

Effective dose and energy imparted in diagnostic radiology

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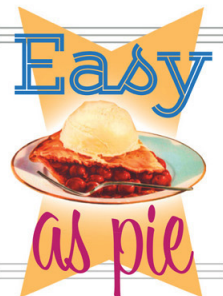
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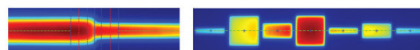
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Effective dose and energy imparted in diagnostic radiology^{a)}

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The patient effective dose, E , is an indicator of the stochastic radiation risk associated with radiographic or fluoroscopic x-ray examinations. Determining effective doses for radiologic examinations by measurement or calculation is generally very difficult. By contrast, the energy imparted, ϵ , to the patient may be obtained from the x-ray exposure-area product incident on the patient. As energy imparted is approximately proportional to the effective dose for any given x-ray radiographic view, the availability of E/ϵ ratios for common radiographic projections provides a convenient way for estimating effective doses. Ratios of E/ϵ were obtained for 68 projections using E and ϵ values obtained from published dosimetry data computed using Monte Carlo techniques on an adult anthropomorphic phantom. The average E/ϵ ratio for the 68 projections in adults was 17.8 ± 1.4 mSv/J, whereas uniform whole body irradiation corresponds to 14.1 mSv/J. The major determinant of E/ϵ ratios was the projection employed (the body region irradiated and x-ray beam orientation), whereas the tube potential and beam filtration were of secondary importance. Adult E/ϵ ratios may also be used to obtain effective doses to pediatric patients undergoing x-ray examinations by application of a correction factor based on the patient mass. © 1997 American Association of Physicists in Medicine. [S0094-2405(97)02208-6]

Key words: patient dosimetry, pediatric dosimetry, effective dose, energy imparted

I. INTRODUCTION

The effective dose, E , is a dosimetry parameter which takes into account the doses received by all irradiated radiosensitive organs and may be taken to be measures of the stochastic risk.^{1,2} Although the effective dose is an occupational dose quantity based on an age profile for radiation workers, this dose descriptor is being increasingly used to quantify the amount of radiation received by patients undergoing diagnostic examinations which use ionizing radiation.³⁻⁵ Notwithstanding the fact that there are problems associated with converting effective doses to a corresponding detriment,⁶ there are important benefits to be gained by using effective dose to quantify patient doses in diagnostic radiology. One advantage is that the effective dose attempts to measure the risk to the patient, which is the motivation for all patient dosimetry studies in diagnostic radiology. In addition, the effective dose to a patient undergoing any examination may be compared to that of any other radiologic procedure as well as natural background exposure and regulatory dose limits, which are increasingly expressed using effective dose values.^{2,7,8}

Measurement or computation of effective doses for any x-ray examination is difficult and time consuming. An additional problem is that most measurements or calculations make use of a standard phantom based on the reference man as defined by the International Commission on Radiological Protection.⁹ Although the importance of patient size for medical radiation dosimetry has been recognized,^{10,11} it is not obvious how to scale the effective dose computed for the standard man to different sized patients, such as pediatric patients, who undergo similar examinations. These limitations impede the wider use of effective dose in radiology. A

practical method to estimate values of effective dose associated with common x-ray examinations would clearly be advantageous to the radiology community.

In this study, we propose a method to determine the effective dose to patients undergoing any diagnostic x-ray examination using the energy imparted to the patient, ϵ . Values of E/ϵ were obtained from the radiation dosimetry data presented for 68 x-ray projections computed using Monte Carlo calculations on an adult anthropomorphic phantom.¹² The energy imparted to patients may be determined from values of the exposure-area product incident on the patient¹³⁻¹⁷ and can be combined with E/ϵ ratios to yield values of the patient effective dose. In addition, this method was extended to determine effective doses in patients who differ in mass from the adult-sized phantoms used in current patient dose assessment procedures.^{18,19}

