

Prenatal Radiation Exposure: Dose Calculation

Pränatale Strahlenexposition: Dosisermittlung

Authors

C. Scharwächter¹, A. Röser², C. A. Schwartz¹, P. Haage¹

Affiliations

¹ Department of Diagnostic and Interventional Radiology, HELIOS Klinikum Wuppertal, University Hospital Witten/Herdecke, Wuppertal, Germany

² Department of Radiotherapy and Radio-Oncology, HELIOS Klinikum Wuppertal, University Hospital Witten/Herdecke, Wuppertal, Germany

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Correspondence

Dr. Christian Scharwächter
Klinik für diagnostische und interventionelle Radiologie, HELIOS-Klinikum Wuppertal, Klinikum der Privaten Universität Witten/Herdecke Heusnerstr. 22 42283 Wuppertal Germany
Tel.: ++49/2 02/8 96 21 05
Fax: ++49/2 02/8 96 17 51
christian.scharwaechter@helios-kliniken.de

Abstract



The unborn child requires special protection. In this context, the indication for an X-ray examination is to be checked critically. If thereupon radiation of the lower abdomen including the uterus cannot be avoided, the examination should be postponed until the end of pregnancy or alternative examination techniques should be considered. Under certain circumstances, either accidental or in unavoidable cases after a thorough risk assessment, radiation exposure of the unborn may take place. In some of these cases an expert radiation hygiene consultation may be required. This consultation should comprise the expected risks for the unborn while not perturbing the mother or the involved medical staff.

For the risk assessment in case of an in-utero x-ray exposition deterministic damages with a defined threshold dose are distinguished from stochastic damages without a definable threshold dose. The occurrence of deterministic damages depends on the dose and the developmental stage of the unborn at the time of radiation.

To calculate the risks of an in-utero radiation exposure a three-stage concept is commonly applied. Depending on the amount of radiation, the radiation dose is either estimated, roughly calculated using standard tables or, in critical cases, accurately calculated based on the individual event. The complexity of the calculation thereby increases from stage to stage. An estimation based on stage one is easily feasible whereas calculations based on stages two and especially three are more complex and often necessitate execution by specialists.

This article demonstrates in detail the risks for the unborn child pertaining to its develop-

mental phase and explains the three-stage concept as an evaluation scheme. It should be noted, that all risk estimations are subject to considerable uncertainties.

- ▶ Radiation exposure of the unborn child can result in both deterministic as well as stochastic damage and hitherto should be avoided or reduced to a minimum.
- ▶ In case of radiation a suitable hygiene consultation may be necessary.
- ▶ For risk assessment a three-stage concept is applied, which, depending on the radiation exposure, estimates or calculates the dose for the unborn child.
- ▶ The radiologist plays a crucial role as a competent advisor and provider of reliable expert information.

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Zusammenfassung



Embryo und Fetus bedürfen eines besonderen Schutzes. In diesem Kontext ist die Notwendigkeit einer Röntgenuntersuchung besonders kritisch zu prüfen. Bei einer nicht vermeidbaren Mitbestrahlung des Unterbauches und damit des Uterus, sollte die Untersuchung bis zum Ende der Schwangerschaft verschoben oder die Möglichkeit alternativer Verfahren erwogen werden. Unter speziellen Umständen kann es jedoch, entweder inzidentell oder nach reiflicher Risikoabwägung gezielt, zu einer Röntgenuntersuchung und konsekutiv zu einer Strahlenbelastung des Ungeborenen kommen. In diesem Fall kann eine strahlenhygienische Beratung erforderlich werden. Diese enthält die zu erwartenden Risiken für das Ungeborene, ohne unnötige Ängste und Sorgen sowohl bei der

Schwangeren, als auch bei behandelnden Kollegen zu induzieren. Für die Risikobewertung werden im Falle einer Exposition in utero deterministische Strahlenschäden mit einer definierbaren Schwellendosis und stochastische ohne Schwellendosis differenziert. Das Auftreten von deterministischen Schäden ist zusätzlich zur Dosis vom Entwicklungsstadium des Ungeborenen zum Zeitpunkt der Strahlenexposition abhängig.

Als Bewertungsschema hat sich im Falle einer Strahlenexposition in utero ein dreistufiges Konzept bewährt. In Abhängigkeit der Expositionsausprägung wird entweder eine Abschätzung der Dosis bzw. eine grobe Berechnung anhand von Rechenmodellen vorgenommen oder es erfolgt im ausgeprägtesten Fall eine auf den Einzelfall bezogene Berechnung so exakt wie möglich. Die Komplexität der Bestimmung nimmt dabei mit jeder einzelnen Stufe zu. Während eine Abschätzung nach Stufe eins normalerweise problemlos machbar ist, ist eine Berechnung nach Stufe zwei und insbesondere drei komplex und oft nur von Spezialisten durchführbar.

