Effective Doses from Diagnostic X-Ray Procedures

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Abstract

It is useful to set into perspective the doses received from diagnostic medical procedures when considering human exposure to low doses of ionizing radiation. The manner in which diagnostic x-ray doses are specified leaves confusion and makes their significance difficult to evaluate. On the one hand, the numbers may be quoted in terms of entrance skin exposure; on the other hand, knowledgeable radiation workers are accustomed to specifications in terms of effective dose. This paper discusses doses received from conventional diagnostic x-ray procedures in terms of effective doses and determines the effective doses for standard procedures from recent survey measurements of medical x-ray units.

The conversion of the exposure data to effective doses requires a step wise approach. Firstly, exposure data are converted into air kerma, then the absorbed doses to critical organs in the field of view are determined and, finally, the tissue weighting factors are applied to convert absorbed dose equivalents to effective dose. A body-compartment model has been used in the apportioning of critical organs for the various fields of view in imaging procedures.

We have applied the information in ICRP-74 to determine absorbed dose equivalents from air kerma for x-ray procedures. To simplify calculations we advocate the use of a compartment-weighting-factor model in converting organ dose equivalents to effective doses for the respective diagnostic procedures. Compartment weighting factors have been derived from a Health Physics Society Standard prepared for multiple badging of radiation workers.

The objective of this discussion is to provide dose information for diagnostic x-ray procedures in terms of effective dose. In this way an appropriate comparison can be made with effective doses arising from other activities and an assessment can be made of the role of diagnostic procedures in the discussion of potential low-dose effects. As an example, the average effective dose for a chest x-ray in our jurisdiction is 0.02 mSv (2 millirem) corresponding to the average entrance skin exposure of 11.7 mR (1997).

1. Introduction

Next to natural sources of ionizing radiation, members of the public are most frequently exposed to radiation in diagnostic imaging procedures. A mystique has arisen concerning doses in diagnostic procedures, partly because the benefits of the procedures are accepted on their face value, partly because of a limited need for quantitative rationalization of doses within the medical community, and partly because of the misinformation obtained when measurements made for quality control purposes are offered as dose data. It is the purpose of this discussion to express dose information from diagnostic imaging procedures in the quantitative form of "effective doses" in order to set the doses into perspective with, for example, effective doses received during employment as an Atomic Radiation Worker.

This discussion is limited to specific procedures in conventional x-ray imaging.

Typically, the quantity of radiation delivered in a diagnostic procedure is quoted in the traditional unit of exposure: roentgens or milliroentgens. Despite the general application of SI units, instruments continue to be used that give this form of output. The data are valid enough for the purpose served by the measurement because the measurement is part of a quality control program used in the medical-technical community to assess the performance of the equipment. The error arises when these exposure data are immediately converted to SI units and quoted as "doses".

To digress for a moment, the regulation of x-ray equipment is a provincial jurisdiction. Although x-ray equipment is governed at point-of-sale by standards in the Regulations of the Federal Radiation Emitting Devices Act, compliance of the operating equipment is regulated provincially. There is more to compliance than the operating characteristics of the x-ray equipment itself. The techniques used by the technologists, the choice of film, the film-screen combination, choice of anti-scatter grid, the processing of the film, the view box and the preference of the reading radiologist influence the x-ray exposure in addition to the x-ray generator characteristics. These parameters are tested in the complete quality assurance program.

In this paper, exposure measurements for standard imaging procedures, obtained as one of the quality control parameters, are converted to effective doses, in millisieverts, conforming to the recommendations of the ICRP.

2. Provincial X-ray Regulation and the Measurement of Standard Procedures.

The approach to quality assurance of x-ray procedures in Manitoba includes a program of regular visitation to all x-ray facilities. Medical and chiropractic facilities are inspected annually. Dental clinics are visited on a three-year cycle, supplemented by an annual mail survey of bite-wing procedures using thermoluminescent dosimeters. Radiation exposure in an imaging procedure is measured with a calibrated ion chamber using a phantom of standard dimensions to represent the patient. For example, the procedure for examination of a lumbar spine is typically measured using a 23 cm. thick presswood phantom (Specific Gravity 1.0) that generates the backscattered beam typical of the patient. Average data for standard procedures are tabulated from the annual surveys. The exposure data are used in a particular facility to advise the staff with respect to their technique in comparison to the average province-wide exposures for that procedure.

Table 1 presents measurements of exposures for a representative set of procedures.

TABLE 1. Average entrance skin exposure data for standard diagnostic x-ray procedures in Manitoba hospitals and medical clinics, 1997. Data shown are from machines with manual timing, with grids, and were obtained with a phantom in place.

