PATIENT DOSIMETRY IN DIAGNOSTIC RADIOLOGY

by

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The objective of this work is to assess patient organ doses, effective doses and entrance surface doses in conventional diagnostic radiology procedures for standard adult patient. The survey consists of measurements of doses delivered to 239 patients in nine types of X-ray examinations. Three types of data were collected: X-ray machine data, patient data, and output measurements. Entrance surface dose was assessed based on the survey data, and subsequently, using conversion coefficients, the organ doses and effective doses were calculated. Values of the entrance surface dose and the effective dose were estimated to be 0.4 to 5.8 mGy and 0.03 to 3.00 mSv for different examinations. Derived doses were compared with recommended general diagnostic reference levels. The impact of examination parameters on dose values was discussed. Except for posterior-anterior chest examination, all estimated doses are lower than stated reference levels. Survey data are aimed at helping development of national quality control and radiation protection programme for medical exposures.

Key words: X-rays, diagnostic radiology, entrance surface dose, effective dose, optimization

INTRODUCTION

X-ray examinations are an established tool of medical diagnosis. Their widespread use means that, on the average, health system in Serbia and Montenegro provides annually 880 examinations per 1000 inhabitants [1]. Patients undoubtedly enormously benefit from these examinations, although the ionizing nature of X-rays means that their use is not entirely deprived of risk. For this reason, all exposures to diagnostic X-rays need to be justified and optimized in terms of benefit and risk [2]. One of the basic requirements for this is to know patient doses.

Unfortunately, appropriate dosimetric data for diagnostic radiology in Serbian hospitals have, so far, been limited. In the past period, in Radiation and Environmental Protection Laboratory of the VINČA Institite of Nuclear Sciences, Belgrade, an effort was made to collect data on patient doses during standard radiological examinations, as part of the quality assurance programme [3]. In the first years of the programme, tasks related to equipment and shielding evaluation were of primary concern [4]. The patient dose aspect was introduced at a later stage, as it was recognized that diagnostic radiology was the major source of doses administered to the population from manmade sources. The patient dose survey was performed in order to examine the situation and evaluate how the principle of optimization of the International Commission on Radiological Protection could be implemented in practice [5]. This paper presents the results of entrance surface doses per radiograph and the assessment of organ doses, observed in patients undergoing a selection of common X-ray examinations. Further analysis of patient doses (including image quality aspect) are in progress and will be reported subsequently.

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PATIENT DOSE SURVEY

The extent of dose survey must be limited and measurements have to be confined to most frequent X-ray examinations, which account for a large col-

lective dose to the population. In that sense, measurements were concentrated on high-frequency examinations. In practice, this means examinations of the respiratory system, skeletal examinations of the spine and pelvis, and urinary system. Initially, measurements were performed in two non-specialized local hospitals, performing annually more than 80.000 and 40.000 examinations, respectively. Details on 239 X-ray examinations were collected, during a period of 2 months, so at least 10 patients were observed for each examination type. The examinations were carried out in three X-ray rooms, equipped with three-phase, 6-pulse X-ray machines, and a room equipped with a three-phase, 12-pulse machine. None of these are using automatic exposure control. Using established Quality Control Protocol [6, 7], all X-ray tubes and generators were tested before performing patient dose measurements. In order to check the compliance with stated quality criteria [8], the equipment was tested using calibrated Keithley quality control set of instruments (Keithley Instruments, Cleveland, USA) [9].

Each patient record was stored in a data file to facilitate calculation of entrance surface doses and organ doses. A form containing information on the patient (sex, age, weight) and technical parameters used (applied tube voltage, tube current and exposure time, and X-ray field size in the film plane) was filled out for each examination. In this paper, the survey is summarized in terms of median values, mean doses and associated range, to illustrate the often-wide distributions of observed doses for each type of examination. This will provide a useful baseline for future measurements of patient doses.