Im folgenden Artikel werden die Risiken für das Ungeborene in Abhängigkeit von den verschiedenen Entwicklungsphasen differenziert dargestellt und das Drei-Stufen-Konzept als Bewertungsschema näher erläutert. Hierbei ist zu berücksichtigen, dass die entsprechenden Risikoschätzungen mit nicht unerheblichen Unsicherheiten behaftet sind.

1. Introduction

In every organism, ionizing radiation can cause both deterministic as well as stochastic damage. The prenatal phase is a particularly vulnerable period of time [1]. Prior to every planned application of ionizing radiation it must be determined whether the patient is pregnant. Before every examination using ionizing radiation on a pregnant patient, sufficient protections must be employed, such as shielding measures, in order to avoid radiating the lower abdomen and uterus. In individual cases, the uterus of a pregnant patient might receive a relevant radiation dosage; this may be inadvertent in instances of an unknown pregnancy, or as a result of an urgent medical indication such as a potentially life-threatening situation. There is considerable uncertainty in both the general population as well among non-radiologist physicians regarding action following such radiation exposure. Thus, the radiologist plays a crucial role as a competent advisor and provider of reliable expert information in this difficult patient situation.

This article is intended to provide assistance to physicians prior to or after a pregnant patient is exposed to radiation. First, possible effects of prenatal radiation exposure will be discussed in relation to the level of maturity of the embryo; in conclusion, the “three-level concept” for risk assessment of the unborn child and related recommendation for action will be presented. With respect to the three-level concept, there will also be a discussion of how the uterine dose can be estimated, or if needed, calculated. Since the desires of the affected patient are crucial with respect to subsequent consequences, there are no compulsory guidelines in this regard; however concrete recommendations have been proposed for the patient as a function of the applied dosage which are described at the end.

The article is based on the “DGMP and DRG Report on Prenatal Radiation Exposure due to medical Indications,” last

revised in 2002 [2], as well as DIN standards identified here; the current literature has likewise been included. Since the DGMP and DRG (German Society for Medical Physics/German X-ray Society) report was written, studies of long-term consequences of the use of atomic weapons at the end of the Second World War as well as of the Chernobyl catastrophe have been published [3–6]. In 2011, the nuclear accident at Fukushima took place. Initial studies of affected human beings as well as various animal populations have been published [7–11]. Of particular interest are comparisons with earlier events which have somewhat varying results due to differences in how they unfolded, yet which can offer additional insight nonetheless [7, 10, 11] (see below). In addition, psychological factors and their effects on births have been investigated with respect to Fukushima [12].

2. Possible effects after prenatal radiation exposure

Prenatal development of a human being is essentially influenced by three processes: cell proliferation, cell differentiation and cell migration. All three processes can be damaged by ionizing radiation; therefore the entire prenatal phase must be considered especially sensitive to irradiation. Both the extent as well as the type of damage vary in relation to the developmental phase of the embryo or fetus. Prenatal development is generally divided into three phases: (1) pre-implantation phase which extends up to two weeks post-conception (p.c.), (2) organ-formation phase which extends from approx. the second to the eighth week p.c., and (3) fetal phase which extends from the eighth to the 39th week p.c. The potential injuries, their risk and estimated dose thresholds can be found in [Table 1](#) as well in the discussion below.

Since for obvious reasons no direct research data can be collected, in the following discussion it should be kept in mind that all data is subject to uncertainty. This is due, for example, to assumptions based on animal experiments or investigations applied to humans, or extrapolation of high dose values to lower values. However, in the past, threshold values as well as risk coefficients for injury to the embryo or fetus have been defined. The use of these values provides a general estimate of the occurrence of various biological effects, taking into account the dosage level of the exposure. Based on this, it is possible to provide a risk assessment to the pregnant patient as part of a pending or completed diagnostic examination, a therapeutic measure, or possible consideration of termination of the pregnancy. The following dosage values relate to the uterus dose equivalent H_{U} .

2.1. Effects during implantation phase

The pre-implantation phase is subject to the “all or nothing” rule when it comes to injury [18]. This means that in the event of sufficiently severe injury, the implantation fails and the embryo dies, or, if the damage is below a certain threshold, implantation of the blastocyst occurs without further injury. In general pregnancy is not detected at this stage, and the failed implantation is not recognized as such. Radiation doses above 100 mSv are considered the lower threshold for failed implantation. Above this dose an additional risk of 0.1 % per mSv is presumed (risk coefficient

Table 1 Summary of biological effects of prenatal radiation exposure taking in account time point of exposure related to conception as well as the threshold value of risk. The spontaneous risk in the population is offered as a comparison – where comparable [2, 13–17].

effect	time period p. c.	lower threshold	risk in %/mSv above the threshold	spontaneous risk in the population
death during implantation phase	1 st – 2 nd week	100 mSv	0.1 %/mSv	30 %
malformation	2 nd – 8 th week	100 mSv	0.05 %/mSv	6.7 % ^{1*}
severe mental retardation	8 th – 15 th week	300 mSv	0.04 %/mSv	Normal Gauss distribution
	16 th – 25 th week	300 mSv	0.01 %/mSv	
IQ reduction	8 th – 15 th week	above 0 mSv (no threshold value)	0.03 %/mSv	Normal Gauss distribution
	16 th – 25 th week	above 0 mSv (no threshold value)	0.01 %/mSv	
malignant disorders	total pregnancy	above 0 mSv (no threshold value)	0.006 %/mSv	50.7 % (male) ² 42.8 % (female) ²
heritable defects	total pregnancy	above 0 mSv (no threshold value)	0.003 %/mSv (male) 0.001 %/mSv (female)	2%/generation

¹ Prevalence [15].

