Eur. Radiol. 7, 1127–1132 (1997) © Springer-Verlag 1997

Physics

European
Radiology

Original article

Effective doses to members of the public from the diagnostic application of ionizing radiation in Germany*

A. Kaul, B. Bauer, J. Bernhardt, D. Nosske, R. Veit

Institut für Strahlenhygiene, Bundesamt für Strahlenschutz, Postfach 100149, D-38201, Salzgitter, Germany

Received 12 June 1996; Revision received 21 October 1996; Accepted 8 November 1996

Abstract. The exposure of the German population to man-made radiation results mainly from diagnostic X-ray and nuclear medical examinations. Data are presented about the annual frequency and the average dose of the various examination types for West Germany in the years 1990–1992. According to these data a yearly average of approximately 1550 diagnostic examinations using ionizing radiation were performed per 1000 inhabitants resulting in an annual per caput effective dose of 1.9 mSv. Despite the frequent use of alternative examination techniques, such as sonography, nuclear magnetic resonance and endoscopy, the frequency of X-ray and nuclear medical examinations is still increasing. If collective risk assessments are done using the per caput effective dose, at least the age distribution of the patients must be considered. This leads to a "risk-modifying factor" of 0.6–0.7 for patients to be applied to the ICRP risk coefficient of 5 % per Sv valid for the general population. However, radiation risk must always be viewed in context with disease- and therapy-related risks and balanced against the benefit of the diagnostic examination, which should always exceed the risk for a well-indicated procedure.

Key words: Diagnostic radiology (Germany) – Annual frequency of examinations – Effective doses – Collective doses – Radiation risk for patients

Introduction

According to UNSCEAR in its 1993 report on sources and effects of ionizing radiation [1], approximately 75 % of the collective effective dose of the world population of 840 million manSv from radiation exposure during the 50-year period since 1945 is due to exposure of man from natural sources. More than 80 % of the remainder results from the use of ionizing radiation and radionuclides in medical diagnosis and treatment.

This fraction varies from country to country, and depends on data of the following parameters: (a) the annual frequency of the relevant medical examination types, and (b) the mean effective dose per examination type.

The collective risk in a population from radiation administered to patients in diagnostic medicine depends on the age-dependent risk coefficients for both the radiation-induced cancer mortality or the detriment and the collective effective doses for the same age classes.

The following provides an overview of the frequency of X-ray and nuclear medical diagnostic procedures in Germany, the effective dose per examination type, the collective and per caput effective doses, trends in frequency and effective dose, and the risk evaluation, based on age-dependent risk coefficients.

Frequency of diagnostic procedures

X-ray diagnostics

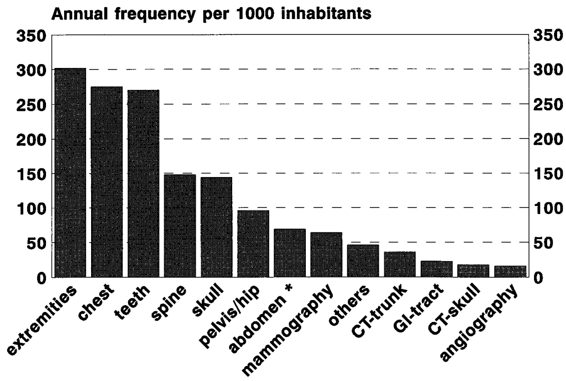
The information on annual frequencies of the various examination types was obtained from different sources with different degrees of accuracy, but only for West Germany [11]. Exact numbers were obtained for outpatients of practicing physicians and dentists, who are members of the legal health insurance. The frequencies for privately insured outpatients were calculated from a trial of these insurances to account for approximately 15 % of the X-ray examinations of the regularly insured outpatients.

The number of inpatient examinations was calculated from a representative trial in big acute medical care hospitals (> 50 beds) of the year 1990 made by a commercial institute (Infratest). Small hospitals (< 50 beds) and special medical care hospitals were assumed

---

Correspondence to: R. Veit

* Dedicated to Prof. Dr. F.-E. Stieve on the occasion of his 80th birthday



* incl. biliary tract and urinary tract

Fig. 1. Frequency of X-ray examinations in West Germany, 1992

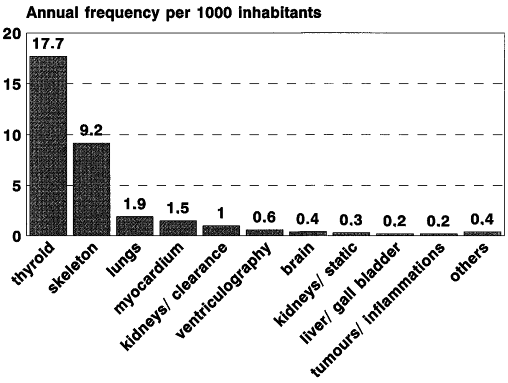


Fig. 2. Frequency of nuclear medical examinations in West Germany, 1990

to contribute 1.5 and 15 %, respectively, of the examinations performed in the big acute medical care hospitals.