Entrance surface dose

Various dosimetry quantities are applied in patient dosimetry with respect to actual examination type and equipment performance [10]. It is important that patient dose measurements are time-effective and they should not disturb the patient and staff during the examination. We give here a brief outline only of the method applied. Full details of patient dosimetry techniques are given elsewhere [11, 12]. After having evaluated several options available, it was decided to use the indirect method of dose assessment, *i. e.* air kerma measurements. Dosimetry in diagnostic radiology is in the air kerma domain [13]. It is the energy equivalent of the air ionization in the definition of exposure, with correction for bremsstrahlung production. Absorbed dose was defined by the International Commission on Radiological Units and Measurements [14] as the amount of energy deposited in medium per unit mass. Absorbed dose and air kerma are almost equal in the diagnostic energy range, but vary if the medium is different [12]. In addition, air kerma is easier to measure accurately, due to the practical problem associated with achieving electronic equilibrium in the field [15]. The radiation measurements of air kerma were made using a Keithley dosimeter Model 36065 [9], calibrated in traceable Secondary Standard Dosimetry Laboratory at the VINČA Institute of Nuclear Sciences [16].

The dosimetry method involves measurement of X-ray tube output (Y_D), *e.g.* air kerma at defined geometry for a range of tube voltages, followed by the use of backscatter factor (*BSF*) data and geometry corrections to determine the entrance surface dose. This methodology enables a relatively large number of patient dose estimates from a small number of measured parameters, the measurements are part of a quality assurance programme and they are useful for the estimation of low surface doses. However, it is not possible to apply this methodology for automatic exposure control settings and complex examinations involving multiple projections [12].

The knowledge of tube output, tube voltage, tube current, exposure time, and focal spot-skin distance, enables deduction of the air kerma at the point corresponding to the position of the patient's skin. Entrance surface dose (*ESD*) is air kerma measured in the primary X-ray beam in the entrance plane of the patient and therefore it is closely related to the backscatter factor, which is defined as the ratio of the air kerma on the surface of a phantom and air kerma free-in-air [13]. Measured and calculated backscatter factors are reported in literature [13, 17]. Typical backscatter values for diagnostic X-ray beam qualities range from 1.25 to 1.55. Then entrance surface dose is given by [12]:

$$ESD = \frac{Y_D \cdot mAs \cdot D^2}{[L-(d+b)]^2} \cdot BSF \qquad (1)$$

where Y_D [μGy/mA·s] is X-ray tube output at distance D normalized by *mAs*, *mAs* is the product of the tube current and exposure time, L is focus-film distance and b and d are film-table top distance and patient thickness, respectively. To calculate entrance surface dose, X-ray tube output Y_D was measured at the distance of 1 m for X-ray tube voltage peak in range 50 to 120 kV, in 10 kV steps. Patient thickness was deduced from the recorded patient weight and height [18]. For each patient entrance surface dose was calculated using real examination data, according to eq. (1).

Doses to organs

Entrance surface dose has a small biological significance regarding health risk, but it enables organ dose to be derived, using appropriate conversion factors. Organ doses are specified in terms of absorbed dose to muscle, soft tissue or water. The International Commission on Radiological Protection [2] introduced the equivalent dose (H_T) in tissue as:

$$H_T = \sum_R w_R D_{T,R} \quad (2)$$

where $D_{T,R}$ is the average absorbed dose to tissue from radiation of type R, and w_R is the radiation weighting factor. For X-rays, the value w_R is 1. Finally, taking into account the values for tissue weighting factor w_T, ICRP defines effective dose E as [2]:

$$E = \sum_{T,R} w_T w_R D_{T,R} \quad (3)$$

The effective dose is operationally useful in diagnostic radiology as a measure of detriment from partial body irradiation in terms of whole-body irradiation. It can be used to compare relative radiation detriment among diagnostic radiology procedures for populations with comparable age and gender distributions. It can also be used for purposes of optimization radilogical procedures and comparing against alternative methods or background radiation.