² Lifetime risk in 2008 [16].

1 Sv⁻¹). Malformations resulting from damage during the pre-implantation phase occur rarely when there is a corresponding parental predisposition, as shown in animal experimentation [19–24].

2.2. Effects during organ formation phase

At certain dose levels, radiation exposure during the organ formation phase can trigger functional disorders, growth inhibition or organ malformations. Likewise, approx. 100 mSv is considered the lower threshold value for the induction of such changes. Animal studies have determined that above the threshold value, the risk of occurrence of fetal malformations increases by about 0.05 % per mSv (risk coefficient 0.5 Sv⁻¹). This value is also accepted to apply to humans in the organ formation period between the second and eighth week of gestation. At approx. 200 mSv, the fetal malformation risk is assumed to double. A reduction of head circumference in children exposed to in utero irradiation above 500 mSv could be determined among survivors of atomic bomb explosions at Hiroshima and Nagasaki, as well as after the catastrophe at Chernobyl [3, 4, 25, 26]. Possibly due to a generally lower radiation leak and rapid evacuation measures after the accident at Fukushima in 2011, there was no statistically verifiable increase in deformations among humans [7]. However, typical morphological and genetic changes could be shown among animal life in the disaster area [8, 9].

2.3. Effects during fetal phase

Formation of the central nervous system is in the foreground during the last six months of fetal development. Since this period is relatively long, injuries are relatively frequent in this phase. Especially sensitive are the periods from the 8th to the 15th week and from the 16th to the 25th week. Exposure above the threshold dose can result in substantial mental retardation. The threshold value is 300 mSv from the 8th to the 25th week. Above this value there is an additive risk of approx. 0.04 % per mSv (risk coefficient 0.4 Sv⁻¹) for weeks 8 to 15, and 0.01 % per mSv (risk coefficient 0.1 Sv⁻¹) for weeks 16 to 25. In addition to severe mental retardation, a decrease in intelligence quotient (IQ) among affected children can be observed [27, 28]. The existence of a threshold dose is unclear; the possible expected

reduction of intelligence is so minimal in the low dose range that it is not measurable. Based on studies of atomic bomb survivors in Japan, it was determined that radiation exposure during the 8th to the 15th weeks resulted in a reduction of about 30 IQ points per Sv. Radiation exposure during weeks 16 to 25 was reflected in a reduction of approx. 10 IQ points per Sv [5, 29–31].

2.4. Malignant disorders after in utero exposure

In addition to the previously described deterministic radiation damage at a definable threshold dose, stochastic radiation damage may also occur. When taking into account radiation protection, it is presumed that the risk of the occurrence of such injuries in these cases increases linearly with the dose regardless of any existing threshold dosage. This type of stochastic dose response is assumed for the induction of malignant disorders. However, the available data is somewhat contradictory. While in animal experiments [6] and retrospective studies, particularly the Oxford study [1, 32] as well as studies of atomic bomb survivors [33], a significant increase in the occurrence of leukemia and other malignant tumors could be demonstrated; such occurrences, at least for leukemia, could not be confirmed for survivors of the accidents at Chernobyl and Fukushima [3, 10, 11]. Thus, due to a number of different factors, the underlying events have only limited comparability. For example, various absorption mechanisms are discussed – primary extracorporeal radiation at Hiroshima and primary intracorporeal absorption of radioactive iodide at Chernobyl and Fukushima [11]. Various cohort studies have demonstrated a decreasing tumor risk with increasing age [33]. Interestingly, low doses of radiation have been shown to provide protection against tumors as well as life-prolonging effects; this is based on studies of cohorts of atomic bomb survivors, mouse experiments as well as those exposed to naturally-occurring radiation. This is referred to as radiation hormesis [34–36]. In general, the presumption is that there is susceptibility to radiation during the entire prenatal gestation period without a specified threshold level. Based on estimates, cancer mortality is approx. 0.006 % per mSv (6 % per Sv) [3, 37, 38]. The first trimester of the prenatal phase is possibly the most susceptible; however, an exact assess-

ment of the relative risk during individual phases of gestation cannot be ascertained based on available data.