Partly calculated from trials and partly estimated were the number of examinations performed by the public health service and for legal, military or professional purposes.

According to these data, in the old federal states (West Germany, prior to reunification in 1990) an average of nearly 100 million X-ray examinations per year were performed during the years 1990–1992, resulting in 1520 annual X-ray examinations per 1000 inhabitants. The most frequent examinations are those of the extremities (ca. 20 %), followed by those of the chest (ca. 18 %) and dental examinations (ca. 18 %; Fig. 1) [2].

All numbers represent complete examinations, i. e. partially consisting of several single radiographs. It should be mentioned that in other countries some examination types might be assigned to different groups. More than half of the X-ray examinations are performed on outpatients by practicing physicians. Nearly 25 % of all X-ray examinations are performed by dentists and only approximately 20 % of all examinations on inpatients in hospitals. At present, no relevant data are available from the new federal states (former German Democratic Republic) due to the fact that the public health system has undergone a complete restructuring since reunification.

Diagnostic nuclear medicine

Diagnostic nuclear medical procedures are performed in Germany on both outpatients and inpatients. Extensive data are available on examinations of outpatients from health insurances in the old federal states from 1988 to 1992. In addition, for the old federal states the number of inpatient examinations performed in 1990 was estimated from a representative trial in acute medical care hospitals made by the same commercial institute as mentioned previously. The number of examinations performed in special medical care hospitals was assumed to account for 15 % of examinations performed in acute medical care hospitals. The examination frequencies determined for 1990 are summarized in Fig. 2.

According to these results, in 1990 a total of 33 examinations per 1000 inhabitants were performed in the old federal states with frequencies ranging from approximately 18 thyroid examinations to less than 0.2 liver/gall bladder and tumour/inflammation examinations per 1000 inhabitants.

As in X-ray diagnosis, at present no relevant data are available from the new federal states.

Effective dose per examination type

X-ray diagnosis

The majority of data on doses to the patients for different examination types was determined either by measuring the dose area product (DAP) for adults in cGy × cm^2 or by performing thermoluminescence dosimetry (TLD) measurements of the entrance surface dose in mGy. From a total of 5000 individual DAP measurements performed between 1992 and 1994, mean values for all types of examinations were calculated. For the same type of examination the variation width of these values proved to be up to two orders of magnitude. The most important factors are build and weight of the patient as well as body composition. Additional factors are length of time of fluoroscopies and numbers of radiographs per examination of an individual patient. By means of conversion factors [3, 10], the effective doses were calculated to be between 30 mSv (CT of abdomen) and 10 μSv (dental) per examination type (see Fig. 3).

Diagnostic nuclear medicine

For estimating the effective dose per examination type, the commonly used radiopharmaceuticals and typically administered activities were assumed for each examination as shown in Table 1 [4].

The effective doses of adult patients based on the dose coefficients, i. e. the dose per unit administered activity in Addendum 1 to ICRP publication 53 [5] (i. e. with the tissue-weighting factors of ICRP publication 60 [6]) are summarized in Fig. 4. The dose coefficients are usually higher for children and adolescents. Because

