

## REVIEW ARTICLE

# Radiation Protection in Diagnostic Radiology

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## SUMMARY

**Introduction:** The use of ionizing radiation is regulated by legislative bodies to limit both individuals' and the population's exposure to radiation. Germany has implemented the European 97/43/EURATOM directive in national law by updating the existing radiation protection regulations. The German Commission on Radiological Protection regularly publishes statements and recommendations on radiation protection in medicine and diagnostic radiology, such as the introduction of diagnostic reference levels and referral guidelines for radiological and nuclear medicine imaging.

**Methods:** Review of selected literature, national and international recommendations and legal texts.

**Results:** From a radiological protection perspective, clear justification for radiological examinations and techniques aimed at minimizing radiation dose while providing the required diagnostic information, are essential.

**Discussion:** Referring doctors should be sure to use existing guidelines for medical imaging, and liaise with radiologists and nuclear medicine specialists, with whom they share the responsibility for choosing appropriate imaging modalities. *Dtsch Arztebl Int* 2008; 105(3): 41–6  
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**Key words:** radiation protection in medicine, radiation dosimetry, radiation risk, German Commission on Radiological Protection, Directive 97/43/EURATOM

Radiation protection is almost as old as the invisible rays discovered by Wilhelm Röntgen on 8 November 1895. The damaging effects of X-rays were discovered shortly afterwards. Physicians and patients who had been exposed to radiation for a protracted period often developed erythema. Although it follows that ionizing radiation can have adverse effects on health, radiological investigational procedures are now an accepted part of clinical practice, as the advantages for the patient far outweigh the risks of radiation exposure.

To restrict the radiation exposure of individual persons and of the overall population, work and contact with ionizing radiation is regulated by recommendations, directives, ordinances, and laws. As a contract state of the European Atomic Community EURATOM, in the 1957 Rome agreements, Germany undertook to convert the EURATOM directives into national law. The first of these directives dealt with protection of employees, not of patients (1). The 1984 directive 84/466/EURATOM (2) specified basic measures for radiation protection in medical investigations and treatments and was the first directive to deal with radiation protection of patients at the European level. This directive laid down for the first time that a justification must be given for each medical use of radiation. This was incorporated in 1987 in the X-ray Ordinance (Röntgenverordnung, RöV) and in 1987 in the Radiation Protection Ordinance (Strahlenschutzverordnung, StrlSchV).

Directive 97/43/EURATOM (5) – also known as the Patient Protection Directive (Patientenschutzrichtlinie, PatSRL) – was converted into national law in Germany through amendments in these two ordinances (3, 4) in 2001 and 2002. The Council of the European Community had already issued the PatSRL in 1997, with the aims of creating harmonized legislation in Europe, as this could stimulate and enhance the protection of patients from ionizing radiation throughout Europe. Recommendations of the International Commission on Radiological Protection (ICRP) were then adopted which greatly tightened the requirements for justification, optimization, training, as well as for equipment and quality control of X-ray systems (6).

The Radiological Protection Committee (Strahlenschutzkommission, SSK) was founded in 1974, with the aims of supporting and advising the federal ministries with responsibility for protection from ionizing

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TABLE 1

Review of different dose formulas and units

Abbreviation	Name	Formula	Unit
J	Ion dose	$J = \frac{dQ}{dm_L}$	C/kg
D	Energy dose	$D = \frac{dE}{dm}$	Gy
H	Equivalent dose	$H = D \cdot w_R$	Sv
E	Effective dose	$E = \sum_T w_T \cdot H_T$	Sv

$w_R$  = radiation weighting factor  
 $w_T$  = tissue weighting factor

BOX

Abbreviations

ALARA	As low as reasonably achievable
CT	Computed tomography
CTDI	Computed tomography dose index
DAP	Dose-area product
DLP	Dose-length product
Gy	Gray
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
PatSRL	Patientenschutzrichtlinie (Directive for Patient Protection)
RERF	Radiation Effects Research Foundation
RöV	Röntgenverordnung (X-ray Ordinance)
SI	International System of Units
SSK	Strahlenschutzkommission (Commission on Radiological Protection)
StrlSchV	Strahlenschutzverordnung (Radiation Protection Ordinance)
Sv	Sievert

and non-ionizing radiation. It currently consists of seven subcommittees, one of which deals with radiation protection in medicine. The SSK regularly publishes statements and recommendations on various themes related to radiation protection, most of which are freely accessible on the internet ([www.SSK.de](http://www.SSK.de) [in German, with a list of international links]).

The recommendations of the SSK and new laws related to diagnostic radiology will now be discussed, accompanied by a refresher on the basic knowledge required for physicians dealing with ionizing radiation, as revealed by analysis of selected literature.

