THE ROLE AND DETERMINATION OF PATIENT DOSE IN X-RAY DIAGNOSIS

M. Zankl, N. Petoussi-Henß, W. Panzer

GSF - Forschungszentrum für Umwelt und Gesundheit
Institut für Strahlenschutz
Postfach 1129
D-85758 Neuherberg

ABSTRACT

In radiation protection of the patient in x-ray diagnosis all three principles of radiation protection should be applied. So-called dose constraints which limit entrance surface doses ensure implicitly that patient doses should not exceed certain levels. With respect to justification, it is believed that there is a large potential for patient dose reduction by avoiding both clinically unjustified examinations and unnecessary repetition of diagnostic procedures. While this appears to be quite straightforward, the strategy for optimisation is more complicated. Here, a reasonable compromise between high image quality and low patient dose has to be found, as often measures aimed at improved image quality lead to an increase of patient dose, and, vice versa, measures aimed at a reduction of patient dose result also in reduced image quality.

Whereas the problem to quantitatively assess the quality of a given image is still not solved satisfactorily, the determination of patient doses has become increasingly feasible in recent years. For this purpose, computer codes, often based on Monte Carlo techniques, simulating the radiation transport in material are commonly used together with computational models of the human body. Most of the computational body models in use are so-called mathematical models, that means, mathematical expressions representing simple geometrical bodies are used to describe idealised arrangements of body organs. Additionally, tomographic models were developed in recent years which use computed tomographic data of real persons to provide three-dimensional representations of the body.

Using these computational models of the human body, numerous studies concerning organ and tissue doses from diagnostic radiology were performed. Although it is not recommended to apply the calculated doses to assess individual patient doses, the influence of single exposure conditions as, e.g., tube voltage, filtration, field size and location, focus-to-skin distance, on organ and tissue doses can be studied readily, thus resulting in information prerequisite for optimisation in x-ray diagnosis. Additionally, the tomographic models enable to assess the influence of moderate variations of the patient size on organ doses and, therefore, improve to a certain extent the applicability of literature data on patient doses to individuals.

INTRODUCTION

Because most procedures causing medical radiation exposures are clearly justified and because the procedures are usually for the direct benefit of the exposed individuals, less attention has been given to the optimisation of protection in medical exposures than in most other applications of radiation sources (1). On the other hand, it is a well-known fact that the radiation doses from diagnostic radiology are the largest contribution to the collective dose from all man-made sources of radiation (2). From this, it is obvious that diagnostic radiology should be of major concern for radiation protection and that, consequently, the guidelines established by

the ICRP for occupational radiation protection should be applied also to diagnostic radiology as far as possible.

(1) Justification:
In relation to the justification of examinations in diagnostic radiology it is accepted that most examinations result in information beneficial to the patient and that, consequently, the benefit of these examinations will, in general, by far outweigh the radiation detriment. It is, nevertheless, believed that there is a large potential for patient dose reduction by avoiding both clinically unjustified examinations and unnecessary repetition of diagnostic procedures. Furthermore, it should also be considered whether imaging techniques not involving ionising radiation could be applied if they result in the same diagnostic benefit.

(2) Optimisation:
Optimisation in diagnostic radiology commonly involves two aspects: the first is to establish quality assurance and quality control programmes to ensure a proper performance of the x-ray equipment; the second is the necessity to find a reasonable compromise between high image quality and low patient dose, as often measures aimed at improved image quality lead to an increase of patient dose, and, vice versa, measures aimed at a reduction of patient dose result also in reduced image quality.

(3) Limitation:
It is generally accepted that there is little use of dose limits in diagnostic radiology, as there are large ranges of doses due to the different complexity of the situations considered. It is, however, of concern that dose differences of up to two orders of magnitude for the same type of examination have been reported in diagnostic radiology (1). Therefore, more and more consideration is given to dose constraints for application in some common diagnostic procedures (3-5). These should be applied with sufficient flexibility to allow higher patient doses where indicated by sound clinical judgement.