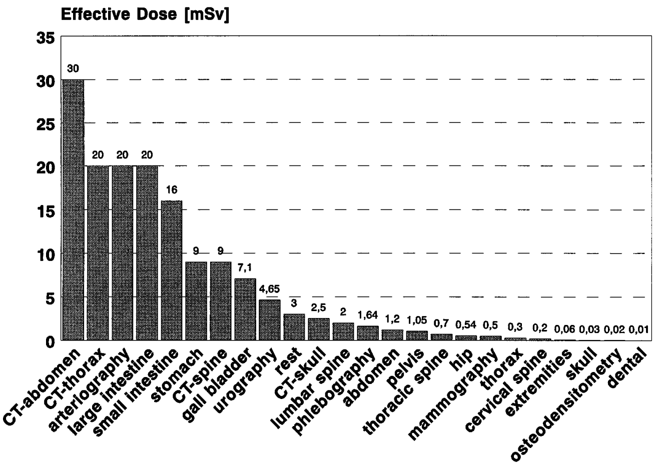


Fig. 3. Effective dose per examination type in X-ray diagnosis

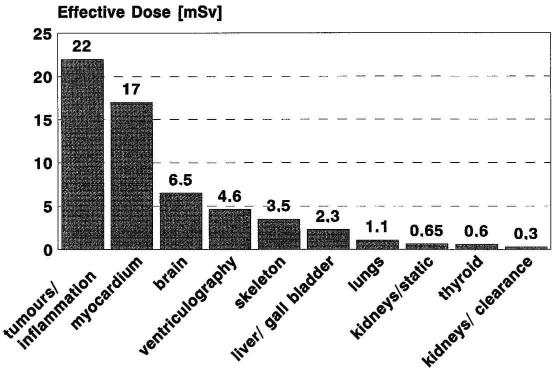


Fig. 4. Effective dose per examination type in nuclear medical diagnosis (see text)

Table 1. Typically administered activities in diagnostic nuclear medical examinations

Type of examination	Radiopharmaceutical	Activity (MBq)
Kidney clearance	[^{123}I]-hippurate	35
Thyroid	[^{99m}Tc]-pertechnetate	50
Myocardium	[^{201}Tl]-chloride	75
Kidney static	[^{99m}Tc]-DMSA	75
Lung	[^{99m}Tc]-MAA	200
Liver/gall bladder	[^{99m}Tc]-HIDA	150
Tumour/inflammation	[^{67}Ga]-citrate	200
Skeleton	[^{99m}Tc]-phosphonate	600
Ventriculography	[^{99m}Tc]-ery	700
Brain	[^{99m}Tc]-HMPAO	700

this is partially compensated for by the lower activity usually administered to children and adolescents, these dose values of approximately 20 mSv (tumours/inflammations) down to approximately 300 μSv (kidneys/clearance) per examination were assumed to be generally applicable.

Collective effective dose

The annual collective effective doses from X-ray and nuclear medical diagnosis were obtained by multiplication of the estimated effective doses per examination type with the corresponding annual frequencies and summation over all types of examinations.

X-ray diagnosis

For West Germany (1992) a collective effective dose of approximately 115 000 manSv was calculated for X-ray diagnosis. According to these results only five examination groups are responsible for nearly 80 % of this dose: Urography and angiography (including interventions) contribute 9 % each, and examinations of the spine and gastrointestinal (GI) tract 10 and 15 %, respectively. By far, the biggest portion, i. e. 35 % of the collective effective dose of X-ray diagnosis, is caused by CT.

For the West German population of 65 million in 1992 the annual per caput effective dose proved to be approximately 1.8 mSv. However, this value is purely computational, because it includes also those fractions of the population where no X-ray diagnosis was performed. Therefore, the per caput dose may not be used for calculating individual risks. The value is only suitable for comparison of countries with different medical care systems [1].

Diagnostic nuclear medicine

A collective effective dose of approximately 5000 manSv was calculated for the old federal states (1990). As mentioned previously, the doses per examination type for adults were assumed to be applicable for all age groups. The resulting error can be regarded as negligible, because in addition to the small dose differences the examination frequencies for children and adolescents are relatively low.

Based on these data, only three examination types are responsible for approximately 84 % of the collective effective dose. Examinations of the thyroid contribute 13 %, and examinations of the myocardium and skeleton contribute 31 and 40 %, respectively, to this dose. The annual per caput effective dose of diagnostic nuclear medicine is approximately 0.1 mSv.

Trends

X-ray diagnosis

Despite the introduction of alternative examination techniques, such as sonography, mainly for parenchymal organs, and endoscopy, mainly for oesophagus, stomach and large intestine, the number of X-ray examinations has altogether increased, namely by approximately 10 % between 1988 and 1992. The frequency of some types of X-ray examinations was very strongly increasing, i. e. CT by approximately 80 %, angiography by approximately 50 % and mammography by approximately 40 %. Examinations of the skeleton and of the urinary tract increased moderately by 12 and 8.5 %, respectively. Other examination types were markedly decreasing, i. e. mainly those of the GI tract by approximately 30 %. The frequency of chest and abdomen examinations remained practically constant.

