INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

H4.SMR/773-37

College on Medical Physics: Radiation Protection and Imaging Techniques

5 - 23 September 1994

Summary of Organ Doses in Diagnostic Radiology

K.A. Jessen

Department of Medical Physics
Aarhus University Hospital
Aarhus, Denmark

Lecture notes: College on Medical Physics: Radiation Protection and Imaging Techniques, Trieste, September 1994.

Summery of organ doses in diagnostic radiology.

K.A. Jessen, Department of Medical Physics, Aarhus University Hospital

Introduction. For the relative low absorbed doses as the patients receive from diagnostic X-ray examinations only stochastic radiation effects are in general of interest. For estimates of stochastic risk, the average absorbed dose in each radiosensitive organ or tissue is assumed to be the relevant quantity. In radiological protection this quantity has to be weighted for the radiation quality that is of interest. For diagnostic radiation qualities the radiation weighting factor, w_R, always can be set equal to one and therefore the socalled equivalent dose in a tissue or organ:

$$H_T=\sum_R w_R \cdot D_{T,R}=D_T$$

is equal the mean absorbed dose but with the special name sievert (Sv). The relationship between the probability of stochastic effects and equivalent dose is found also to depend on the organ or tissue irradiated. The factor by which the equivalent dose in tissue or organ T is weighted, is called the tissue weighting factor, w_T which represents the relative contribution of that organ or tissue to the total detriment due to these effects resulting from uniform irradiation of the whole body.

The ICRP has introduced the quantity, the effective dose as the sum of the weighted equivalent doses in all tissues and organs of the body. It is given by the expression:

$$E=\sum_T w_T \cdot H_T$$

where H_T is the equivalent dose in tissue or organ T and w_T is the weighting factor for tissue T. The unit is the joule per kilogram with the special name sievert. The tissue weighting factors recommend by ICRP have been developed from a reference population of equal numbers of both sexes and a wide range of ages (see page 10).

Mathematical and tomographic models. Mean absorbed doses in various organs and for various diagnostic x-ray procedures have been calculated using Monte Carlo techniques and mathematical phantoms. These computational human models can be devided into mathematical and tomographic models. In the mathematical models mathematical expressions representing planes, cylindrical, conical, elliptical or spherical surfaces are used to describe idealised arrangements of body organs. The best known representative of the mathematical models is the MIRD phantom, originally defined for determination of the effective dose in radiation workers from intake of radioactive nuclei. It has been commonly called the "MIRD -5 phantom", due to being published in the MIRD Pamphlet No. 5. The phantom is bisexual, with both ovaries and testes but with no female breast. The phantom was modified by Rosenstein for females by adding breast to its chest walls. Kramer introduced male and female adults mathematical models and several paediatric models have been derived to represent infants and children of various ages. For all of these models, the organ volumes are in accordance with the ICRP data or. Reference Man given in ICRP Publication 23.

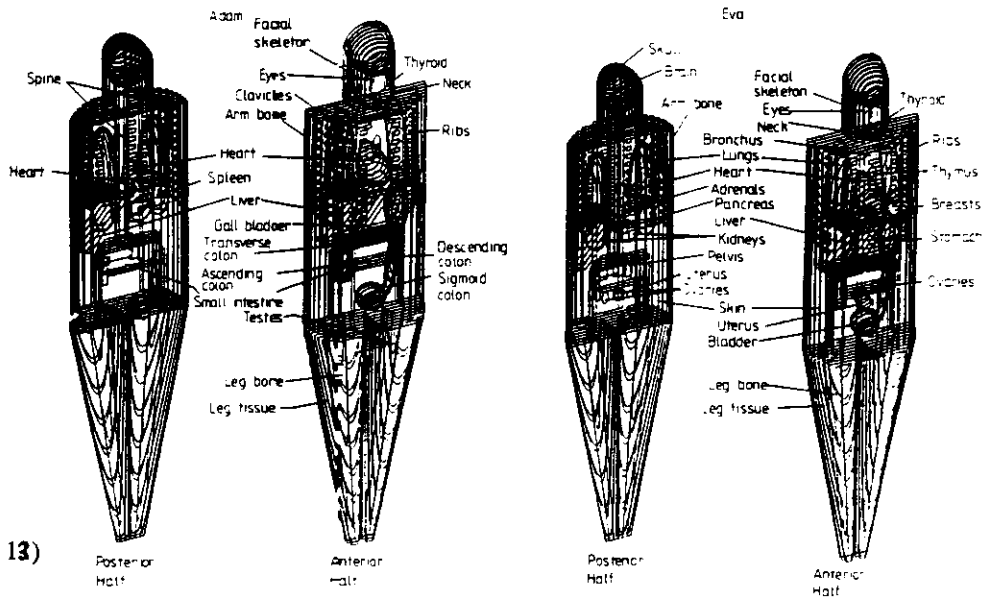

Figure 1 (ref. 13)