## Radiation dosimetry

Radiation dose parameters were defined with the aim of permitting quantification of the dose of ionizing radiation and its effects on tissue. The dose parameters summarized here are based on the definitions published by the ICRP and the International Commission on Radiation Units and Measurements (ICRU) and which have been adopted internationally in the radiation protection legislation in most countries. The dose units are SI units.

### Energy dose

The energy dose is the basic physical parameter in radiation dosimetry. This describes energy transfer from ionizing radiation to materials other than air. The unit is the gray (Gy), which corresponds to 1 joule/kg. The energy dose can hardly be determined on a routine basis and must usually be calculated from the ion dose with an ionization chamber. *Table 1* summarizes the formulas and units for the various dose parameters.

### Equivalent dose

The equivalent dose is the most important dose parameter for evaluating the effects of radiation and to assess radiation risk, as it incorporates the dimensionless radiation weighting factor  $w_R$  to allow for the different biological activity of various types of radiation. Multiplication of the applied energy dose in an organ or tissue by the corresponding weighting factor gives the equivalent dose. The weighting factor is equal to unity ( $w_R = 1$ ) for the types of radiation used in radiological diagnosis and nuclear medicine (gamma rays and X-rays), so that the energy dose and equivalent dose are numerically the same. The weighting factor  $w_R$  for neutron, proton, and alpha radiation is 5- to 20-fold greater than for photon radiation (gamma or X-radiation) or for electron radiation (beta radiation). To avoid confusion with the energy dose, the unit for the equivalent dose is the sievert (Sv).

### Effective dose

The effective dose is used to quantify radiation exposure in individuals. Exposure of the individual organs and tissues in the body triggers radiation effects with different probabilities, depending on the organ. The combined damage in all organs and tissues in the body is estimated by multiplying the equivalent dose in each organ and tissue with a tissue weighting factor  $w_T$  and then summing the results over the whole body to give the effective dose. The unit for effective dose is again the sievert (Sv).

The weighting factors  $w_T$  published by the ICRP (6) are average values for the overall population, for both genders and with the age distribution from 0 to 75 years. The effective dose was introduced by the ICRP to allow estimation of the nominal stochastic risk after radiation exposure. This is largely based on findings on the victims of the atomic bomb attacks of Hiroshima and Nagasaki, regularly updated with the newest findings of the Radiation Effects Research Foundation (RERF).

Use of the effective dose to quantify doses and risks in medicine is intended to improve the comparability of different procedures for radiological investigation (7).

### Diagnostic reference levels

The ALARA principle (see *box*) demands that, during work with ionizing materials, every reasonable effort should be made to minimize exposure of man, animals, and material – even below the dose limits. In spite of the obligation to comply with the ALARA principle and the precept of optimizing patient protection during medical exposure, it has been found that the radiation exposure of patients during comparable investigations can vary by several orders of magnitude (8, 9). For this reason, "dose limits" or "reference values" have been specified for the most frequent procedures in medical diagnosis. These "reference dose values" should be easy to determine. They are intended to be practical aids to help in the easy recognition of situations in which the administered activity or radiation is on average unusually high for the patients.

The dose parameters discussed above are intended for the determination of patient exposure, but can only be calculated with complex measurement procedures and conversion factors. They are therefore rather unsuited as "reference values" in diagnostic radiology. For routine work, dose parameters have become established which are physically easier to determine, such as the surface dose or dose-area product (DAP) for projection radiography and the  $CTDI_w$  value and the dose-length product (DLP) for computed tomography (CT). These dose parameters can be directly measured or read off (10).

The diagnostic reference values are standard values which must be complied with in nuclear medicine. They may be exceeded in X-ray diagnosis in individual cases, if this is justified. If they are permanently exceeded, measures must be taken to reduce the dose, in accordance with the requirement of optimization in radiation protection. These reference values are specified and published by the Federal Office for Radiation Protection (Bundesamt für Strahlenschutz, BfS) (3); routine checks of compliance are a medical responsibility. The SSK has recently published a guideline for investigations in radiology and nuclear medicine. This gives typical effective doses from medical radiation exposure (review in *table 2*) (11). This leads to the conclusion that a chest CT leads to 400-fold greater radiation exposure for the patient than conventional chest projection radiography and 16-fold greater radiation exposure than a normal two-plane bilateral mammography.

### Effect of ionizing radiation and radiation risk

Radiation protection is necessary because ionizing radiation has biological effects that affect the organism. A distinction is made between non-stochastic (deterministic) effects and stochastic (random) effects. In addition, somatic effects (such as radiation sickness or cancer) are differentiated from genetic effects in the offspring.