II. METHOD

A. Reference man

The National Radiological Protection Board (NRPB) has recently performed a comprehensive series of Monte Carlo (MC) dose calculations for the most common x-ray projections.¹² The Monte Carlo runs made use of a hermaphrodite anthropomorphic phantom with a mass of 70.9 kg and a height of 174 cm and which included the testes, ovaries, uterus, and female breasts. Each MC run tracked the pattern of energy deposition in the anthropomorphic phantom from primary and scattered photons for a total 4 000 000 photons used with each x-ray projection. A total of 68 separate views were obtained using x-ray spectra generated between 50 and 120 kV with added filtration ranging from 2 mm Al to 5 mm

Al. X-ray spectral data were obtained using an updated version of a computer program published by Iles.²⁰

For each x-ray examination, the MC dosimetry data generated by the NRPB permitted the computation of the effective dose, E , as defined by the International Commission on Radiological Protection.^{1,2} The phantom breast dose and the mean of the testes and ovary doses were used to determine the contributions to the effective dose from the breast and gonads, respectively. The MC dosimetry data also provided the mean doses to three-body regions consisting of the head, D_h , trunk, D_t and legs, D_l . The mean energy imparted to the patient, ϵ , was obtained using

$$\epsilon = D_h \times 5.8 + D_t \times 43.0 + D_l \times 22.1 \text{ J}, \quad (1)$$

where the mass of the head is 5.8 kg, the mass of the trunk, including the arms, is 43.0 kg, and the mass of the legs is 22.1 kg.²¹

The complete dosimetry results of these MC simulations have been made available in a software format²² and were used to obtain the values of energy imparted, ϵ , employed in this study. For each x-ray projection, values of E/ϵ were obtained at eight tube potentials ranging between 50 and 120 kV and generated at 10 kV intervals with a beam filtration equivalent to 3 mm Al. The effective dose per unit energy imparted, $(E/\epsilon)_i$ (mSv J^{-1}), for each projection i was obtained by averaging these eight values (\pm one standard deviation).

B. Nonreference man

By definition, 1 Gy of uniform whole body irradiation to x rays results in an effective dose of 1 Sv and is *independent* of the mass of the exposed individual. For a 70.9 kg anthropomorphic adult subject to uniform whole body irradiation, absorbed energy can be directly converted into effective dose with 1 J corresponding to an effective dose of 14.1 mSv. For uniform whole body irradiation, the effective dose $E(M)$ to an individual with a mass M who absorbs a total of ϵ J is given by

$$E(M) = \epsilon \times 14.1 \times \frac{70.9}{M} \text{ mSv}. \quad (2)$$

Figure 1 shows how the effective dose varies with the patient mass for uniform whole body irradiation with a total of 1 J imparted to the individual.

For the nonuniform exposures normally found in diagnostic radiology, the relative radiosensitivity of the irradiated region needs to be taken into account when obtaining the effective dose. The *relative* radiosensitivity of any body region remains approximately constant with age.^{2,23} For instance, if the head accounts for x% of the total stochastic risk in adults uniformly exposed to x rays, this body region will also account for approximately x% of the total stochastic risk for any other age group. As a result, the effective dose to a patient of mass M kg for a given x-ray projection i who absorbs ϵ J is obtained using

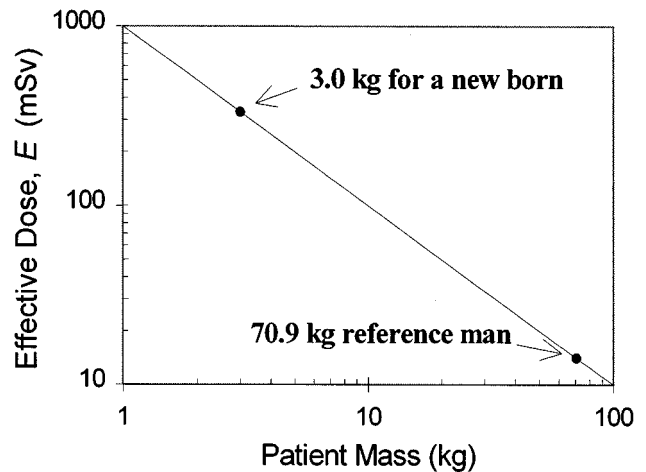


FIG. 1. Effective dose vs patient mass for one joule of uniform whole body irradiation.