Imaging Procedure	View	Tube Voltage (kVp)	Patient Thickness (cm)	Average Exposure (mR)	Exposure Range (mR)
Chest	PA	110	10	11.7	8.3-15.1
Abdomen	AP	80	18	222	158-286
Cervical Spine	AP	80	13	59	39-80
Thoracic Spine	AP	80	18	168	109-226
Lumbar Spine	AP	80	23	327	226-428
Lateral Skull	LAT	80	15	65	43-88

In keeping with guidance from the ICRP, the direction of irradiation is important. Diagnostic x-ray exposures are characterized in terms of antero-posterior (AP), postero-anterior (AP) or lateral (LAT) views. The application of these views becomes significant later in this discussion when the dose equivalents to specific organs at depth are determined.

3. Methodology for Effective Dose Calculations

The approach that has been followed in converting the primary data, entrance skin exposures, to effective dose is given in the Table 2.

TABLE 2: Steps in the conversion of entrance skin exposure to effective dose for specific diagnostic x-ray procedures.

a. Account for back scattering;
b. Convert exposure to air-kerma, free in air;
c. Express air-kerma, free in air, in SI units;
d. Determine dose at depth for each critical organ in the field of view, respecting the radiation direction;
e. Multiply 'resultant weighting factor' times organ dose equivalent to determine organ effective dose;
f. sum the resultant effective doses for each organ in the field of view.

3.1 Backscatter

A fraction of the primary beam is scattered at 180 degrees when the beam encounters the patient. The back-scattered component increases the entrance skin exposure measurement relative to that without the patient. However, the free-in-air exposure rate is required for the calculations undertaken in this report. For the energies and field sizes used in diagnostic imaging reported here, the exposure at the phantom surface with backscatter included is approximately 1.35 times the free-in-air exposure. Hence the exposure data in Table 1 are multiplied by a factor of 0.74 to convert to the free-in-air exposure.

3.2 Air Kerma, Free-in Air

Conversion from an exposure in roentgens to a dose in rads is governed by the relation:

$$1 \text{ roentgen} = 0.873 \text{ rad.}$$

Hence the exposure data that have been corrected for backscatter are converted to doses with this expression. These data are further converted from rads to grays (or milligrays) in order to express them as air kerma in SI units.

$$1 \text{ rad} = 0.01 \text{ gray}$$

3.3 Conversion of Air Kerma to Organ Dose

Determining organ dose based on air kerma data could be complicated, requiring calculations that account for the attenuation of the beam by overlying tissue. The recent publication of detailed tables and graphs (ICRP - 74) has simplified the calculation, permitting a look-up approach for conversion coefficients for specific organs, based on the effective energy of the imaging beam and the orientation in which the image was taken. Hence the process of determining the dose at depth for a specific organ is to multiply the air kerma by the appropriate conversion coefficient obtained from ICRP-74.

The ICRP-74 conversion coefficients are based on monoenergetic photons incident on adult anthropomorphic models. The x-ray beams for diagnostic imaging have a spectrum of energies from the peak tube voltage downward. In this work, the effective energy for the purposes of applying the ICRP conversions has been taken as fifty-percent of the tube kVp.

Because the beam is a photon beam, the radiation weighting factor is unity and the organ dose in gray can be immediately converted to a dose equivalent in sievert.

3.4 Calculating Effective Dose

The final step in the process is to convert the organ dose equivalent to effective dose. This not only requires application of the ICRP tissue weighting factors (ICRP - 60), it also requires an apportioning of the organs according to the diagnostic image field of view.

This cannot be done in an arbitrary fashion. Nor is it really practical to apportion the critical organs on an image by image basis.

For the work being reported here, use was made of a recently published Health Physics Society Standard (HPS-1997). This standard establishes four body compartments in developing a uniform method of assessing occupational doses where dose rates are spatially varying and multiple badging is used. The Standard was written using the information of ICRP-26, and is out-dated by virtue of that reference base. However, the Standard does apportion critical organs into four compartments and we have taken the opportunity to utilize this apportioning methodology in our own work. At the same time we have updated the weighting factors to conform with the information of ICRP-60. The updated table of organ apportioning and weighting factor calculations is given in Table 3.

TABLE 3: Body Compartment Weighting Factors

Critical Organ	Weighting Factor ICRP - 60, WT	Fraction of WT Assigned to Compartment	Resultant Weighting Factor
HEAD AND NECK COMPARTMENT			
Thyroid	0.05	1.0	0.05
Bone Surface	0.01	0.33	0.003
Bone Marrow	0.12	0.165	0.02
Oesophagus	0.05	0.6	0.03
Skin	0.01	0.2	0.002
Remainder	0.05	0.1	0.005
Total, this Compartment		0.11	
THORAX COMPARTMENT			
Bone Surface	0.01	0.33	0.003
Bone Marrow	0.12	0.33	0.04
Oesophagus	0.05	0.40	0.02
Breast	0.05	1.0	0.05
Lung	0.12	1.0	0.12
Stomach	0.12	0.4	0.05
Liver	0.05	0.4	0.02
Colon	0.12	0.4	0.05
Skin	0.01	0.35	0.004
Remainder	0.05	0.2	0.01
Total, this Compartment		0.37	