Whereas for the justification of diagnostic radiological procedures patient doses do not play an important role, they are of major consequence for optimisation and limitation. Furthermore, the necessity to determine patient doses may arise routinely due to legal regulations (as, e.g. the German X-ray Ordinance) or in special cases, e.g. due to possible legal consequences of an individual examination. The various dose quantities considered for these specialities will be characterised in the following, and methods to determine these dose quantities will be described.

THE ROLE OF PATIENT DOSES IN X-RAY DIAGNOSIS

There are several aspects in x-ray diagnosis where patient doses are considered:

(1) Dose constraints:
A strict limitation of doses to patients comparable to the practice in other fields of radiation protection is unthinkable in x-ray diagnosis as this would adversely affect the care for the patient in special situations. On the other hand, it seems unnecessary that dose differences of orders of magnitude should occur for routine examinations. Therefore, dose constraints can be established in a sense that recommended dose values normally should not be exceeded for a certain examination of an average patient. These recommended values are based on the results of extended field studies where good radiographic technique and equipment were to be used. The dose constraints for each specific examination usually were then derived as the third quartile of all doses reported for this examination (3-5). It is important both for carrying out

such a field study and for testing of compliance with the recommended values in routine that the reference doses are of a simple nature and accessible to routine practice. Therefore, usually easily measurable dose quantities are used for this purpose as, e.g., entrance dose (free in air), entrance surface dose or dose-area product.

In this context, the demand for measuring the dose-area product in specified has recently arisen (6). The fields considered are extremely dose-intensive x-ray examinations, paediatric examinations (especially frequent examinations of premature babies), examinations in connection with surgical measures or in interventional radiology with extended fluoroscopy times. Furthermore, it was recommended to measure the dose-area product during the training of medical staff and at facilities equipped to switch to a performance involving high dose-rates. Although no attempt was made to establish dose constraints for these fields, the necessity was recognised to increase the awareness of the magnitude of doses involved; with this increased awareness it is hoped that also the sense of responsibility for the doses applied to patients would increase.

(2) Optimisation of examinations:
Optimisation in x-ray diagnosis means achieving a reasonable compromise between high image quality and low dose to the patient. For this purpose, special quality criteria characterising a good radiographic technique for different types of examinations were evaluated by CEC study groups (3,4). These include detailed requirements for the image as well as a set of technical parameters for the performance of the examination. As the recommended technical parameters are accepted to result in sufficient image quality, optimisation considerations can be based on the resulting patient doses. Here easily accessible doses as, e.g., entrance surface dose, are insufficient because the dependence of doses within the patient on the technical parameters varies with depth in the body and distance from the x-ray field. This is demonstrated by an example in Table 1. The increase of tube voltage from 90 to 125 kV for a chest examination of a female phantom reduces the entrance surface dose markedly, whereas organ doses decrease by much less or even not at all, depending on the position of the organ within the body.

Table 1: *Organ doses, entrance surface dose and effective dose from a postero-anterior chest examination for two different tube voltages, calculated for a female mathematical phantom (7). Focus-to-skin distance: 150 cm; field size: 35 cm · 35 cm; anti-scatter grid: 12/40; dose at image receptor: 5 µGy (Data from (8)).*

	Organ doses (µSv)			Organ doses (µSv)	
Tube voltage	90 kV	125 kV		90 kV	125 kV
Thyroid	22.6	22.8	Adrenals	146.6	116.5
Thymus	37.6	36.6	Kidneys	15.0	11.4
Breast	48.9	43.4	Red bone marrow	45.1	38.4
Oesophagus	79.0	59.4	Skeleton	120.3	86.6
Lungs	214.3	164.5	Skin	37.6	27.4
Liver	52.6	45.7	Muscle	37.6	27.4
Spleen	67.7	54.8			
Pancreas	45.1	38.8	Entrance surface	466.2	301.6
Stomach wall	22.6	22.8	Effective dose	47.5	38.2