$$E = \epsilon \times (E/\epsilon)_i \times \frac{70.9}{M} \text{ mSv}, \quad (3)$$

where $(E/\epsilon)_i$ is the ratio of effective dose to energy imparted (mSv J^{-1}) obtained for the same projection i in the adult anthropomorphic phantom with a mass of 70.9 kg.

III. RESULTS

Figure 2 shows values of $(E/\epsilon)_i$ for the head, chest, stomach, and rectum for the three common projections: anterior–posterior (AP), posterior–anterior (PA), and lateral (LAT). For each projection, $(E/\epsilon)_i$ data are plotted as a function of tube potential for beam filtrations of 3 and 5 mm Al. Increasing the beam filtration from 3 to 5 mm Al had very little effect on the $(E/\epsilon)_i$ ratio. For the three head examinations depicted in Fig. 2, the average increase in $(E/\epsilon)_i$ at 80 kV due to an additional 2 mm Al filtration was only 5.6%.

Increasing the tube potential generally increased the value of the $(E/\epsilon)_i$ ratio. Exceptions to this trend, however, can occur (e.g., AP rectum projection) where the presence of a small radiosensitive organ (i.e., male gonads) at the patient surface results in a decrease of the $(E/\epsilon)_i$ ratio with increasing tube potential. For head examinations, the increase in the $(E/\epsilon)_i$ ratio when the tube potential increased from 80 to 90 kV was 5.6%.

Table I shows the tube potential averaged values of the $(E/\epsilon)_i$ ratio ($\pm\sigma$) for the 68 x-ray projections. In addition to the three most common projections, Table I also includes left anterior oblique (LAO), right anterior oblique (RAO), left posterior oblique (LPO), and right posterior oblique (RPO) views. An estimate of the importance of x-ray tube potential (kV) is provided by the standard deviation values, which is expressed as a coefficient of variation ranged between 0.8% and 26%. The eight bolded values in Table I correspond to those which demonstrated a decrease in the $(E/\epsilon)_i$ ratio as the tube potential increased, similar to the AP rectum data shown in Fig. 2.