Because dose-intensive examinations, such as CT and angiography, including in particular interventional radiology, significantly increased and their absolute number is larger than that of GI-tract examinations of decreasing frequency, the collective effective dose increased between 1988 and 1992 by approximately 15 000 manSv or 15 % of 100 000 manSv in 1988. The annual per caput effective dose increased by only 8.5 % during this period, because the West German population also increased from approximately 61.5 million in 1988 to 65 million in 1992.

Diagnostic nuclear medicine

For estimating the trend, only data on regular health-insured outpatients were available for the old federal states and the years 1988 – 1992. For the individual types of examinations the frequency trend between 1988 and 1992 in this patient group is quite different.

Examinations of tumours/inflammations increased very strongly by several factors, myocardial examinations by 100 % and examinations of thyroid, skeleton and lungs by approximately 20 % each. On the other hand, brain examinations decreased by 22 %, ventriculography by 35 % and liver/gall bladder examinations by 43 %. Static kidney examinations decreased by 46 %, whereas kidney clearance increased by 9 %. Altogether, diagnostic nuclear examinations of these outpatients increased by 22 %.

Assuming the same trend for the remaining patient groups, the increase in annual collective effective dose between 1988 and 1992 is approximately 45 % from 4400 to 6400 manSv in 1992. However, it must be considered that, particularly for the types of examinations involving high dose values and extremely high increase rates (tumours/inflammations, myocardium), new investigative methods have been developed to lower the radiation dose (PET diagnostics for myocardium, ^{99m}Tc-labelled monoclonal antibodies for tumours/inflammations). Accordingly, the increase in collective effective dose might be overestimated.

Risk estimation

Age-dependent risk coefficients

In its publication 60, Annex C [6], the ICRP has estimated the lifetime probability of radiation-induced fatal cancer to be 5.2 % per Sv for an average population of both genders and all ages including children. The nominal probability coefficient of the radiation detriment, which includes fatal cancer, non-fatal cancer and severe hereditary effects, is 7.3 % per Sv. Both values apply to low doses (< 0.2 Gy) at all dose rates and to high doses at low dose rates (< 0.1 Gy per hour).

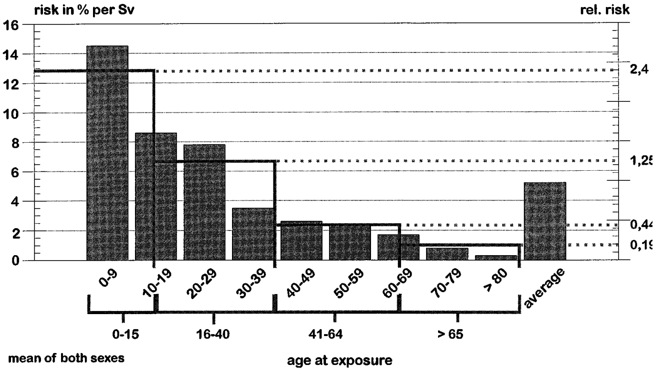


Fig. 5. Attributable lifetime risk (mortality) in percent per Sv from ICRP 60, Fig. C-5 (for 10-year age classes) projected to four age classes (acc. UNSCEAR, [1])

In addition, in Annex C of ICRP 60 it is shown that the radiation-attributable lifetime probability of fatal cancer varies with gender and predominantly with age at the time of exposure. For the multiplicative risk projection model, which is presently preferred by the ICRP at least for solid tumours, the lifetime mortality risk decreases with increasing age at exposure. This is illustrated in Fig. C-5(b) of ICRP 60 for 10-year age intervals [6].

Because existing data on the age structure of patients in Germany are divided into only four age classes according to UNSCEAR [1], the mean risks for both genders of these four age classes were graphically derived from this figure as shown in Fig. 5.

According to Fig. 5 the relative risk, i. e. the risk per age class referring to the average risk of the population, is between 2.4 (class I) and 0.19 (class IV). In a similar way the relative risks in terms of the detriment have been determined for three age classes in the UK [7] using the baseline cancer rates for the UK population. Because German baseline cancer rates and lethality fractions for the different organs are not available, a specific German age-dependent detriment cannot be calculated. Thus, the information given in ICRP 60 for a "world population" had to be used. Due to the fact that the age dependence of the radiation risk in ICRP 60 (Fig. C-5 (b)) refers to the fatal cancer risk and not to the detriment, further risk considerations for patients are restricted to fatal cancer risks only. One must keep in mind that especially the risk of severe hereditary effects additionally must be considered for younger patients.

Consequently, the average risk of the population is not applicable to a group of people such as patients with different age distribution and health conditions. On the other hand, a mean risk coefficient for patients can be derived if their age distribution is known. The influence of health status cannot be considered due to lack of information.