**TABLE 2**

#### Typical effective doses from exposure to medical radiation (11)

Diagnostic procedure	Typical effective dose (mSv)	Number of chest X-rays leading to comparable exposure
Chest (p.a)	0.02	1
Extremities and joints	0.01	0.5
Skull	0.07	3.5
Thoracic vertebra	0.7	35
Lumbar vertebra	1.3	65
Hip	0.3	15
Pelvis	0.7	35
Abdomen	1.0	50
Mammography (bilateral in 2 planes)	0.5	25
Intravenous urography	2.5	125
Head CT	2.3	115
Chest CT	8	400
Abdomen or pelvis CT	10	500
Renal function scintigraphy	0.8	40
Thyroid scintigraphy	0.9	45
Lung perfusion scintigraphy	1.1	55
Skeletal scintigraphy	4.4	220
Brain scintigraphy	5.1	255
Myocardial perfusion scintigraphy	6.8	340
Positron emission tomography	7.2	360
Myocardial scintigraphy	17	865

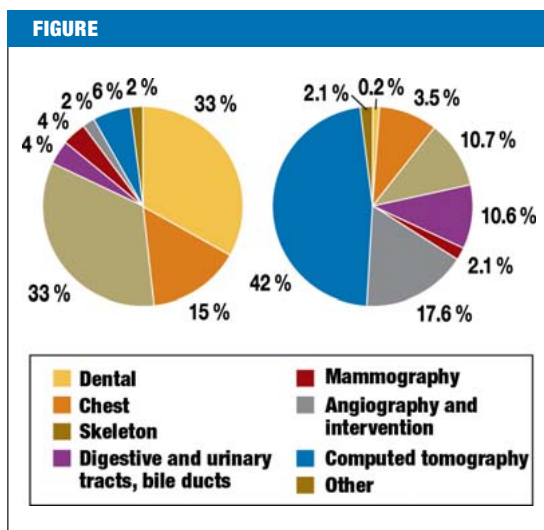
### Stochastic and deterministic damage

There is a "deterministic" and non-stochastic effect if the extent of damage depends on the applied dose and its spatial and temporal distribution. In this case, there is a threshold value. Once this is exceeded, the effects of radiation are observed. Deterministic effects include cell, tissue, and organ damage in radiation erythema, skin necroses, and acute radiation sickness.

If the probability that an effect occurs depends on the dose, but the severity of the effect does not, the effect is said to be "stochastic." The probability of the effect is very low at low doses. It is now assumed that there is no threshold under which damage is absolutely excluded. Cancers and genetic damage are, for example, consequences of stochastic effects. Direct dose-dependent radiation damage is extremely rare in X-ray diagnosis. At most, stochastic effects are observed (12).

### Radiation risk

The radiation risk is the quantification of the potential damage which can arise from ionizing radiation. The emphasis here is mainly on malignant disease; there are limited data on cardiovascular effects. Risk assessment



Relative frequency of different X-ray procedures in Germany in 2001, together with their relative contributions to the collective effective dose. Taken from: Brix G, Nekolla E, Griebel J: Strahlenexposition von Patienten durch diagnostische und interventionelle Röntgenanwendungen – Fakten, Bewertung und Trends [Radiation exposure of patients from diagnostic and therapeutic X-ray procedures – facts, evaluation, and trends]. Radiologe 2005; 45: 340–9 (14), with kind permission of Springer Verlag, Heidelberg

is mainly based on epidemiological studies. Reliable risk values can mostly only be determined for the intermediate and high dose ranges. For the low dose range – under 100 mSv – the risk values are extrapolated. This is carried out using different dose-response relationships.

The calculations are still largely based on data from atomic bomb survivors from Hiroshima and Nagasaki. On the basis of the observed linearity in the higher dose range, it has been assumed that the dose-action relationship is also linear in the low dose range. The data for leukemia are better described with a linear-quadratic function. Using empirical evidence and theoretical principles on the effects of lower doses, risk coefficients for the low dose range have been corrected with a dose reduction factor – a controversial procedure. The risk coefficients calculated from the Japanese data were adopted by the ICRP in 1990 (6).

For the risk assessment for the population (adults and children), the ICRP proposes the following so-called lifetime risk coefficients for cancer mortality: 5% per Sv for low doses and 10% per Sv for high doses. A risk coefficient of 10% per Sv means that a radiation exposure of 10 mSv for 10 000 persons leads to 10 additional deaths from cancer or leukemia. (Without the effects of radiation, about 2500 of 10 000 people die of cancer). The leukemia risk after radiation of the red bone marrow is 0.5% per Sv, corresponding to one tenth of the total cancer risk in the lower dose range. It becomes clear that the risk coefficients are very different in the different organs. The genetic radiation risk – the probability that future generations will suffer from severe genetic damage –

has been given as 1% per Sv. Thus the genetic radiation risk is five times less than the risk of fatal cancer. New considerations will probably lead to even lower figures in the future.

Radiation doses to healthy normal tissue from radiation scatter during radiotherapy are markedly greater than the normal dose values in X-ray diagnosis. For this reason, these values cannot be extrapolated to assess the risks, e.g., of a second malignancy or of genetic damage after radiotherapy (13).