More recently, tomographic models have been developed, which use computed tomographic (CT) data of real persons to provide three-dimensional representations of the body. From a whole-body CT scan consisting of contiguous slices such models can be constructed for both sex and for different age groups and a whole family of such voxel models has been constructed.

In the mathematical models, organ shapes are reduced to a very simple form and therefore do not describe any real individual in detail but rather represent a mean of a population. The tomographic models are constructed from CT data of real persons and might therefore deviate significantly from reference data in both external and internal dimensions. Most of the mathematical models are rigid in size where the external dimensions of tomographic models can be adapted to any size, for each of the three dimensions independently. This possibility of scaling up or down the original model may of course be kept within reasonable magnitudes not to introduce considerable errors in the body proportions.

The tomographic model has a great advantages in modelling the distribution of bone marrow in the skeleton compared to the mathematical models, where all skeletal components are homogeneously distributed in the skeleton. In the tomographic models, the amount of bone marrow and hard bone in each single skeletal voxel can be assessed, based on the CT data.

Computational Methods. Standard Monte Carlo techniques have been used to track the paths of energy deposited by many photons in the organs and tissues and following the photons until they were absorbed or escaped. In diagnostic radiology we can concentrate on the simulation

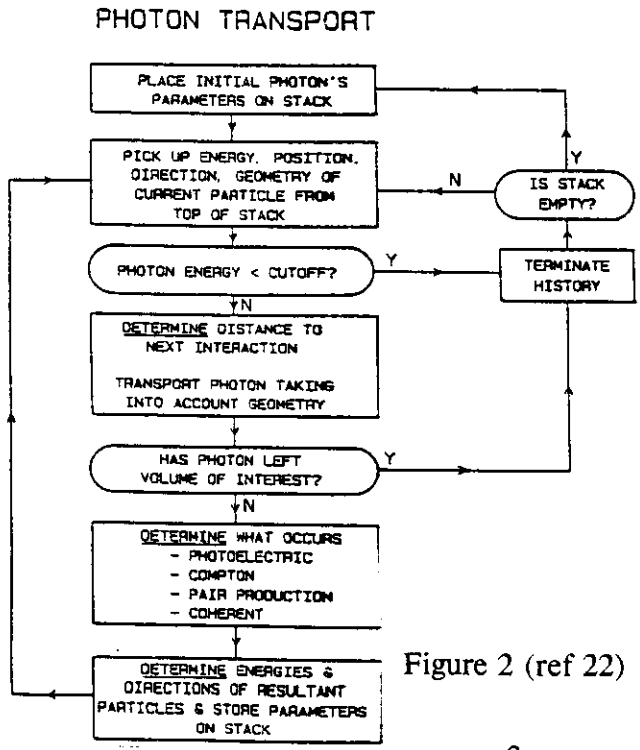

Figure 2 (ref 22)

of particularly low energy photons in the energy range of 5 KeV to 300 KeV. In this energy range, many dosimetric problems can be solved assuming charged particle equilibrium (CPE) to exist and thus the transport of the secondary electrons will not be needed. The electrons can be assumed to impart their energies at the spot of generation and bremsstrahlung photons generated, when the secondary electrons are slowed down, can be neglected. The only source of photons is the primary source. In figure 2 an example of a flow chart of a photon transport program is shown.

The energy of electrons ejected in the interactions cannot exceed the maximum photon energy of f.ex. 150 KeV and is generally much less than 0.3 mm, and since the probability of bremsstrahlung is very low, it is assumed that the energy of the electron is totally absorbed at the interaction site. The energy deposited at a point of interaction is calculated by summing the photoelectric and the incoherent scattering energy components. That is, the total energy deposited in the interaction is the addition of the energy deposited by each of the processes multiplied by its probability of occurence and the statistical weight of the photon at the time. Each point of interaction can be definitely attributed to a specific organ in the phantom by the coordinates of the interaction point. For each organ the energy depositions are summed and the energy absorbed in each organ is determined. From this the organ dose can be easily computed.