To allow practical estimation of effective dose, several different methods were developed, each of these based on mathematical models of the human body. Monte Carlo computation techniques are used to model the radiation interactions for commonly used beam spectra, projections and radiation field sizes [12]. The United Kingdom's National Radiological Protection Board [19] has modelled 68 radiographic views, in order to estimate organ doses and effective doses per unit dose-area product or entrance surface dose. The normalised organ doses were calculated by simulating X-ray examinations on a mathematical phantom representing an average adult patient of 70 kg mass and 174 cm height, following $4 \cdot 10^6$ photon histories for each projection. Appropriate conversion factors for each irradiation are primarily dependent on the applied tube potential and total filtration of the X-ray beam and, to a lesser extent, on the voltage waveform of the generator and the target angle of the X-ray tube. Entrance surface doses, as the input parameter, allowed organ equivalent dose and effective dose assessment for each patient and actual radiation quality.

PATIENT DOSE ASSESSMENT

Details of randomly selected adult patients included in each type of examination are presented in tab. 1, where numbers of patients and their mean weights (and range) are indicated, together with the applied tube voltage peak. The mean patient weights indicated for the examinations are close to the 70 kg mass of the mathematical phantom used in organ dose calculations. Table 1, also summarizes dose assessment results for individual radiographs with radiographic projections commonly used during X-ray examinations. The broad classification is: anterior-posterior (AP), posterior-anterior (PA) and lateral (LAT) projections. Mean values of entrance surface doses, median and third quartile values are also shown, as well as the effective dose values in the final column.

Great variations in patient doses were found in this survey. Some reasons for the variations became apparent, as the speed class of film-screen combination, which was 200 to 400, and manual exposure control settings. The typical technical factors used vary by a wide range. For instance, loading factors extend from 75 to 90 kV and from 16 to 40 mA·s, for chest radiography (tab. 1). In spite of the observed fluctuations in the applied workload (tube current and exposure time product), there is a tendency of smaller product of tube current and exposure time for high tube voltage. This combination provides a lower entrance surface dose. Besides tube voltage, current and exposure time, other equipment related technologically limited factors also affect patient dose in all examinations. These are three phase generators, 2.5 mm Al nominal total filtration and manual exposure control setting.

Distributions observed for various dose quantities are typical skewed, with mean values generally greater than corresponding medians, so a small number of patients receive high doses. Since the survey was not extensive and the median value is not influenced by the values that lie outside the main part of distribution as the mean value, it can be argued that the median is very helpful in typical practice assessment. Exceptions are chest, urinary tract, and lumbal spine AP examinations, due to softer X-ray spectra, which is the consequence of low applied tube voltage and insufficient beam filtration.

For each patient, doses to organs were calculated and mean values are presented in tab. 2. Apparently, these values vary with respect to the relative position of organs in relation to central beam axis and radiation field size associated with different examinations and could be successfully controlled by beam collimation, projection choice and use of shielding devices. Despite the present use of Monte Carlo conversion coefficients to overcome

Table 1. Means of patient weight and applied tube voltage and tube loading; means, medians and third quartile values of entrance surface doses, and mean effective doses for different radiographic examinations