2.5. Heritable defects after in utero exposure

A stochastic dose-effect relationship is presumed for the occurrence of heritable defects, analogous to the emergence of malignant disorders. There is no data for humans regarding radiation-induced genetic changes. Animal experiments indicated that the induction of genetic damage is possibly lower prenatally than post-natally. This is due to an increased regeneration capacity during early gestational phases. Based on data obtained from animal experiments, the risk of induction of a genetic defect is approx. 0.0003 % per mSv (0.3 % per Sv) for male fetuses and about 0.0001 % per mSv (0.1 % per Sv) for female fetuses [39 – 41].

3. The three-level concept for determining uterine dosage

Previous discussions make it clear that sufficiently strong radiation exposure will have a seriously damaging effect on the fetus.

After radiation exposure during a pregnancy, in order to determine the risk and extent of radiation-induced damage to the fetus, the attending physician or medical physics expert (MPE) must determine the equivalent dose H_U in the uterus, considered representative for the degree of exposure of the embryo or fetus. Decisions regarding further action and counseling of the pregnant patient depend on the level of the ascertained uterine equivalent dose

Unlike radiotherapeutic and nuclear medical applications in which the uterine dose in the event of a possible patient pregnancy can be primarily integrated into therapeutic planning using a treatment planning system and tabular distribution models taking into account the administered radionuclides, corresponding procedures are absent in the area of X-ray diagnostics. Instead, a three-level concept was established for the latter circumstance, the individual steps of which will be explained below. The determination of uterine dose during radiotherapeutic and nuclear medical applications is based on the statements of the joint report of the DGMP and DRG [2].

Prior to the actual employment of the three-level concept, the determination of the time period between conception and exposure is of prime importance. If this can be indicated with certainty to be less than 10 days, then according to the discussion in section 2.1, no further dose assessment is required, since the all-or-nothing rule applies (see above). If this cannot be reliably ascertained, then the examined body region as well as the examination method used are decisive for further action.

When low-dose projection radiographic procedures are used (conventional X-ray), additional assessment is only necessary if the unborn child is located in the useful beam. In all other instances, the lower threshold value cannot be reached with normal equipment use. For radiation-intensive procedures, particularly CT, a further assessment is necessary if the uterus is physically located in the vicinity of the region to be examined without being irradiated itself. This assessment can be omitted in cases of examinations of areas far removed from the uterus, such as the skull. The exact calculation of the uterine

equivalent dose is complex. In order to keep the number of complex calculations by medical physicists to a minimum, the determination of the uterine dose for diagnostic radiology is performed in three gradations, with increasing complexity, depending on the extent of required radiation exposure.

Level I: General assessment of the uterine dose based on tables,
Level II: Assessment of the uterine dose using examination parameters and typical device and patient data,
Level III: The uterine equivalent dose is calculated based on individual examination parameters and device- and patient-specific data.

When this concept is applied, it should be kept in mind that the levels should be followed sequentially, and the amount of the dose established in the related level determines the application in the next higher level as well as the implications for counseling the pregnant patient.

3.1. General assessment of the uterine dose (Level I)

In a number of unintended or even necessary radiation exposures, the applied dose remains relatively low, resulting in no predictable consequences for the pregnant patient. According to figures provided by the German Federal Office for Radiation Protection, the uterine dose for approx. three-quarters of examinations during pregnancy is below 5 mSv [42]. The purpose of the initial general assessment using tables is to reduce extensive exact calculations to those actually required for the individual case. The bases for this are standardized basic parameters for the examination which may lead to realistic yet higher dose values, to avoid a false sense of security [2].

3.1.1. Radiography/fluoroscopy

With respect to the equipment, the uterine dose is dependent on the parameters set for the examination. Certain assumptions for the equipment parameters are established to permit a tabular assessment in the initial level (Table 2). In addition to beam quality which is determined by the tube voltage and filtering installed in the equipment, the dose registered on the uterus is influenced by the dose requirement on the image receptor and beam attenuation caused by grids and other irradiated media.

Otherwise the dose is essentially determined by the thickness of the patient. Any positional anomalies of the uterus are not considered in this instance; instead the presumption for a.p. images is that the uterus is 3/10 of the patient diameter, and lies in the center for lateral images. Three irradiated body thicknesses are always listed in the table to account for differences in patient constitution.

X-ray dosage values based on these assumptions are shown in Table 3, the dose rate values for fluoroscopic examinations are contained in Table 4. However, the actual technical frequency range of X-ray and fluoroscopic equipment is wide so that the actual dose values vary correspondingly. The foundational tables are based on the worst case. If, according to the measured values, the dose or dose rate requirement during the acceptance test are presumed to be less than indicated in Table 2 in a concrete case, the tabular values can be reduced proportionally. The same applies to the equipment attenuation factor. Since the worst case is also presumed for fluoroscopic equipment, only the fluoroscopy time in which the uterus was exposed to the primary beam should be used for calculation [2].