ABDOMEN COMPARTMENT

Bone Surface	0.01	0.33	0.003
Bone Marrow	0.12	0.33	0.04
Stomach	0.12	0.6	0.07
Liver	0.05	0.6	0.03
Bladder	0.05	1.0	0.05
Colon	0.12	0.6	0.07
Gonads	0.20	1.0	0.20
Skin	0.01	0.35	0.004
Remainder	0.05	0.6	0.03

Total, this Compartment 0.50

EXTREMITIES COMPARTMENT

Bone Marrow	0.12	0.044	0.005
Skin	0.01	0.025	0.0002
Remainder	0.05	0.025	0.0012

Total, this Compartment 0.0064
Total of 4 Extremities 0.026

4. Sample Calculation: Lumbar Spine

The conditions for the imaging of the lumbar spine are shown in Table 4.

TABLE 4. Imaging the Lumbar Spine

Imaging View:	AP
Imaging Tube Voltage:	80 kVp
Effective Imaging Energy	40 keV
Entrance Skin Exposure:	327 mR
Convert ESE to account for Backscatter:	242 mR
Convert Exposure in Air to Air Kerma:	211 mrad
Convert Air Kerma to SI Units:	2.11 mGy

The calculation of the effective dose for a lumbar spine image is illustrated in Table 5. The table lists the critical organs in the field of view, provides the apportioned weighting factor (from Table 3) and lists the ICRP-74 conversion coefficient from air kerma to organ dose. In the final column, the results of calculations of the effective doses for the critical organs are provided when the air kerma for the image was 2.11 mGy. Implicit in the calculations for the final column is the use of the unit radiation weighting factor for photons. The sum of the individual effective doses is the total effective dose (0.92 mSv) for the image.

TABLE 5: Data for Lumbar Spine

Critical Organ	Apportioned Weighting Factor	Kerma/Dose Coefficient	Effective Dose (mSv)
Bone Surface	0.003	0.998	0.0063
Bone Marrow	0.04	0.211	0.0178
Stomach	0.07	0.998	0.1474
Liver	0.03	0.732	0.0463
Bladder	0.05	0.970	0.1023
Colon	0.07	0.661	0.0976
Gonads	0.20	1.10	0.4642
Skin	0.004	0.808	0.0068
Remainder	0.03	0.527	0.0334
Total			0.92

Conclusion: A single x-ray image of a lumbar spine, AP view, imaged at 80 kVp, incurs an effective dose of 0.92 mSv.

5. Effective Doses for Standard Procedures

Using the methodology described in this paper, effective doses have been calculated for the standard procedures identified in Table 1. The final calculations are compared with the entrance skin exposure data in Table 6.

TABLE 6: Summary of entrance skin exposures and the calculated effective doses for standard x-ray imaging procedures, based on 1997 Manitoba averages.

Imaging Procedure	Entrance Skin Exposure (mR)	Effective Dose (mSv)
Chest	11.7	0.02
Abdomen	222	0.73
Cervical Spine	59	0.05
Thoracic Spine	168	0.30
Lumbar Spine	327	0.92
Lateral Skull	65	0.02

6. Summary and Conclusion

A methodology has been developed to express the quality-control parameter of "entrance skin exposure" in terms of effective dose for standard x-ray procedures. The resulting numbers range from three to thirty times lower than the initial measurements and set the doses from medical procedures into perspective with respect to effective doses observed during other human activities. These data are based on routine measurements of x-ray imaging in Manitoba. The entrance skin exposures are more easily converted to effective doses now that the data of ICRP-74 are available. However, an important intermediate step is the application of the model for apportioning organs in various fields of view and determining the apportioned organ weighting factor for the correct conversion from organ dose equivalent to effective dose. That model was published in a Health Physics Society Standard.

While the resultant effective dose data are much less than the exposures initially measured, the results are still conservative. Use of the compartment model assumes that the whole compartment is in the field of view. On the contrary, good imaging technique collimates the x-ray imaging beam and limits the field of view to the body region of interest. It is not possible to account for this protective activity in assessing all images and the conservative model has therefore been chosen.

The results of the determination of effective doses from standard imaging procedures leads to the conclusion that the oft-quoted exposure data significantly over state the risk in medical imaging.

7. References

HPS-1997. Health Physics Society Standard: Criteria for Performing Multiple Badging, An American National Standard. HPS.N13.41-1997.
Health Physics Society, 1313 Dolley Madison Blvd. Suite 402, McLean, VA, 22101, USA.

ICRP-60. Recommendations of the International Commission on Radiological Protection, ICRP Publication 60. Annals of the ICRP, 21 (1-3), Pergamon Press, Oxford, 1991.

ICRP-74. Conversion Coefficients for use in Radiological Protection Against External Radiation, ICRP Publication 74. Annals of the ICRP, 26 (3,4), Pergamon Press, Oxford, 1996.

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