Examination	Sample size	Patient weight [kg]	Tube voltage peak [kV]	Tube loading [mA·s]	Entrance surface dose [mGy]			Diagnostic reference level [20, 21] [mGy]	Effective dose [mSv]
					Mean	Median	Third quartile		
Cervical spine AP	29	70 (50-90)*	79 (75-85)	33 (16-18)	2.41 (0.77-3.27)	1.58	2.01	not available	0.09 (0.03-0.12)
Cervical spine LAT	29	70 (50-90)	79 (75-90)	33 (16-125)	1.72 (0.31-3.02)	1.54	2.09	not available	0.06 (0.01-0.11)
Pelvis AP	17	69 (55-80)	73 (67-85)	37 (25-64)	2.36 (2.07-2.75)	1.42	1.49	10	0.35 (0.29-0.45)
Thoracic spine AP	13	71 (57-80)	81 (80-85)	58 (32-85)	4.08 (3.62-4.39)	2.80	3.60	7	1.75 (1.53-1.90)
Thoracic spine LAT	13	71 (57-80)	88 (85-95)	85 (40-125)	5.79 (4.89-6.93)	3.65	4.95	20	2.99 (2.49-3.44)
Lumbal spine AP	26	72 (55-87)	67 (65-75)	40 (20-50)	1.70 (1.37-2.23)	1.89	2.23	10	0.24 (0.15-0.28)
Lumbal spine LAT	26	72 (55-87)	81 (75-90)	69 (40-85)	5.21 (3.79-6.49)	4.01	5.28	30	0.81 (0.54-1.05)
Chest PA	50	73 (56-94)	83 (75-90)	25 (16-40)	0.43 (0.28-0.80)	0.56	0.78	0.30	0.03 (0.003-0.09)
Urinary tract AP	36	77 (60-98)	71 (70-80)	43 (32-52)	1.86 (0.34-3.08)	2.32	3.01	10	0.64 (0.12-1.18)

*The parentheses include the range of the values

Table 2. Mean organ doses [mGy] for different tupes of radiographic examinations

Organ/ Examination	Cervical spine AP	Cervical spine LAT	Pelvis AP	Thoracic spine AP	Thoracic spine LAT	Lumbal spine AP	Lumbal spine LAT	Chest PA	Urinary bladder AP
Breasts	*	*	*	0.50	0.02	0.01	*	0.03	*
Urinary bladder	*	*	0.06	0.09	0.03	0.58	0.18	0.02	*
Stomach	*	*	0.04	0.28	0.01	0.68	0.02	0.03	*
Colon	*	*	0.78	0.01	*	0.77	0.24	*	0.27
Liver	*	*	0.02	0.32	0.28	0.39	0.59	0.08	*
Lungs	0.01	*	*	0.48	0.44	0.03	0.02	0.18	*
Testes/ Ovaries	*	*	1.24	*	*	0.31	0.18	*	0.41
Skin	0.03	0.05	0.14	0.14	0.15	0.10	0.15	0.05	0.05
Thyroid	0.70	0.09	*	0.55	0.03	*	*	0.01	*
Esophagus	0.03	0.03	*	0.33	0.17	0.06	0.01	0.07	*
Bone	0.06	0.07	0.08	0.23	0.25	0.08	0.10	0.12	0.02
Red bone marrow	0.01	0.02	0.04	0.10	0.11	0.05	0.08	0.05	0.14

* Denotes <0.01 mGy

the basic inability to measure organ doses directly, the uncertainties may exist for many of the doses derived for individual patients. One should be very careful with high precision of air kerma measurements due to differences in the anatomy and X-ray field geometry between mathematical phantom and real patients. However, these uncertainties are likely to be of less importance in case of a large number of measurements on heterogeneous population of patients in various X-ray departments.

The entrance surface dose to patients in diagnostic radiology is a dose descriptor to quantify