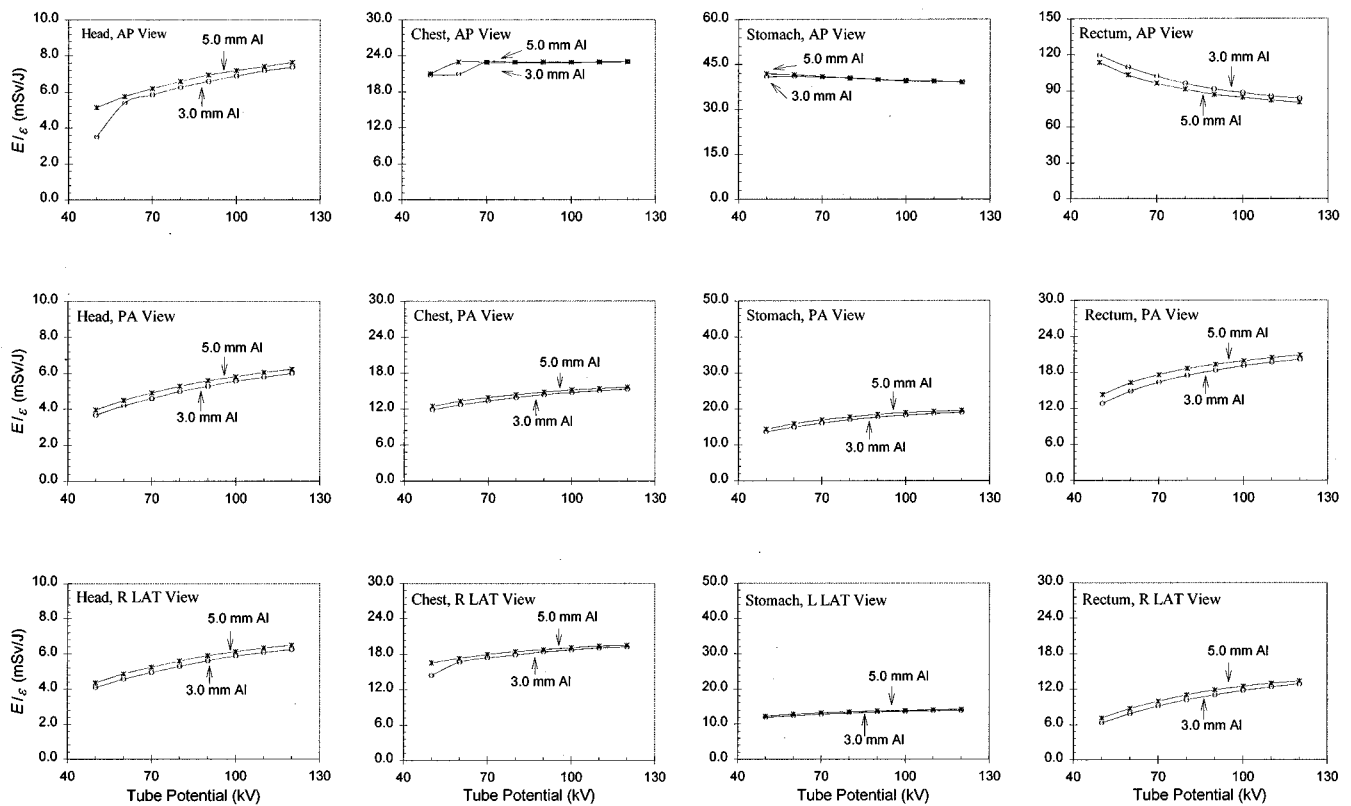


FIG. 2. Values of $(E/\epsilon)_i$ as a function of applied x-ray tube potential.

IV. DISCUSSION

Determining the effective dose using the procedure described in this study requires an estimate of the energy im-

parted to the patient. The energy imparted to patients is a well-defined quantity²⁴ and may be estimated using one of several methods published in the scientific

TABLE I. Values of $(E/\epsilon)_i$ (mSv/J) for common medical x-ray examinations and projection views (3.0 mm Al).

Exam	AP	PA	Left LAT	Right LAT	LAO	RAO	LPO
Head	6.1±1.3	5.0±0.8	5.3±0.7	5.3±0.8			
Cervical spine	24.2±2.0		4.6±0.8	5.0±0.7			
Throat			16.8±0.5	16.8±0.5			
Left shoulder	7.9±0.7						
Right shoulder	7.7±0.7						
Esophagus					13.2±1.3	13.4±1.0	22.9±0.6
Thoracic spine	22.3±0.3		12.3±1.1	13.5±1.4			
Chest	22.4±0.9	13.9±1.2	14.7±0.8	17.7±1.6			
Heart	12.7±1.6	14.0±1.7	18.4±1.2	18.9±1.5	18.1±0.7	20.3±0.9	
Upper stomach	49.9±1.0	22.1±2.2					
Stomach	40.2±0.7	16.8±1.9	13.1±0.7		14.1±1.0	21.2±2.5	26.9±1.9
Kidneys	22.6±0.4	13.3±1.2					
Lumbar spine	23.2±1.0		9.6±1.3	15.2±2.3			10.3±1.1 ^a
Left flexure					11.6±1.7		
Right flexure						10.8±1.4	
Duodenum	22.9±1.5	12.2±2.2				12.2±2.5	14.9±2.2
LSJ			8.3±2.0	11.8±2.8			
Abdomen	21.3±1.1	12.9±1.9					
Small intestine	20.1±2.3	14.9±2.9					
Pelvis/colon	25.2±0.4	25.2±0.3					
Colon					7.9±1.8	10.1±2.2	22.9±0.2
Urinary bladder	34.6±0.5						
Left hip	24.6±0.3						
Right hip	18.5±0.2						
Rectum	97.2±12.6	17.4±2.5	5.5±1.4	10.2±2.3		10.7±2.2	48.9±3.3