Table 2 Underlying radiographic/fluoroscopic. Technical parameters used as benchmark data for general dose assessment according to Level I of the three-level concept [2].

beam quality	70 – 80 kV
filter	2.5 mm Al
image receptor dose requirement for film-screen systems	5 μ Gy / image
image receptor dose requirement for digital I. I. images	2 μ Gy / image
image receptor dose requirement for DSA images	10 μ Gy / image
dose rate at image intensifier input during fluoroscopic examinations	0.6 μ Gy/s at 25 cm I. I. diameter
grid and tabletop attenuation	equipment attenuation factor 4

Table 3 Highest value of uterine equivalent dose in mSv of radiographic and fluoroscopic images for assessment according to Level I of the three-level concept [2].

projection	uterine equivalent dose in mSv per image						
	a. p.			p. a.			lateral
constitution	thin	normal	thick	thin	normal	thick	normal
	17 cm	22 cm	26 cm	17 cm	22 cm	26 cm	36 cm
film-screen system grid image	2	3	5	1	1.5	2.5	4
digital I. I. image	1	1.5	2	0.5	0.8	1	2
DSA image	4	6	10	2	3	5	8

Table 4 Highest value of uterine equivalent dose in mSv/min during fluoroscopic examinations using an image intensifier-television system for assessment according to Level I of the three-level concept [2].

projection	uterine equivalent dose in mSv per minute						
	a. p.			p. a.			lateral
constitution	thin	normal	thick	thin	normal	thick	normal
	17 cm	22 cm	26 cm	17 cm	22 cm	26 cm	36 cm
FL with I. I. television system	16	24	40	8	12	20	32

3.1.2. Computed tomography

Computed tomography (CT) uses a different approach compared to radiographic examination. If the uterus was positioned in the direct examination field, then conservative general assessment always results in values above 20 mSv. In this case, a more precise calculation is required (see section 2.4). This is also required if the uterus was not positioned directly within, but rather adjacent to, the examination volume. Decisive here is the dose required per slice or rotation determined by the tube current-time product (mAs product) [2].

If, on the other hand, an examination was performed on a body region far removed from the uterus, dose values in **Table 5** apply to the general assessment of all CT examinations. The values shown in the table are based on 100 mAs per slice or revolution. These values are converted applying the rule of three to the mAs product [2].

3.1.3. Example 1

A patient in the fourth week of pregnancy with a sagittal diameter of 21 cm receives an emergency X-ray of the thorax on two planes as well as of the abdomen on one plane, and then is subjected intraoperatively to an additional fluoroscopy of 3 minutes, during which the pelvis was exposed for 30 seconds.

Assessment

Only the abdominal image pertains to the general assessment of the X-ray images, since only the uterus lay in the

Table 5 Values for assessment of uterine equivalent dose in mAs / slice or rotation during computed tomography corresponding to an assessment according to Level I of the three-level concept [2].

tube voltage (kV)	uterine equivalent dose in mSv at 100 mA / slice or rotation
80	1.0
120	2.0

main beam in this case. According to **Table 3** the equivalent dose for a normally constituted patient using an image with a film/screen system is 3 mSv.

Only the abdominal image is relevant for the general assessment of the X-ray images, since only the uterus lay in the main beam in this case. According to **Table 4** the equivalent dose rate for a normally constituted patient is $0.5 * 24 \text{ mSv} = 12 \text{ mSv}$.

In total, the general assessment in our example according to Level I yields a uterus equivalent dose value of 15 mSv. Since the limit of 20 mSv is not exceeded, a more exact calculation can be omitted. The assessment should be documented in the patient's file. Refer to **section 2.5** for the resulting recommendations for the pregnant patient.

3.2. Uterine dose calculation (Levels II and III)

Determination of the uterine dose according to Levels II and III is more complicated and is generally calculated with the help of a medical physicist. The differences between Levels

II and III lie in the source data used to determine the uterine dose. In Level II, equipment-specific data from relevant tables is sufficient for calculation; in the third level, equipment-specific variables are used for the related examination, e. g. taken from the logs of the acceptance test. Further, Level III takes into account the individual patient geometry as well as exposure conditions.

3.2.1. Radiography/fluoroscopy

In order to calculate the uterine dose apart from a pure tabular assessment, it is necessary to determine the incident dose K_E . This can be performed in two ways. Using the so-called source concept, the incident dose is calculated directly from the examination parameters. Critical in this instance is the characteristic dose rate of the X-ray tube measured in air which is dependent on the selected tube voltage and total filtering, and which as a rule is measured at a fixed focal length. Based on the imaging or fluoroscopy time as well as the focus-skin distance, the incident dose can be calculated according to **Fig. 1a**.

In contrast, when the image receptor concept is applied, the dose incidence is estimated based on the dose requirement on the image receptor taking into account attenuation factor S (**Fig. 1b**).

When newer equipment is used, and especially during fluoroscopic examinations, the incident dose can also be determined from the measured area dose product. However, to do this, data regarding the size of the image on the receptor as well as values for the focus-image receptor and focus-skin distance are required (**Fig. 1c**).