Consequently, in a first step, a set of organ doses seems to be a more appropriate descriptor of patient exposure. On the other hand, a whole set of doses is rather unpractical, since single

organ doses are influenced by the altered exposure parameter to a different extent. There may occur situations where a change of one or more technical exposure parameters may result in the decrease of some organ doses and in the increase of some others. Then a list of organ doses does not allow an unequivocal decision which of the techniques considered is preferred with respect to patient dose. In these situations, a more condensed form of the information, preferably in one single number, is of advantage. For this purpose, the effective dose is of benefit, the sum of the weighted equivalent doses in selected organs and tissues of the body as introduced by the ICRP (1). Although this quantity should be used with caution in the field of x-ray diagnosis (8), it allows the ranking of various examination techniques with respect to patient dose in a rather simple and unequivocal way.

(3) Determination of doses to individual patients:
There are very few cases in X-ray diagnosis where a determination of doses to an individual becomes necessary. These are mainly: examinations in the pelvic region of pregnant patients; frequent examinations in the course of occupational diseases after which cancer occurs and the question arises with which probability this was caused by the examinations; unnecessary or inadequately conducted examinations entailing litigation; examinations leading to extremely high doses which might be followed by deterministic effects. In these rare situations, the determination of single organ doses is indispensable. In any situation where the probability has to be determined that a specific disease having occurred in an individual could have been caused by a certain exposure, the dose to the diseased organ is of major importance. In the case of deterministic effects, the knowledge of single organ doses can support further patient care.

(4) Determination of collective doses:
Doses of the whole or of groups of a population are determined to provide data for the following purposes: justification of examinations and risk-benefit analysis as, e.g., in the case of screening programmes; evaluation of the contributions from different examinations to decide where optimisation measures would be most necessary and effective; balancing of exposures due to statistical reasons and comparison with exposures from other sources. Here again, effective dose is of major importance, although the derivation and use of a slightly different quantity employing risk factors more appropriate to a patient population than those specified by the ICRP for a population representative of all ages and both sexes (1) would be highly desirable.

THE DETERMINATION OF PATIENT DOSES IN X-RAY DIAGNOSIS

In those cases where measurable dose quantities can be used, their determination is quite straightforward. Devices for the measurement of dose-area product are becoming more and more frequently available in common x-ray practice; if the field size applied during an examination is known, the entrance dose free in air can be easily deduced. The entrance surface dose can be measured directly on the patient using appropriate dosimeters without hindering the examination.

As soon as organ and tissue doses or effective dose have to be used, the situation is more complicated, as these doses are, in principle, unmeasurable. There is some indication that effective dose could be deduced from measured values of the dose-area product to within approximately 30% accuracy using a single conversion coefficient for groups of projections, field positions and beam qualities (9). Further investigations showed, however, that the numerical uncertainties of converting dose-area product to effective dose exceed 30% in many cases, when generally valid conversion coefficients are used (10). To refine this approach, it becomes

necessary to consider additional exposure parameters like tube voltage and field size, shape and position. Furthermore, this approach is not feasible for single organ doses.

A convenient method for the determination of organ and tissue doses are calculations using radiation transport codes together with computational models of the human body. The calculations are mostly based on the Monte Carlo method; that means that single particle histories are simulated whose exact course is sampled from known probability distributions of the influencing parameters; the dose quantities of interest are finally evaluated by averaging over millions of these single histories.

Types of computational models

The models of the human body used for this type of simulations are mostly so-called mathematical models, that means, mathematical expressions representing planes, cylindrical, conical, elliptical or spherical surfaces are used to describe idealised arrangements of body organs. This type of models was introduced by Fisher and Snyder (11) and further refined and extended by various authors. At the GSF, male and female adult mathematical models have been introduced (7). The best known representative of the mathematical models is that by Snyder et al. (12,13) which has been commonly called the "MIRD-5 phantom" due to being published in the MIRD Pamphlet No. 5. Referring to this, mathematical models are sometimes also called MIRD-type models.