Uncertainties of calculated organ doses. In all dose calculations using Monte Carlo methods, a statistical uncertainty is inherent in the calculated doses depending on the frequency and homogeneity of the interaction events in an organ. Large organs within the beam are characterised by small uncertainties, whereas small organs outside the beam may have large statistical errors. Random errors in the calculated organ doses can be reduced by increasing the number of photons that deposit energy in each organ - normally the computer employed sets the limit. One million photon histories in the NRPB calculations gave a standard error in the organ dose conversion factors below 5% for all important organs receiving a significant proportion of the dose.

Linear attenuation coefficients are derived from atomic cross-sections and the elemental compositions and densities of the tissues. The cross-sections have uncertainties of only a few percent and the differences in density and composition between the various soft tissues in the body

and those modelled in the phantom are relatively small and are unlikely to introduce errors of more than $\pm$ 10% in the organ dose factors.

Human anatomy deviates from patient to patient and the phantom represents no more than a standard model of the human body and the results obtained with it should not be interpreted as applying to any particular individual. Calculated organ doses are in fact only valid for exposure situations similar to those simulated with respect to irradiation geometry, patient size and geometry and radiation quality. Small deviations in the field size and location may introduce deviations in organ doses, especially in small organs located at the edge of the field. Also the dimensions of the patient strongly influence the absorbed dose distribution in the body. Depending on the quality of the X-ray beam and the tissues being irradiated, the half-value layer is approximately 2 to 6 cm in soft tissue. An increase in patient thickness by one half-value layer causes an approximate doubling of the entrance skin dose, increasing the organ doses by up to a factor of 2, depending on the depth of the respective organs.

Comparison between different calculations. A direct comparison of the results of different sets of Monte Carlo organ dose calculations is complicated because different quantities, phantoms, X-ray field geometries and X-ray spectra have been used by the various authors. An attempt to present comparative organ doses per unit exposure measured free-in-air at the entrance point on the phantom are given in Table 1 for two X-ray fields for calculations performed by NRPB, GSF and Rosenstein and reasonable agreement is obtained between the three sets of organ dose conversion factors.

Organ doses in conventional radiology. Values of mean absorbed organ doses are given by GSF (Drexler et al, 1985) for a variety of diagnostic x-ray procedures and radiation qualities (kilovolts and beam filtrations). The values are normalized to the exposure free-in-air (without backscatter) on the central axis in the entrance field. NRPB (Jones & Wall, 1985) has produced similar extensive tables of organ mean absorbed doses from 11 common examinations, with clear indication of beam size and position on the phantom. The positions of the various organs

Comparative organ dose data from three sets of calculations

Organ	Organ dose per unit exposure at surface					
	AP abdomen (90 kV, 2.5 mm Al)			PA chest (90 kV, 2.5 mm Al)		
	NRPB	GSF	Rosenstein*	NRPB	GSF	Rosenstein*
Breast	0.004	0.005 ≐	-	0.090	0.124 ≐	0.060
Lung	0.011	0.011	0.015	0.480	0.486	0.431
Red bone marrow	0.045	0.047	0.048	0.147	0.150	0.102
Bone	0.056	0.060	-	0.297	0.315	-
Thyroid	<0.001	<0.001	<0.001	0.051	0.048	0.040
Ovaries	0.267	0.311 ≐	0.258	0.003	0.004 ≐	0.002
Testes	0.017	0.019	0.022	<0.001	<0.001	<0.001
Uterus	0.353	0.383	0.330	0.002	0.004	0.002

* Data taken from Kerlakes and Rosenstein (1980) for 3.0 mm Al HVL. Assumed to be similar spectrum to that generated at 90 kV with 2.5 mm Al total beam filtration.

≐ Calculated for female phantom (EVA) with smaller physique and different breast model than other phantoms.

Table 1 (ref.10)

within the primary field are also shown. A bisexual phantom including the female breast was used. In addition to the organ mean absorbed doses, values of imparted fractions, easily obtained from the Monte Carlo calculations, and backscatter absorbed dose coefficients are given.

Organ doses in paediatric radiology. There is no fundamental difference between the method used to determine mean organ absorbed doses in children and that used in adults. Rosenstein et al (1979) compiled organ doses for examinations in paediatric radiology using MIRD-type child phantoms. The organ doses for each type of examination are given for three different spectra, which are characterized by their half-value layer in aluminium.