When evaluating the risk of medical radiation exposure, the age at time of exposure and the patient's life expectancy in comparison to the general population must be considered. The risk of mortality from ionizing greatly decreases with increasing age. This is linked to the fact that most tumors have a long latency period, so that they cannot be identified within the exposed person's life-time (12).

### Radiation exposure in radiology

In industrial countries, most radiation exposure linked to civilization is from medical diagnosis (14). For this reason, the European PatSRL, the StrlSchV and the RöV demand that the medical radiation exposure of the general population and relevant reference groups should be regularly determined (3, 4, 5).

According to the BfS, about 148 million X-ray investigations were performed in 2001 – one third being in dentistry. This corresponds to 1.9 investigations per inhabitant (14). Although there was essentially no change in the number of X-ray investigations per 1000 inhabitants between 1996 and 2001, the mean effective dose per inhabitant rose from 1.6 mSv to 1.8 mSv within this period. The reason for this is evidently the increasing use of CT and interventional radiography. Although CTs make up only about 7% of all X-ray investigations in Germany, they make a disproportionate contribution – 47.2% – to patients' radiation exposure (*figure*). This trend towards an increasing contribution of CT to medical radiation exposure is also observed in other countries (*table 3*). For these reasons, CT should be an important and worthwhile aspect of radiological protection.

In 1999, a review on CT exposure in practice was performed throughout Germany (19). This review, as well as other publications (20, 21) makes it clear that the patients' radiological exposure during CT is highly dependent on the technical parameters set. Potential dose reductions of 50% were identified in half the participants in the survey (19). The introduction and maintenance of dose reference values for CT investigations thus seems to be both sensible and necessary.

It has been estimated that medical diagnosis in Germany leads to an additional "attributable" cancer mortality of 1.5 to 2% (22, 23). The risk is similar in other countries with comparably high patient exposure, such as Luxembourg and Belgium, but markedly lower in England, the Netherlands, and Switzerland (0.6%, 0.7%, and 1%, respectively). Nevertheless, Berrington de Gonzalez and Darby, the authors of the English



study, do not exclude the possibility that the risk from ionizing radiation in diagnostic radiology is being overestimated. In any case, it is quite clear that there are major differences in the risks in the 15 countries compared (23).

# Résumé

It is essential for radiological protection that ionizing radiation is only used when there is a clear justification. The qualification in radiological protection is acquired by suitable training in the relevant area and appropriate practical experience, together with theoretical knowledge. This must be updated at least every five years by successful participation in a course which is recognized by the responsible authority – usually the local Medical Association. Only a qualified physician can justify the medical use of ionizing radiation and establish that the expected benefit of the investigation outweighs the radiation risk (3, 4).

As is evident in the SSK recommendations and in the BfS reports, rules for the referral for radiological investigation can influence the type and scope of the procedures used (24). Exposure may be reduced by optimizing the procedure and by avoiding unnecessary imaging, particularly repeats, or inexpertly performed tests. Particularly in exclusion diagnoses by imaging procedures, ultrasound and magnetic resonance tomography should be the procedures of first choice, in so far as this is possible, as these supply information for further diagnostic and therapeutic measures without using ionizing radiation (25).

Communication between the referring physicians and specialists in radiology and nuclear medicine is of essential importance in justifying the use of ionizing radiation and in identifying the optimal procedure. In 2001, the SSK recommended the preparation of "Guidelines for Referral for Imaging Techniques" (24). This was published in summer 2006 under the title "Orientierungshilfe für radiologische und nuklearmedizinische Untersuchungen" (Guideline for Investigations in Radiology and Nuclear Medicine) (11). This guideline covers pregnancy and protection of the fetus together with the necessary optimization of radiation exposure in investigations of children and adolescents. It particularly emphasizes the selection of suitable imaging procedures to avoid unnecessary patient exposure.

Technical radiological protection in isolation therefore is not the most effective method to reduce radiation exposure in medicine. Physicians must ensure that unnecessary investigations are not performed. The referring physician bears special responsibility and should use guidelines for diagnosis to a greater extent. In difficult cases, they should also consult with their colleagues in radiology and nuclear medicine in the selection of the most suitable procedure. If cooperation between these two groups of physicians in the selection of imaging procedures for common diseases could be enhanced, this would be a major contribution towards radiological protection.

TABLE 3

## Frequency and dosage from CT investigations in 2000: an international comparison

Country	CT investigations per 1000 inhabitants	CT dose per inhabitant (mSv)
Germany (14)	90	0.73
USA (15)	200	1.60
Japan (16)	290	2.30
Luxembourg (17)	115	0.84
Belgium (18)	115	0.90

## Conflict of interest statement

The authors declare that no conflict of interest exists according to the guidelines of the International Committee of Medical Journal Editors.

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