More recently, tomographic models were developed, which use computed tomographic (CT) data of real persons to provide three-dimensional representations of the body. The first step for the construction of these models is to obtain a whole-body CT scan consisting of contiguous slices. The data are then processed using appropriate image processing software. Each organ or tissue is represented by those volume elements (voxels) which were identified as belonging to it from the CT slice images. The tomographic type of models (also called "voxel models") was introduced by two groups independently, approximately ten years ago (14,15). More recently, voxel models were constructed by various workers (16,17). At the GSF, five models of this type were constructed so far, two paediatric, two adult and a model of an Alderson-Rando physical phantom (18-20).

Comparison of mathematical and tomographic models

In mathematical models, organ shapes are reduced to a very simple form to limit the software and computational requirements. Consequently, the mathematical models are not designed to describe any individual in detail but rather to represent whole populations. On the other hand, tomographic models are constructed from CT data of real persons who might deviate significantly from reference data. The shapes of the body organs are determined by identifying all the voxels belonging to each organ. Thus, the shape of each organ is more realistic than for the mathematical models, although, being reconstructed from a specific individual, it might not be representative of large populations.

Mathematical models are usually rigid in size, whereas the external dimensions of tomographic models can be adapted to any size, for each of the three dimensions independently. All internal dimensions of the resulting scaled-down or scaled-up version of the original model are also changed with the same scaling factors. It is, however, important to keep the scaling factors within rational magnitudes; otherwise, considerable errors in the body proportions might be introduced.

In mathematical models, all skeletal components are homogeneously distributed in the skeleton, and there is no geometric representation of spongiosa. Usually, for estimating the dose to

the red bone marrow, the variation of the red bone marrow distribution among different bones and at various ages is considered (21,22), whereas the variation within single bones is not. In tomographic models, the amount of bone marrow and hard bone in each single skeletal voxel can be estimated, based on the CT data. Although it is not possible to identify functional bone marrow by this method or to model the complicated trabecular bone structure exactly, the distribution of bone marrow can be determined with the resolution of the CT scan, i.e. normally a few cubic millimetres.

Apart from these differences which should be kept in mind, the two types of models, mathematical and tomographic, are, in principle, equally suitable for the calculation of organ and tissue doses in x-ray diagnosis.

Studies performed

The mathematical models, primarily designed for use in internal dosimetry, were soon applied for external exposure conditions also. The first of the studies for diagnostic radiology was performed by Rosenstein (23), presenting organ doses for frequent x-ray examinations of adult patients. This was followed by work related to paediatric radiology (24,25) and fluoroscopic examinations of the upper gastrointestinal tract (26). The exposure parameters in these studies refer to the situation in the USA and are different from those considered for organ dose calculations due to examinations in Western European countries. The latter were represented mainly by studies performed at GSF and NRPB for conventional x-ray diagnosis (27-29), computed tomographic examinations (30-33) and, more recently, for paediatric radiology (34). Organ doses for fluoroscopic examination of the coronary arteries were evaluated in a co-operation of the Center of Devices and Radiological Health and GSF (35).

Adult tomographic models were used for the calculation of organ doses from dental radiography (14,36-38). The tomographic paediatric models constructed at GSF were used for organ dose calculations in paediatric conventional x-ray diagnosis (18,39) and CT examinations (40,41). Furthermore, work was performed to study the influence of patient size on organ doses in x-ray diagnosis (42,43). Table 2 shows, as an example, some selected organ dose conversion coefficients for CT examinations of paediatric patients.

Table 2: *Summed organ dose conversion factors for head and thorax scans of an eight week old baby and a seven year old child. The tube voltage is 125 kV, the angle of rotation is 360°. An asterisk as table entry means that the conversion factor is less than 0.005 (Data from (41)).*

	Organ dose per air kerma free in air			
	Head scan		Thorax scan	
Organ	BABY	CHILD	BABY	CHILD
Bladder	*	*	0.01	*
Breast	0.05	0.02	0.96	0.88
Colon	*	*	0.03	0.04
Liver	0.01	0.01	0.47	0.36
Lungs	0.05	0.05	0.95	0.77
Oesophagus	0.15	0.09	0.77	0.68
Ovaries	*	*	0.01	0.01
Red bone marrow	0.33	0.15	0.21	0.10
Skeleton	1.33	0.69	0.88	0.43
Skin (whole body)	0.22	0.12	0.26	0.16
Stomach	0.01	*	0.23	0.16
Thyroid	0.59	0.60	0.58	0.41