Mean risk-modifying factor for patients

Based on a representative trial in West German hospitals in 1990, the age distribution of X-ray diagnostic in-

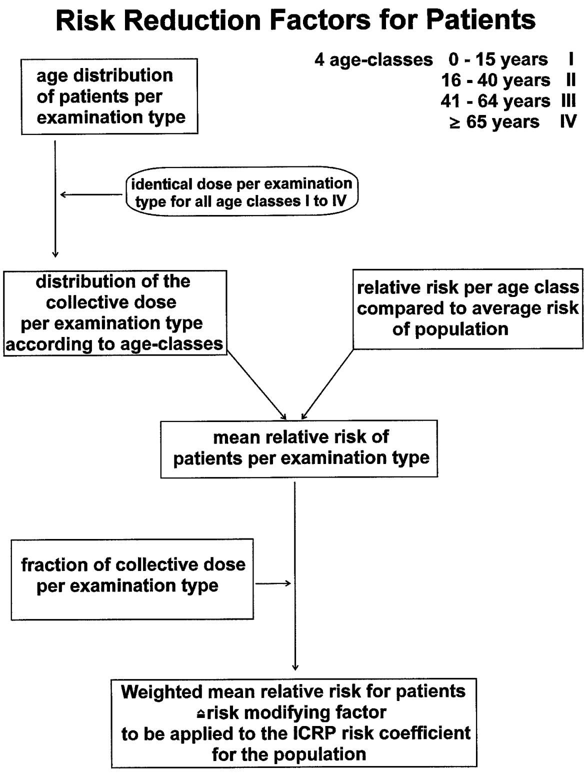


Fig. 6. Assessment of risk-modifying factors for patients

patients is roughly known for seven types of examinations, amounting to approximately 86 % of the collective effective dose of inpatients (see Table 2).

From these data the mean risk-modifying factor for all inpatients is estimated according to the procedure given in Fig. 6. From the age distribution per examination type, the distribution of the corresponding collective dose can be derived by assuming an identical dose per examination type for all age classes.

There is some information that the effective dose per examination type for children (0–15 years) is only approximately half that for adults, but due to the small percentage of examinations performed on this age group, this point does not affect the risk-modifying factor.

The products of relative risk and of examination type-specific collective dose fraction per age class, summed for all four age classes, yield the mean risk-modifying factor for inpatients of the respective examination type to be applied to the average risk coefficient (0.052 Sv^{-1}) of the population. For the seven examination types in Table 2 these factors vary between approximately 0.4 and 0.5.

The weighted mean of these examination type-specific risk-modifying factors, taking into account the different portions per examination type of the total inpatient collective dose, ultimately yields a mean risk-modifying factor of approximately 0.5 for all inpatients. In other words, the stochastic radiation risk of inpatients is only approximately half that of the average population.

The mean risk-modifying factor for outpatients (ca. 75 % of all X-ray examinations) is definitely higher due to their younger mean age. Therefore, a risk-modifying factor of 0.6–0.7 for all patients of diagnostic radiology as calculated for the UK [8] and the Netherlands [9], respectively, seems to be quite reasonable. These factors take into account only the different age structure between patients and population, but no other possible differences in risk related to the different health status of patients.

Risk and benefit

Collective risk

Assuming the annual per caput effective dose of 1.9 mSv caused by diagnostic radiology and nuclear medicine to be applicable for the whole lifetime resulting in a total dose of approximately 150 mSv and applying an average risk-modifying factor of 0.6 to the risk coefficient of the population (5.2 % per Sv) to account for the different age structure of the patients, the average additional lifetime risk of fatal cancer attributable to medical irradiation is approximately 0.5 % (0.15 Sv × 5.2 % per Sv × 0.6) as compared with the average "spontaneous" lifetime cancer risk of approximately 25 %.

This mathematically determined radiation risk may even be lower because a part of X-ray examinations is performed on patients who, independent of age, but due to their disease, have a significantly lower than average life expectancy of their age group. This lower life expectancy can be shorter for these patients than the latency period for development, and even more for the lethal outcome of radiation-induced cancer disease. Accordingly, the proportional amount of the collective effective dose attributed to this population group is radiobiologically ineffective.