^aRPC: 25.8±0.9.

TABLE II. Values of H_E/E for common medical x-ray projections.

Exam	AP	PA	Left LAT	Right LAT	LAO	RAO	LPO
Head	1.5	1.7	1.8	1.8			
Cervical spine	0.68		0.96	0.88			
Throat			0.75	0.74			
Left shoulder	1.1						
Right shoulder	1.1						
Esophagus					1.2	1.2	1.9
Thoracic spine	1.4		1.2	1.2			
Chest	1.4	1.5	1.5	1.4			
Heart	1.2	1.1	1.1	1.0	1.2	1.1	
Upper stomach	0.84	2.8			2.4	1.6	0.81
Stomach	0.83	2.7	1.4				
Kidneys	1.0	2.3					
Lumbar spine	1.0		1.8	1.5			1.9 ^a
Left flexure					1.8		
Right flexure						1.8	
Duodenum	1.2	1.5				1.3	1.3
LSJ			1.8	1.2			
Abdomen	1.0	1.3					
Small intestine	1.9	1.5					
Pelvis/colon	1.3	1.3					
Colon					1.3	1.1	1.4
Urinary bladder	1.3						
Left hip	1.1						
Right hip	1.4						
Rectum	1.2	0.94	1.0	0.78		0.83	1.2

^aRPC: 0.95.

literature.^{13-17,25,26} Commercial dose-area product meters may be used to estimate the energy imparted to a patient from the product of the exposure and x-ray beam cross-section area.²⁷⁻³¹ The exposure-area product may also be obtained directly from the product of the free-in-air entrance skin exposure and the beam area. Use of this latter approach has been shown to generate absolute values of energy imparted to patients with an accuracy of 9%.¹⁷ Representative values of energy imparted to patients undergoing diagnostic examinations range from a few mJ for chest examinations to hundreds of mJ for barium meals and barium enemas.

The data in Fig. 2 show that it is the body region irradiated and the selected projection which are the most important determinants of the $(E/\epsilon)_i$ ratio. The observed differences between body regions and projections result from the presence, or absence, of relatively radiosensitive organs in the irradiated regions which receive the highest doses. For example, AP projections of the chest have a higher effective dose than PA projections for the same energy imparted due to the presence of relatively radiosensitive breast tissue at the patient entrance where the absorbed dose is highest.

In about 90% of the projections investigated, the $(E/\epsilon)_i$ ratio increased with tube potential and filtration. The standard deviation values listed in Table I demonstrate the relative importance of tube potential when selecting an $(E/\epsilon)_i$ ratio for any given projection. Small standard deviations indicate that $(E/\epsilon)_i$ ratios are relatively independent of tube potential. This behavior is primarily determined by the relative location of the radiosensitive organs and tissues which contribute to the effective dose.² To account for the dependence of $(E/\epsilon)_i$ on tube potential, the data in Fig. 2 and

Table I may be used as a guide for estimating appropriate $(E/\epsilon)_i$ values to use for a tube potential which may differ markedly from the "average" value as listed in Table I.