CONCLUSIONS

In radiation protection of the patient in x-ray diagnosis, the three principles introduced by the ICRP for occupational radiation protection should be applied also; it should be recognised, however, that in applying these principles a higher flexibility, compared to occupational radiation protection, is needed in order not to adversely affect the care for the patient in special situations. Whereas for the justification of diagnostic radiological procedures patient doses do not play a significant role, they are of major consequence for optimisation and limitation. Dose limitation is, to a certain extent, achieved by the observation of dose constraints which are defined in form of easily measurable quantities, e.g. entrance surface dose, entrance dose free in air or dose-area product. Optimisation in x-ray diagnosis means to achieve a reasonable compromise between high image quality and low patient dose. For optimisation purposes, the above mentioned easily accessible quantities are of limited value; in this context, organ and tissue doses as well as effective dose are the quantities of interest.

Calculations using Monte Carlo techniques together with computational human models are a very suitable method for the determination of organ and tissue doses from various radiation exposures in diagnostic radiology. The calculated dose values apply, strictly speaking, only to patients with the same body characteristics as the models used and to an exact replication of the exposure parameters simulated. Individual doses are strongly influenced by the body dimensions as well as by the irradiation conditions, such as field size, field position, focus-to-film distance, photon spectrum, etc. Accordingly, organ doses derived from the literature may deviate from the doses in real patients and should, therefore, be applied to individual situations with appropriate caution. An evaluation of the influence of patient size, as included in some of the above mentioned studies, improves the applicability of literature data to individual patients to a certain extent. One of the most powerful applications of organ dose calculations is to quantify the effects of changes in the exposure conditions on the doses to single organs, as these effects are largely independent of individual patient anatomy. Knowledge of the relationships between organ doses and certain technical exposure parameters allow to select an examination set-up, among several possibilities known to result in acceptable image quality, which minimises the dose to certain organs. Thus, dose calculations can play an effective role within optimisation in x-ray diagnosis.

REFERENCES

1. ICRP, ICRP Publication 60 (1991).
2. UNSCEAR, Report to the General Assembly, with annexes (1988).
3. CEC, Working Document XII/173/90 (1990).
4. CEC, Working Document XII/307/91 (1991).
5. IAEA, Report No. IAEA-TECDOC-796 (1995).
6. W. Löster, G. Drexler, F.-E. Stieve (Eds.), *Die Messung des Dosisflächenproduktes in der diagnostischen Radiologie als Methode zur Ermittlung der Strahlenexposition.* H. Hoffmann Verlag, Berlin (1995).
7. Kramer, R., Zankl, M., Williams, G., Drexler, G., GSF-Bericht S-885 (1982).
8. Drexler, G., Panzer, W., Petoussi, N., Zankl, M., *Radiat. Environ. Biophys.* 32, 209-219 (1993).
9. Le Heron, J.C., *Phys. Med. Biol.* 37, 2117-2126 (1992).
10. Petoussi-Henß, N., Panzer, W., Zankl, M., Drexler, G., *Radiat. Prot. Dosim.* 57, 363-366 (1995).
11. Fisher, H.L., Snyder, W.S., Report No. ORNL-4168 (1967).
12. Snyder, W.S., Ford, M.R., Warner, G.G., Fisher, H.L., *J. Nucl. Med.* 10, *Suppl.* 3 (1969).
13. Snyder, W.S., Ford, M.R., Warner, G.G., *MIRD Pamphlet No. 5, Revised* (1978).