Table 2. Age structure of in-patients per X-ray examination (West-Germany, 1990)

X-ray examination	Fraction of collective effective dose (%)	0–15 years (%)	16–40 years (%)	41–64 years (%)	> 65 years (%)	Risk modifying factor
Spine	3	1.5	12.5	31.9	54.1	0.42
Abdomen/pelvis	3.1	3.3	20.2	27.6	48.9	0.51
Oesophagus/stomach	3.2	6.4	16.9	25.8	50.8	0.51
Intestine	5.3	0.0	10.9	31.5	57.6	0.38
Urography	7.3	2.8	19.1	34.4	43.7	0.51
Angiography	17.8	3.4	8.1	45.9	42.6	0.43
CT	46.5	4.8	13.5	34.9	46.8	0.48

Individual risk

In case of frequent diagnostic examinations with a total effective dose of, for example, 50 mSv per year in one and the same individual patient, the calculated average radiation-induced cancer mortality risk would be one third of the average lifetime risk attributable to medical irradiation. For children (0–15 years) this risk is higher by a factor of 4 (0.05 Sv × 5.2 % per Sv × 2.4) and amounts to 2.5 % of the "spontaneous" lifetime cancer mortality risk; however, the net benefit will always justify this mathematically calculated radiation risk if the medical administration of ionizing radiation is medically indicated and the quality of the examination is always according to the latest state of technique.

Assessment of risk and benefit

Assessments of radiation risk in diagnostic radiology are of no value if the risk is considered separately from disease and therapy-related risks, and if the benefit for the patient from the radiological examination is not taken into account.

The difficulty is, of course, to quantify the benefit because it is not easily definable. The benefit could, for example, be measured in years of prolonged life expectancy, which again is difficult to assess. According to other conceptions, the benefit is identified by those portions of radiological diagnoses that lead to – positive or negative – therapeutic decisions because they are the only ones of importance for the patient. Therefore, the most important question before performing an examination should be: Will I get information which really influences the therapy of the primary disease?

When ionizing radiation is applied in medicine, the benefit to the patient should always be the main priority. This benefit is an integral part of the risk–benefit evaluation together with the individual radiation risk for the patient and other individual risks from the examination. For the assessment of the individual radiation risk from an examination, the age-dependent cancer mortality risk coefficient according to the age of the patient may be used together with the average effective dose for the examination type. Additionally, it must be taken into account that the age dependency of cancer mortality varies for different tumours, and also that a very different individual predisposition exists for the development and survival of a cancer disease, which, in part, could be of genetic origin. Added to this, for the exposure of young patients, the genetic risk must be considered, which can largely be disregarded for older patients.

References

1. United Nations Scientific Committee on the Effects of Atomic Radiation: Sources and effects of ionizing radiation. UNSCEAR 1993 report, United Nations, New York
2. Bauer B, Veit R (1995) Initiatives, achievement and perspectives in quality assurance and radiation protection in diagnostic radiology in Germany. Radiat Protect Dosim 57: 43–47
3. Hart D, Jones DG, Wall BF (1994) Estimation of effective dose in diagnostic radiology from entrance surface dose and dose-area product measurement. NRPB-R262, ISBN 0 85951 363 7
4. Reiners Ch, Sonnenschein W (1995) Erhebungen zur Häufigkeit und Altersverteilung sowie zur kollektiven Dosis der nuklearmedizinischen Diagnostik in den alten Bundesländern der Bundesrepublik Deutschland. In: Hähnel S (ed) Strahlenexposition in der medizinischen Diagnostik. Gustav Fischer Verlag, Stuttgart
5. Addendum 1 to ICRP publication 53 (1991) Radiation dose to patients from radiopharmaceuticals. Pergamon Press, Oxford
6. ICRP publication 60 (1990) Recommendations of the International Commission on Radiological Protection. Pergamon Press, Oxford
7. Stather JW, Wall BF (1995) Risks associated with the medical use of ionising radiation at various ages. Proc 10th Int Congr Radiation Research, Würzburg
8. Wall BF (1991) British medical X-ray statistics and their relevance for radiation policies. Radiat Protect Dosim 36: 303–307
9. Beentjes LB, Timmermanns CWM (1991) Patient doses in the Netherlands. Radiat Protect Dosim 36: 265–268
10. Shrimpton PC, Jones PG, Hillier MC, Wall BF, Le Heron JC, Faukneer K (1991) Survey of CT practice in the UK, part 2: Dosimetric aspects. NRPB-R249, ISBN 0 85951 342 4
11. Bauer B, Tsavachidis C (1993) Häufigkeit von Röntgen- und Alternativuntersuchungen. Röntgenpraxis 46: 25–30