Using the known incident dose K_E , the uterine dose can be determined using three methods [43 – 46]:

- using organ dose conversion factors from the incident dose or the dose area product of standardized examinations,
- using the tissue-air ratio based on the incident dose and the derived tissue-energy dose at the uterus level,
- using depth-dose organ tables from the incident dose or the surface dose of the side of the radiation entrance.

With the help of a), an average organ equivalent dose H_T is obtained based on the average total mass of the uterus; using b) and c), the organ-energy dose or organ equivalent dose is obtained as a dot size. Refer to **Fig. 2** for the exact determination of the organ equivalent dose.

3.2.2. Computed tomography

Several factors are required to determine the uterine dose during CT examinations. On the one hand, the uterine dose depends on the average air kerma in the system axis. It is based on the integrated dose across a CT scan normalized to the nominal slice thickness; this is also called $CTDI_{air}$. Further, an organ dose conversion factor is required which indicates the uterine dose (per unit of $CTDI_{air}$) required to effect a 1 cm thick 360° slice as a function of the distance of the related CT slice from the uterus [47 – 49]. The individual components are then added up to a total uterine dose (**Fig. 3**).

For calculations according to Level II, the average air kerma in the system axis can be taken from related tables. The values are normalized to 100 mAs per CT slice; adaptation corresponding to the mAs product is then necessary. Calculations according to Level III use the measured and

a) Calculation of incident dose K_E according to the source concept

$$K_E = K_a^0(l, d_k) \cdot I_r \cdot t \cdot (d_k/d_E)^2$$

$$\begin{aligned} \text{For X-rays:} & \quad K_E = S \cdot K_B \\ \text{For fluoroscopy:} & \quad K_E = S \cdot K_B \cdot t \end{aligned}$$

b) Calculation of attenuation factor S using the image receptor concept

Calculation of attenuation factor S using table values

$$S = S_G \cdot S_{P,100} \cdot S_{T,100} \cdot S_{R,100} \cdot S_F$$

c) Calculation of incident dose K_E using the dose area product

Under constant fluoroscopic conditions and known field size, incident dose K_E can be determined from the dose area product P_F :

$$K_E = P_F / P_E \text{ times } F_E = F_B \cdot (d_E / d_B)^2$$

Legend:

$K_a^0(l, d_k)$: Air kerma strength in focal distance d_k as a function of tube current
 K_B : Dose (air kerma) per image on image receptor
 K_E : Incident dose per image or fluoroscopic segment
 I_r : Tube current
 t : Imaging or fluoroscopy time
 d_k : Focal distance of patient's radiation entrance side (focus-skin distance)
 d_E : Reference focus distance for indicating reference dose rate
 d_B : Image receptor distance focus
 S : Total attenuation factor between the patient's radiation entrance side and the image receptor
 S_F : Field size factor
 S_G : Geometry factor $((d_B / d_E)^2)$
 S_P : Patient attenuation factor
 S_R : Grid factor
 S_T : Table attenuation factor
 P_F : Dose area product
 F_B : Field size on image receptor
 F_E : Field size on patient's radiation entrance side

Fig. 1 Determining incident dose.

documented values in the acceptance test for the specific equipment.

4. Recommendations for the pregnant patient

Once the extent and point of time of the radiation exposure have been established, the radiologist has a crucial task to advise the pregnant patient or other medical colleagues regarding further action. In this situation it is essential to express sound, professionally competent recommendations in order to counter vague fears as well as erroneous downplaying of the situation from the outset.

The following explanations are standard recommendations based on the guidelines of the German X-ray Society; however the final decision is always up to the patient herself [2]. If the exposure to radiation – no matter the dose – definitely took place within 10 days p. c., a record of this is made by the physician; further calculation is unnecessary. The patient should be informed only as she requests to avoid unwarranted worry. Termination of the pregnancy is not discussed.

If exposure occurs more than 10 days after conception, the recommendations are oriented toward the applied dose.

If the dose lies below 20 mSv, the physician records this; additional calculation is not required, and an assessment is performed according to Level I. The patient should be informed regarding possible consequences only upon request. Termination of the pregnancy is not discussed.

If the dose is above 20 mSv, the physician records this; additional calculation is not required, and assessment according to Level II is required. If the value is below 100 mSv, the physician informs the patient regarding potential consequences

a) Determination of uterine dose H_U from incident dose K_E :

$$H_U = K_E \cdot f_U$$

Determination of uterine dose H_U from dose area product P_f :

$$H_U = P_f \cdot f_U$$

b) Calculation of uterine energy dose D_U from incident dose K_E using the tissue-air ratio:

$$D_U = D(d_E, x_U, F_U) = D_{dm}(d_E + x_U) \cdot T_a(x_U, F_U)$$

times

$$D_{dm}(d_E + x_U) = K_E \cdot (d_E / (d_E + x_U))^2 \cdot t_{w/a}$$

results in

$$D_U = K_E \cdot (d_E / (d_E + x_U))^2 \cdot t_{w/a} \cdot T_a(x_U, F_U)$$

c) Calculation of the uterine absorbed dose D_U from incident dose K_E using depth-dose tables:

$$D_U = D_0 \cdot D_{rel}(x_U, F_E)$$

times

$$D_U = K_E \cdot B \cdot t_{w/a}$$

results in

$$D_U = K_E \cdot B \cdot t_{w/a} \cdot D_{rel}(x_U, F_E)$$

The dose equivalent on the uterus H_U is then derived from:

$$H_U = D_U \cdot w_R$$

Legend:

B: Backscatter factor
 d_0 : Focal distance of patient's radiation entrance side (focus-skin distance)
 d_k : Reference focus distance for indicating reference dose rate
 d_E : Image receptor distance focus
 $D(d_E, x_U, F_U)$: Uterine dose (Organ absorbed dose) in focal distance $d_E + x_U$
 D_0 : Side of radiation entrance tissue-surface dose
 D_U : Uterine absorbed dose
 $D_{rel}(x_U, F_E)$: Relative depth dose for uterine dose x_U und field size F_E
 $D_{dm}(d_E + x_U)$: Dose in tissue element dm in focal distance $d_E + x_U$ free in air
 F_0 : Field size on image receptor
 F_E : Field size on patient's radiation entrance side
 F_U : Field size at depth x_U
 f_U, F_U : Organ dose conversion mSv/mGy factor for uterus with respect to the incident dose or to mSv/(mGy · cm²) with respect to the dose-area product for standardized projections.
 H_U : Organ dose for the uterus
 I_k : Tube current
 $K_E^R(I, d_0)$: Air kerma strength in focal distance d_0 as a function of tube current
 K_E : Incident dose per image or fluoroscopic segment
 P_f : Dose area product
 S : Total attenuation factor between the patient's radiation entrance side and the image receptor
 S_f : Field size factor
 S_G : Geometry factor $((d_0 / d_E)^2)$
 S_p : Patient attenuation factor
 S_R : Grid factor
 S_t : Table attenuation factor
 t : Imaging or fluoroscopy time
 $t_{w/a}$: Dose conversion factor (quotient of mass energy-absorption coefficient for water and air)
 $T_a(x_U, F_U)$: Tissue-air ratio for tissue depth x_U and field size F_U
 w_R : Radiation weighting factor for radiation quality R
 x_U : Uterus tissue depth in beam direction

Fig. 2 Determining uterine equivalent dose.

ces, and in the discussion, the physician does not mention termination.

If a determination based on Level II is greater than 100 mSv, accurate calculation according to Level III is required. If the dose is below 100 mSv, the physician informs the patient regarding possible consequences, and in the discussion, the physician does not mention termination.

If the dose according to Level III is between 100 and 200 mSv, the physician records this; the physician informs the patient regarding possible consequences. A detailed discussion between the physician and patient takes place in which the risk of fetal damage must be weighed against the patient's desire to have a child. If termination of the pregnancy is desired, the physician supports this decision. If the dose is above 200 mSv, the physician records this; the physician informs the patient regarding possible consequences. A detailed discussion between the physician and patient likewise takes place in which the risk of fetal damage must be weighed against the patient's desire to have a child. The physician suggests termination during this discussion, as needed.

Calculating uterine dose in computed tomography

$$H_U = K_{CT} \cdot \sum_{z_U}^{z_0} f_{uterus}(z)$$

$$K_{CT} = 1/S \int_{-\infty}^{\infty} K_a(z) dz$$

$$K_{CT} = 100 K_{CT} \cdot I_k \cdot t \cdot 0,01$$

Legend

$f_{uterus}(z)$: Organ dose conversion factor (mSv/mGy)
 H_U : Organ dose for the uterus
 I_k : Tube current
 K_{CT} : Average air kerma in the system axis
 t : Imaging or fluoroscopy time
 z_U, z_0 : Distance of the upper and lower boundary of the examined body from the lower end of the trunk

Fig. 3 Determining the uterine dose during CT examinations.

This course of action is additionally shown in [Fig. 4](#) as a flow chart.

5. Summary

The prenatal phase is a particularly vulnerable period for the development of deterministic as well as stochastic damage caused by the application of ionizing radiation. Therefore pregnancy represents a contraindication for the use of X-rays. However, under special circumstances, irradiation of the fetus may occur either incidentally or after careful risk assessment. In this case, advice regarding the health risks of radiation is necessary, containing the anticipated risks for the fetus without arousing unnecessary fears and concerns on the part of both the patient and the attending physicians.

In principle a differentiation should be made between deterministic injury at a definable threshold dose and stochastic radiation damage without a threshold dose. In this case, the occurrence of deterministic damage is dependent upon the gestational age of the fetus at the time of exposure as well as the level of the dose.