Uniform whole body irradiation for adults (70.9 kg) results in an effective dose of 14.1 mSv for each joule of energy deposited in the patient. Dividing the data in Table I by 14.1 mSv J⁻¹ yields the relative radiosensitivity of each projection per unit energy imparted as compared to uniform whole body irradiation. When averaged over the available projections, the head region sensitivity was 30% lower than that of uniform whole body irradiation when unit energy is imparted to either body region. By the same criterion, both the thorax and abdomen/pelvis regions were 20% more sensitive than uniform whole body irradiation. For the same energy imparted, AP projections had 70% higher effective doses when compared to PA projections where the latter had an average sensitivity which was within 10% of uniform whole body irradiation. On average, lateral projections showed about 80% the sensitivity of uniform whole body irradiation.

The effective dose was introduced to replace the effective dose equivalent, H_E . The E and H_E parameters are both conceptually similar but make use of different organ weighting factors. Table II gives the H_E/E ratios at 80 kV and 3 mm Al filtration.¹² For 56 of these examinations (i.e., 74%), H_E values were greater than E values. The average H_E/E ratio for all 68 examinations was 1.3 ± 0.4 . The data in Table II permit any value of effective dose to be converted into the corresponding effective dose equivalent. This may be useful, for example, when comparing current E doses computed us-