The voxel type phantoms BABY and CHILD developed by GSF have been used to quantify the dependence of organ dose per exit dose conversion factors on patient diameter (Veit et al. 1989). Monte Carlo simulations of the five most frequent examinations in diagnostic paediatric radiology are given for both phantoms. The BABY phantom represents an 8 week old baby and the CHILD phantom represents a 7 year old child. The data can be used as phantom, examination and organ specific scaling factors for correction calculated exit dose conversion factors.

Breast absorbed doses in mammography. The X-ray spectra used for mammography are low energy and the depth dose within the breast decreases rapidly with increasing depth. Breast dose is specified, therefore, using a quantity which is representative of the dose to the whole organ such as the mean dose to the glandular tissues within the breast. It is difficult to measure the mean glandular dose to the breast directly and therefore Monte Carlo calculation of conversion factors for the estimation of mean glandular breast doses has been performed (Dance, 1990). The dose to a standard breast phantom can be determined by measuring the incident air kerma to a Perspex phantom (k) and applying the appropriate multiplicative conversion factors (p and g) given by Dance. The mean glandular dose ,D, to the standard breast can be calculated using the prescription

$$D = k \cdot p \cdot g$$

where p converts the incident air kerma to the Perspex phantom to that for the standard breast and g converts the incident air kerma for the standard breast to mean glandular dose. Both of these conversion factors depend upon radiation quality. The calculations have been performed for breast thicknesses in the range 2 - 8 cm.

Organ doses in Computed Tomography. Computed Tomography offers a high diagnostic capability, but the dose to the patient is high compared to conventional radiography. CT procedures represents still only a few percent of the annual total of all X-ray examinations, yet account for approximately 20% of the resulting collective dose in some EU countries. Consequently, the determination of patient doses resulting from CT examinations becomes increasingly important. Two sets of very valuable catalogues excists from 1991 giving organ doses from CT-examinations - the GSF-Bericht 30/91 and the NRPB-R250 both based on Monte Carlo calculations.

The GSF catalogue contains data from which doses to selected organs and tissues can be estimated for CT examinations as commonly performed in Germany. No beam shaping devices has been introduced between focus and patient. Three different radiation qualities were considered (from 80 KVp to 137 KVp). All dose values are given as organ dose conversion factors, i.e. organ absorbed doses normalised to a measurable quantity, the CT Dose Index (CTDI), expressed in air Kerma free in air at the axis of rotation. The models for the human body

used for the calculations were the GSF adult mathematical phantom "Adam" and "Eva" whose organ masses and volumes are in agreement with the ICRP data or Reference Man. Organ dose conversion factors were calculated for single CT slices at positions varying contignously from 10 cm below the bottom of the trunk up to the top of the head. The width of each single slice is 1 cm. 21 organs are considered in the GSF catalogue. Mean organ doses can be calculated by summing up the values of f (organ, z) as listed in the tables of the catalogue

$$D(organ) = K_{air} \cdot \sum_{ze}^{zu} f(organ, z)$$

where z_l and z_u indicate the lower and upper boundaries of the scanned region and K_{air} is the air kerma free in air on the axis of rotation. The organ doses, D(organ), evaluated by this method are mean organ doses, i.e. they are averaged over the entire organ also in those cases where only a part of the organ is irradiated.

The NRPB catalogue contains a series of Monte Carlo calculations for 23 sets of exposure conditions appropriate to 27 common models of CT scanner from five manufactures. To make the calculations generally applicable, organ doses were determined for the individual irradiation of 208 contiguous 5 mm thick transverse slabs of the hermaphrodite phantom from the top of the legs to the top of the head. The calculations provide estimates of dose tc 27 organs or regions of the phantom, nomalised to unit tissue dose on the axis of rotation of the scanner in the absence of the phantom (CTDI). Corrections were made for the excistance of shaped filters treated as simple X-ray attenuators. The mathematical phantom, cross-section data and methods used for simulating photon interactions in the phantom were the same as in Report NRPB - R186 with a few logical changes.

Figures 3 show the relative locations of the important organs or regions of the phantom and the 208 slabs each 5 mm thick. Estimates of typical patient dose from CT can be made by first summing the normalised organ doses over regions of the phantom appropriate to an examination, using a packing factor to allow for the overlapping or interspacing of slices. These doses must then be multiplied by the free-in-air dose on the axis of rotation of the scanner appropriate for the examination, as described by the computed tomography dose index (CTDI). Dose data for all 23 series of Monte Carlo calculations are made available on computer disk in the related software report NRPB - SR250.