14. Gibbs, S.J., Pujol, A., Chen, T.-S., Malcolm, A.W., James, A.E., *Oral Surgery, Oral Medicine, Oral Pathology* 58, 347-354 (1984).
15. Williams, G., Zankl, M., Abmayr, W., Veit, R., Drexler, G., *Phys. Med. Biol.* 31, 449-452 (1986).
16. Zubal, I.G., Harrell, C.R., Smith, E.O., Rattner, Z., Gindi, G., Hoffer, P.B., *Med. Phys.* 21, 299-302 (1994).
17. Dimbylow, P.J., In: *Proceedings of the Workshop on Voxel Phantom Development* (NRPB, Chilton, UK) (in press).
18. Zankl, M., Veit, R., Williams, G., Schneider, K., Fendel, H., Petoussi, N., Drexler, G., *Radiat. Environ. Biophys.* 27, 153-164 (1988).
19. Veit, R., Zankl, M., Petoussi, N., Mannweiler, E., Williams, G., Drexler, G., GSF-Bericht No. 3/89 (1989).
20. Zankl, M., Petoussi-Henß, N., Wittmann, A., In: *Proceedings of the Workshop on Voxel Phantom Development* (NRPB, Chilton, UK) (in press).
21. Cristy, M., *Phys. Med. Biol.* 26, 389-400 (1981).
22. Cristy, M., Eckerman, K.F., Report No. ORNL/TM-8381/V1 (1987).
23. Rosenstein, M., HEW Publication (FDA) No. 76-8030 (1976).
24. Chen, W.L., Poston, J.W., Warner, G.G., Report No. ORNL/TM-5933 (1978).
25. Rosenstein, M., Beck, T.J., Warner, G.G., HEW Publication (FDA) No. 79-8079 (1979).
26. Rosenstein, M., Suleiman, O.H., Burkhart, R.L., Stern, S.H., Williams, G., HHS Publication FDA 92-8282 (1992).
27. Drexler, G., Panzer, W., Widenmann, L., Williams, G., Zankl, M., GSF-Bericht S-1026 (1984). Revised and amended: GSF-Bericht 11/90 (1990).
28. Jones, D.G., Wall, B.F., Report No. NRPB-R186 (1985).
29. Petoussi, N., Zankl, M., Stieve, F.-E., Drexler, G., In: BIR Report 20, 246-249 (1989).
30. Panzer, W., Zankl, M., *Brit. J. Radiol.* 62, 936-939 (1989).
31. Jones, D.G., Shrimpton, P.C., Report No. NRPB-R250 (1991).
32. Zankl, M., Panzer, W., Drexler, G., GSF-Bericht 30/91 (1991).
33. Zankl, M., Panzer, W., Drexler, G., *Radiat. Prot. Dosim.* 43, 237-239 (1992).
34. Hart, D., Jones, D.G., Wall, B.F., NRPB-Report (in press).
35. Stern, S.H., Rosenstein, M., Renaud, L., Zankl, M., HHS Publication FDA 95-8288 (1995).
36. Gibbs, S.J., Pujol, A., Chen, T.-S., Carlton, J.C., Dosmann, M.A., Malcolm, A.W., James, A.E., *Dentomaxillofac. Radiol.* 16, 67-77 (1987).
37. Gibbs, S.J., Pujol, A., Chen, T.-S., James, A., *Dentomaxillofac. Radiol.* 17, 15-23 (1988).
38. Gibbs, S.J., Pujol, A., McDavid, W.D., Welander, U., Tronje, G., *Dentomaxillofac. Radiol.* 17, 25-32 (1988).
39. Zankl, M., Petoussi, N., Veit, R., Drexler, G., Fendel, H., In: BIR Report 20, 196-198 (1989).
40. Zankl, M., Panzer, W., Drexler, G., GSF-Bericht 30/93 (1993).
41. Zankl, M., Panzer, W., Petoussi-Henß, N., Drexler, G., *Radiat. Prot. Dosim.* 57, 393-396 (1995).
42. Veit, R., Zankl, M., *Radiat. Prot. Dosim.* 43, 241-243 (1992).
43. Veit, R., Zankl, M., *Radiat. Prot. Dosim.* 49, 353-356 (1993).