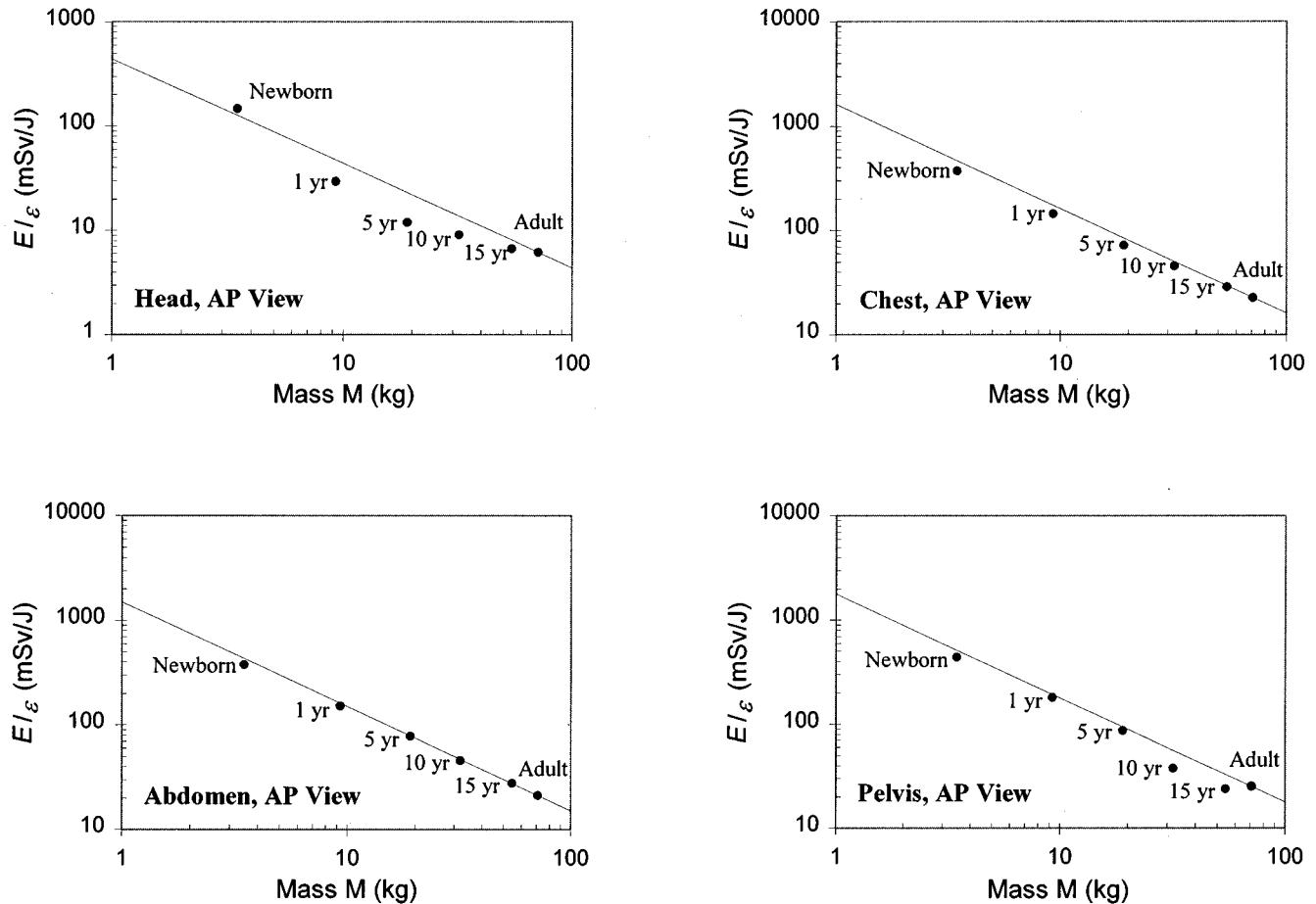


FIG. 3. Comparison of $(E/\epsilon)_i$ vs patient age as determined by Eq. (3) and by using the dosimetry data in Ref. 36.

ing the method given in this paper with previously computed H_E doses.⁵ For most radiographic examinations, the effective dose is smaller than the effective dose equivalent. The major cause is the reduced significance of the ‘‘remainder’’ organs which accounted for 30% of the total stochastic risk in computing H_E but only 5% of the risk in computing E . The high value allocated to the remainder organs increased the values of effective dose equivalent in patient dosimetry.³²

The use of Eq. (3) permits the determination of the approximate values of effective doses to pediatric patients who undergo radiologic examinations and whose entrance skin doses and energy imparted values are much lower than those encountered in adult radiography.^{33–35} The NRPB has recently published dosimetric data on pediatric patients ranging from newborns to 15 year olds.³⁶ Figure 3 shows a comparison between the $(E/\epsilon)_i$ values obtained using Eq. (3) (continuous line) with the NRPB data (solid circles) which were determined by performing MC calculations in a range of anthropomorphic phantoms of different age. Differences between these two data sets, when averaged over the five ages investigated, were 11% for chest, 5% for the abdomen, and 17% for the pelvis. For the head region, however, the average difference between these two approaches to estimating $(E/\epsilon)_i$ was 37%, which may be due to pediatric heads accounting for a markedly larger fraction of the total body

masses in newborns than in adults. It is of interest to note, however, that use of different types of anthropomorphic phantoms to determine pediatric effective doses in planar radiography can result in differences in effective dose of the order of 30%.³⁷

Although knowledge of the pediatric effective dose associated with any x-ray procedure is helpful, it is important to note that any resultant detriment will depend on the age of the exposed individual. The stochastic radiation risks of carcinogenesis and genetic effects are generally greater for children than for adults^{2,38} and these factors would clearly need to be taken into account when converting any pediatric effective doses into a value of risk or detriment. As a result, direct comparisons of pediatric doses with those of adults need to be treated with circumspection.

The effective dose, E , is able to account for nonuniform irradiation of different tissues and organs in the body and use of the effective dose as a dose descriptor in diagnostic radiology enables a direct comparison of the detriment associated with different radiologic procedures. Expressing patient doses in terms of the effective dose provides a consistent method of reporting effective doses from diagnostic radiologic examinations. The use of the effective dose may also permit an estimate of patient risk to be obtained by using current stochastic risk factors.^{2,5,39} These risk factors, how-

ever, clearly need to be treated with great caution given the current uncertainties associated with the extrapolation of radiation risks from high doses to those normally encountered in diagnostic radiology.^{40,41}

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