diagnostic reference doses for radiographic examination. Diagnostic reference doses are part of the quality criteria as laid down in the European Guidelines on Quality Criteria for Diagnostic Radiographic Images [20]. They are also recommended by the International Commission on Radiological Protection [22] and by the International Atomic Energy Agency, as guidance doses [21]. Diagnostic reference dose values provide quantitative guidance to identify relatively poor and inadequate use of techniques and a need for appropriate corrective action. They are usually based on the third quartile values of large patient dose surveys [11]. In practice, compliance with reference doses should be tested by measurements on series of representative patients. If local doses exceed the reference levels, an investigation of the cause of these high patient doses should follow. The mean and median values in this survey for chest PA examination are 0.43 and 0.56 mGy, respectively, which is significantly higher than the reference value of 0.3 mGy. Entrance surface doses for all examinations increase with patient size, due to increased contribution of scattered radiation form of the patient, which is only partial explanation for the discrepancy. The full explanation for relatively high doses lies in the comparison of actual practice with the example of good radiographic technique, where 125 kV voltage peak, 20 ms exposure time and minimum 3 mm Al total filtration are recommended. Applied tube voltage peak was 70 to 95 kV, which, in combination with insufficient tube filtration resulted in soft radiation qualities and increased patient doses. However, low tube potentials are also found in other wider surveys [23], despite suggestions that increasing of the applied voltage should reduce patient dose. For chest film, high physiological contrast among lung and bone tissue is well transformed into a long gray scale at high tube voltage values. It keeps down the relative number of photoelectric events in bone and leads to lower overall patient dose. It is worth mentioning, that although the assessed doses for other examinations were much below the reference level, the actual practice is far from a good radiographic technique. In addition to chest X-ray examinations, the optimization of practice for other X-ray examinations is also necessary.

CONCLUSION

A survey was conducted to investigate patient doses for common diagnostic radiology examinations. Exposure of the total of 239 patients was analyzed. Entrance surface doses, organ doses and effective doses were evaluated. Except for chest examination, all derived doses were below the recommended reference levels. The present survey indicated the need to standardize the medical X-ray examination technique.

Patient doses are determined by multitude factors which interact in a very complicated manner. It is very important to perform real patient dose measurements in hospitals. Besides, the obtained quantitative data allow better understanding of how different working habits and examination technology influence patient doses and help make medical staff aware of patient doses and increase their responsibility for the optimization of daily practice. In that sense, the survey results are a link between patient dosimetry, as the first step in optimization of radiation protection, and quality assurance programme in diagnostic radiology. It is of great importance to extend the survey to a large number of hospitals and to include complex examinations in order to establish diagnostic reference levels on national scale. Reference dose levels for diagnostic radiology examinations provide the benchmark for comparison of X-ray exposures from different facilities, in order to reduce patient doses and maintain good image quality with respect to basic principles of radiation protection (justification and optimization).

The results of this survey will be important inputs for a new set of radiation protection measures in this field. The mean values of dose estimates presented for each type of examination may be representative for an average adult patient undergoing these examinations. These data may be used to assess the collective dose administered to the population by diagnostic X-rays, to evaluate the radiation risk from various radiological procedures and also, to establish a useful baseline for future measurements.

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Оливера ЦИРАЈ, Српко МАРКОВИЋ, Душко КОШУТИЋ

ПАЦИЈЕНТНА ДОЗИМЕТРИЈА У ДИЈАГНОСТИЧКОЈ РАДИОЛОГИЈИ

Циљ рада је одређивање дозе на површини коже пацијента, доза за органе и ефективне дозе за стандардног одраслог пацијента током класичних метода дијагностичке радиологије. Одређивање доза извршено је на основу мерења дозе на површини коже 239 пацијената током 9 типова дијагностичких поступака, при чему су прикупљена три сета података који се односе на карактеристике дијагностичке опреме, индивидуалне карактеристике пацијената и радијациони излаз рендген-апарата. На основу измерених доза на површини коже пацијента, применом одговарајућих конверзионих коефицијената, израчунате су дозе за поједине органе и ефективна доза. У зависности од типа прегледа, вредности дозе на површини коже пацијента износе 0.4 до 5.8 mGy, а одговарајуће ефективне дозе 0.03 до 3.00 mSv. Добијене вредности поређене су са препорученим дијагностичким референтним нивоима. Анализиран је утицај технике снимања на пацијентне дозе. За све типове прегледа изузев снимања плућа, дозе на површини коже пацијента биле су мање од утврђених дијагностичких референтних нивоа. Резултати мерења пацијентних доза представљају један од основних елемената за утврђивање националног протокола за контролу квалитета и програма заштите од зрачења током медицинских излагања изворима зрачења.