A three-level concept has been shown to be effective for risk assessment of in utero irradiation during a radiological examination. Depending on the severity of the exposure, an estimate of the dose or a general assessment is made based on computer models; in the most salient cases, an exact calculation as possible is made with respect to the individual event. The complexity of the determination increases with each level. While an estimate according to level one is normally feasible without a problem, calculation according to level two and particularly level three is complex and should be performed only by an expert medical physicist.

Based on the determination of the uterine dose according to the three-level concept while taking into account the age of the fetus and relying on established threshold levels and empirical values, a largely standardized counseling approach can be used with the patient. Although it contains uncertainties, this approach provides both the pregnant woman as well as attending physicians with a basis for action which can be used for further decisions. The risk to

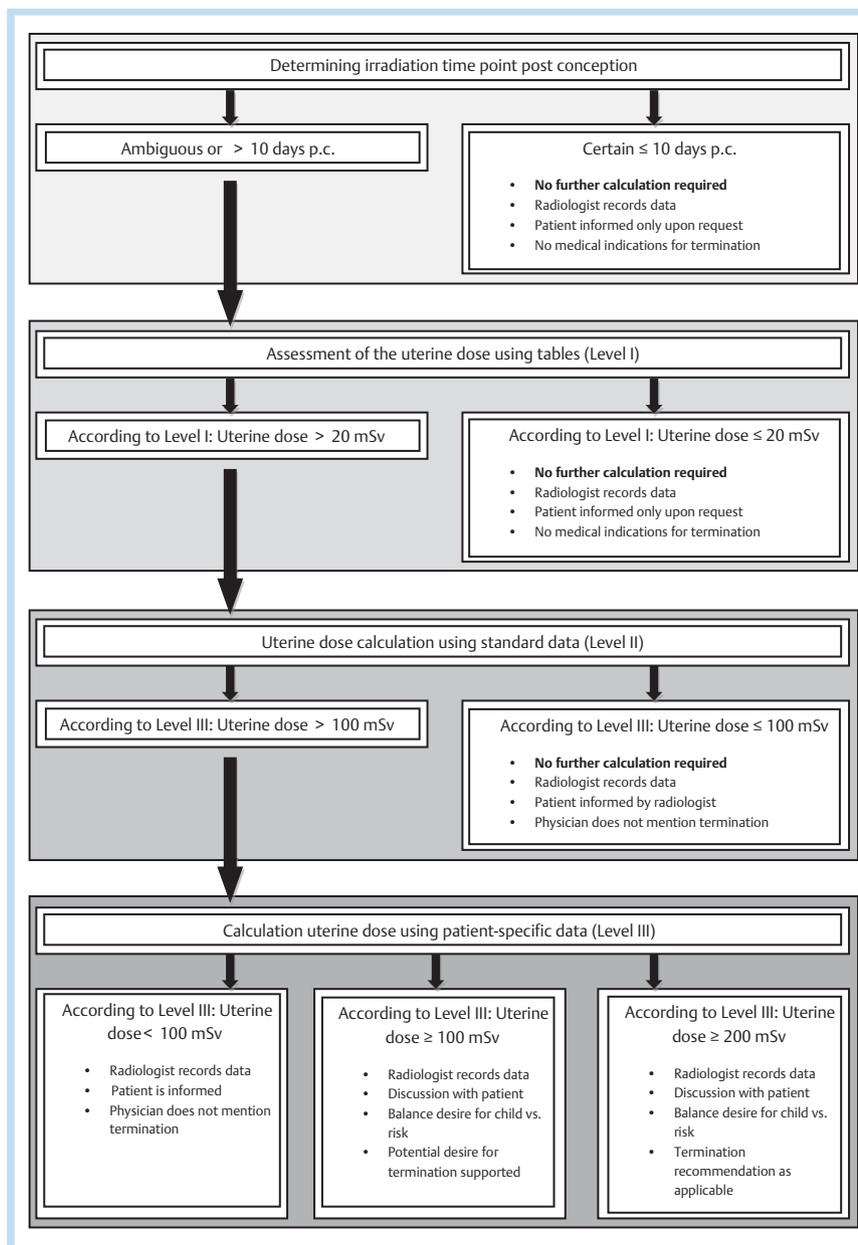


Fig. 4 Flow chart for determining radiation exposure and recommendations for subsequent consequences.

the fetus is generally low if the exposure to radiation occurs in the course of diagnosis. The uterine dose is below 5 mSv for approx. three-quarters of examinations [31]. The physician should always explain the risks in terms of deterministic or stochastic injury compared to the related spontaneous risk of malformation. Calculations are subject to uncertainties, particularly due to the limited study opportunities, the low number of cases as well as data based on animal experiments; the pregnant patient should be made aware of this. During the evaluation, additional potential risks as well as the desire of the patient to have a child should also be taken into account. Furthermore, the results of additional diagnostics should be considered, perhaps in consultation with a human geneticist. However, the final decision should and must rest with the patient herself once she has been fully and objectively informed regarding the possible risks of irradiation.

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