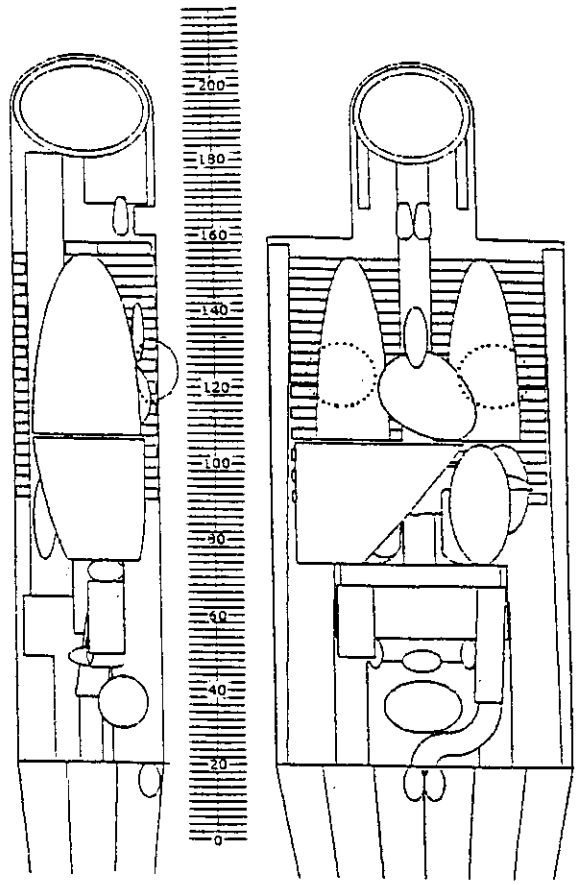

Figure 3 (ref. 12)

A comparison of the NRPB and GSF calculations was made for normalised organ dose provided by GSF and doses to individual slabs were summed from the NRPB tables over three sections of the phantom, and the agreement is generally good. (Table 1, ref. 13)

The GSF has produced a catalogue recently about organ dose conversion factors resulting from CT examinations in Paediatric Radiology GSF-Bericht 30/93. Two radiation qualities and two exposure geometries were simulated as well as the use of assymetrical beams. The use of further beam shaping devices was not considered. The organ dose conversion factors are applicable to babies at the age of ca. 2 months and to children between 5 and 7 years but can be used for other ages as well with the appropriate adjustments. For the calculations, the patients were represented by the GSF tomographic anthropomorphic models BABY and CHILD, which also have been used for conventional radiology. The methodology is similar to the procedure for organ dose determination for adults described above.

Dose measurements. Two types of measurements of patient dose are normally recommended: Entrance surface dose measurements using thermoluminescent dosimeters (TLD's) and dose-area product measurements and from such measurements organ doses can be estimated (NRPB-R262, 1994). Direct measurements of organ doses are complicated and very time consuming often performed in anthropomorphic phantoms (Alderson Research - Lab.)

Calculation of effective doses. The effective dose was defined in the introduction. It is desirable that a uniform equivalent dose over the whole body should give an effective dose nummerically equal to that uniform equivalent dose. This is achieved by normalising the sum of the tissue weighting factors to unity and they are also assumed to be independent of the radiation quality. For purposes of calculation, ICRP 60 give a "reference" list of 10 remainder organs: adrenals, brain, upper large interstime, small interstine, kidney, muscle, pancreas, spleen, thymus and uterus. Together with a much smaller remainder tissue weighting factor, this should lead to more consistent estimates of effective dose for a given irradiation conditions. The remainder tissue weighting factor is applied to the mean dose of the remainder, but ICRP gives no method for calculating this average remainder dose, whether it is a mass-weighted mean or simply the arithmetic mean - the sum of the organ doses divided by the number of organs. If a mass-weighted mean is used, the dose to muscle (90% of the remainder mass) would be extremely important in the context of remainder dose. The method used has therefore to be stated.

1990 RECOMMENDATIONS OF THE ICRP

Table 2. Tissue weighting factors

Tissue or organ	Tissue weighting factor, w_T
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05

REFERENCES

1. Beck, J.W., Dunn, W.L. and O'Foghludha, F. Monte Carlo model for absorbed dose calculations in computed tomography. Med.Phys. 10 314 - 20. 1983.

2. Chan, H. and Doi, K. Radiation dose in diagnostic radiology: Monte Carlo simulation studies. Med.Phys. 11 480-490. 1984.

3. Dance, D.R. Monte Carlo calculation of conversion factors for the estimation of mean glandular breast dose. Phys.Med.Biol. 35 1211-1219. 1990.

4. Doi, K. and Chan, H. Evaluation of absorbed dose in mammography: Monte Carlo simulation studies. Radiology 135 199-208. 1980.

5. Drexler, G., Panzer, W., Widenmann, L., Williams, G. and Zankl, M. The Calculation of Dose from External Photon Exposures using Reference Human Phantoms and Monte Carlo Methods. Part III: Organ Doses in X-ray Diagnosis Rep. GSF-Bericht 11/90. 1990.

6. Hart, Jones and Wall B. Estimation of Effective Dose in Diagnostic Radiology from entrance Surface Dose and Dose- Area Product Measurements. Report NRPB-R262 (1994).

7. Huda, W. and Sandison, G.A. Estimation of Mean Organ Doses in Diagnostic Radiology from Rando Phantom Measurements. Health Physics 47 463-467 (1984)

8. ICRP. 1990. Recommendations of the International Commission on Radiological Protection. ICRP Publication 60 (Pergamon Press). 1991.

9. ICRP. Report of the Task Group on Reference Man. ICRP Publication 23 (Pergan Press). 1975.

10. Jones, D.G. and Wall, B.F. Organ doses from medical X-ray Examinations Calculated using Monte Carlo Techniques. Report NRPB-R186. 1985.

11. Jones, D.G. and Shrimpton, P.C. Normalised Organ Doses for X-ray Computed Tomography Calculated using Monte Carlo Techniques. Chilton, NRPB-SR250. 1993.

12. Jones, D.G. and Shrimpton, P.C. Survey of CT Practice in the UK. Part 3: Normalised Organ Doses Calculated using Monte Carlo Techniques. Chilton, NRPB-R250 (London: HMSO).1991.

13. Kramer, R., Zankl, M., Williams, G. and Drexler, G. The Calculation of Dose from Photon Exposures Using Reference Human, Phantoms and Monte Carlo Methods. Part I: The Male (Adam) and Female (Eva) Adult Mathematical Phantoms Rep. GSF-Bericht

S-885 (München, GSF). 1982.

14. Monte Carlo Simulation in the Radiological Sciences. ed R.L. Morin (Boca Raton, Florida: CRC) 1988.

15. Okkalides D. and Fotakis M. Patient effective dose resulting form radiographic examinations. Brit.Jour.Rad. 67 564 - 467 (1994)

16. Persliden J. and Alm-Carlsson, G. Energy imparted to water slabs by photon in the energy range 5 - 300 keV. Calculations using a Monte Carlo photon transport model. Phys.Med.Biol. 29 1075-88. 1984.

17. Raeside, D.E. Monte Carlo principles and applications. Phys.Med.Biol. 21. 181-97. 1976.

18. Rosenstein, M., Beck, T.J. and Warner, G.G. Handbook of Selected Organ Doses from Projections Common in Paediatric Radiology. HEW Publication (FDA) No. 79-8079 (Bureau of Radiological Health, Rockville, MD). 1979.

19. Rosenstein, M. Organ Doses in Diagnostic Radiology. HEW Publication (FDA) No. 76-8030 (Bureau of Radiological Health, Rockville, MD). 1976.

20. Sandborg, M., Dance D.R., Persliden, J. and Alm-Carlsson G. A Monte Carlo program for the calculation of contrast, noise and absorbed dose in diagnostic radiology. Comp. Prog. Biomed. 42 167 - 180. 1994.

21. Snyder, W.S., Ford, M.R., Warner. G.G. and Fisher. S.B. Estimates of Absorbed Fractions for Monoenergetic Photon Sources Uniformly Distributed in Various Organs of a Heterogeneous Phantom. MIRD Pamphlet No. 5, J. Nucl. Med. 10 (Suppl), No 3. 1969.

22. The Dosimetry of Ionizing Radiation. Vol. III ed. K.R. Kase, B.E. Bjärngard and F.H. Attix. (Academic Press, Inc.). 1990.

23. Veit, R., Zankl, M., Petoussi, N., Mannweiler, E., Williams, G. and Drexler, G. Tomographic Anthropomorphic Models, Part 1: Construction Technique and Description of Models of an 8 Week Old Baby and a 7 Year Old Child. GSF-Bericht 3/89. 1989.

24. Zankl, M., Panzer, W. and Drexler, G. The Calculation of Dose from External Photon Exposures using Reference Human Phantoms and Monte Carlo Methods. Part VI: Organ Doses from Computed Tomographic Examinations. GSF-Bericht 30/91. 1991.